Why Nuclear Power has been a Flop
at
Solving the Gordian Knot
of
Electricity Poverty and Global Warming

Third Edition

Jack Devanney

Sisyphus Beach

Tavernier, Florida

2023

Published by The CTX Press
142 Lyons Road
Stevenson, WA 98648

Publishers's Cataloging-in-Publication Data
Devanney, Jack

Why Nuclear Power has been a Flop / Jack Devanney — Tavernier, Fla :
The CTX Press, 2023

p. : cm.
ISBN xx: xxx-x-xxxxx-xxx-x
Version: /nfs/TC/gordian/x1/

1. Energy Poverty. 2. Global Warming. 3. Nuclear Power. 4. Electricity. I. Devanney, Jack. II. Title

Printed in the United States of America
10 09 08 07 06 • 5 4 3 2 1

Contents

List of Tables

List of Figures

Precis

This book is a collection of essays focused on the Gordian knot of our time, the closely coupled problems of electricity poverty for billions of humans, and global warming for all humans. The central thesis is that nuclear electricity is not only the only solution, it is a highly desirable solution. The three main objections to nuclear power are addressed in the order of waste, safety, and cost. The book argues that nuclear power is not inherently costly. Nuclear power is inherently cheap. This brings us to the heart of the beast.

Why the Flop If nuclear power has everything going for it: dispatchable, incredible energy density, tiny amount of waste, tiny amount of land, near zero pollution, near zero CO2 emissions, why has nuclear power never produced much more than 15% of the planet's electricity? And now even that paltry percentage is declining. In much of the world, nuclear electricity is so expensive that fully depreciated plants cannot compete with fossil fuel on operating cost. We could have lifted billions out of electricity poverty. We could have had massive reductions in air pollution and CO2 emissions. Instead nuclear power is withering away. Why despite the remarkable promise, has nuclear power been such a tragic flop?

ALARA The usual answer is radiation, radiation, radiation. But, as we shall see, nuclear power priced itself out of the market before there was wide spread concern about nuclear power safety. The real problem lies within. Nuclear power never escaped from its government sponsored and controlled birth. In the process, it developed a regulatory regime explicitly mandated to increase costs to the point where nuclear power is barely economic, while at the same time convincing everyone that low dose radiation is perilous. Under this policy, known as ALARA, no amount of radiation exposure is acceptable if the plant can afford to reduce it further.

- Under ALARA, unless nuclear electricity is as expensive as the alternatives, the regulator is not doing his job. This same regime does an excellent job of stifling competition and technical progress by eliminating investor incentives and erecting layers of barriers to entry
- Under ALARA, the standard solution: a cheaper nuclear technology won't work. If any such technology really is inherently cheaper, that simply provides regulators with more room to drive costs up.
- Under ALARA, nuclear electricity can never be cheaper than coal or gas electricity. Our goal should not be to just make nuclear power as cheap as coal or gas fired power. Our goal must be to keep pushing the cost of nuclear electricity down and down, allowing us to replace fossil fuels almost everywhere, including transportation and industrial processes.

The Enemy is Us This can be done but only in a harshly competitive environment. But the nuclear power establishment has opted to feed at the public trough, falling into the trap of spending billions of taxpayer dollars annually to solve problems that either don't exist, or have simple, cheap solutions. This requires that they embrace a model which massively exaggerates the risks of low dose radiation. This in turn forces them to make the false claim that the probability of a sizable release of radioactive material is so small that we don't have to worry about it. This lie is quickly revealed and an angry public turns against nuclear power. The nuclear power establishment is the reason why nuclear power has been a flop. It is a tragic story. But it is also reversible if we have the will. Let's get started.

Product Warning, added October, 2022

Everything is breaking in nuclear power's favor. The reality that wind and solar cannot come close to supporting a decarbonized planet is just beginning to set in. With coal at over $400 per ton, Henry Hub gas at $8/mmbtu, and European gas at god knows where, even atrociously expensive nuclear looks like a bargain. The Finns are bragging about a plant that cost over $9000/kW and took 15 years to build. Hell, even Vogtle 3/4 might look economic if things continue to deteriorate.

One of the many tragedies of the current mess is that fossil fuel prices have temporarily outpaced ALARA, which will convince the nuclear establishment that ALARA and all its implications are acceptable. All we need is more taxpayer money and everything will be fine.

This is a repeat of 1970's boom, which took nuclear's real cost from less than 3 cents/kWh to multiples of that price. This tragedy is described in Chapter 9. When fossil fuel prices crater, nuclear will be worse off than ever, and humanity will be screwed.

We must have truly cheap nuclear, like the nuclear we had in the late 1960's.

If and only if we have nuclear that is cheaper than fossil fuel's long run cost, will we have a low carbon, dispatchable source of electricity that the developing world can afford.

If and only if we have such low CO2, dispatchable electricity at less than 3 cents per kWh, do we have a shot at producing hydrogen at $1.50/kg. Then we can make ammonia for fertilizer without methane, and possibly convert primary steel making away from coal and coke.

If and only if we have hydrogen at this price, we may be able to produce synthetic liquid fuels, at a cost that is close enough to petroleum that a tolerable carbon tax will make them competitive.

Expensive nuclear is no where good enough. Expensive nuclear will continue to be a Flop.

All you need to know

Nuclear power is remarkably simple. But to read this book does require just a bit of technical background. For non-technical readers, here's what you need to know.

Just about all ordinary matter is made up of about 100 *elements.* The elements in turn are made up of a tiny nucleus surrounded by a cloud of electrons. The nucleus is made up of protons and neutrons. Each element is distinguished by the number of protons in its nucleus; hydrogen has 1 proton, helium has 2 protons, and so on. But the number of neutrons in a hydrogen nucleus can be 0, 1, or 2. Most elements have the capability of accommodating differing numbers of neutrons in their nucleus, at least for a while.

A particular combination of protons and neutrons is called an *isotope.* Hydrogen nuclei with 0 or 1 or 2 neutrons are all isotopes of hydrogen. There are over a 1000 known isotopes, although most are very rare. In this book, a particular isotope is indicated by ^{n}Xx where the superscript tells us the total number of neutrons and protons, the isotope's *mass*, and the 1 or 2 letters tells us which element we are talking about (the number of protons). The three isotopes of hydrogen are ^{1}H, ^{2}H, ^{3}H. Sometimes I will just spell this out, e.g Hydrogen-2.

A few isotopes will split into two much lighter isotopes when hit with a neutron. The only such isotope that occurs naturally in usable amounts is Uranium-235 (92 protons, 143 neutrons) or ^{235}U. When such an isotope splits or *fissions*, it releases a remarkable amount of energy, ***about 50 million times more energy than that created by combining a carbon atom with oxygen to produce CO2.*** It also releases 2 or 3 neutrons. Under the right conditions, those neutrons can hit another fissionable nucleus producing a self-sustaining chain reaction. The job of a nuclear reactor is to maintain the right conditions for a chain reaction, known as controlling the *reactivity*, while capturing the energy that is released in the process.

The lighter isotopes that result from this split are called *fission products.* Some of these fission products are unstable, combinations of protons and neutrons that cannot stay together for long. These unstable isotopes spontaneously *decay* to another isotope. We will sometimes talk about becquerels (Bq) which is the number of atoms that decay in one second. If the daughter isotope is also unstable, that isotope will decay to yet another isotope. This process continues until it reaches a stable daughter isotope.

Each unstable isotope decays at its own rate, which is measured by the isotope's *half-life*, the time it takes for half of the isotope to decay to something else. Some fission products decay extremely rapidly. They have half-lives that are a small fraction of a second. A few decay very slowly with half-lives of thousands of years. If an isotope has a half-life of 1 year, than half the isotope will have decayed in the first year after its creation, another half in the second year, and so on. Ten half-lives will reduce the isotope to one-thousandth of its original mass.

When an isotope decays, it releases energy. For our purposes, this energy can take one of three forms:

1. An alpha particle which is made up of two protons and two neutrons tightly bonded together.

2. An electron similar to the electrons produced by old fashioned, cathode ray televisions.
3. A high energy photon. This is the same particle that makes up sunshine, but higher energy.

The health hazard associated with these three particles will be the subject of a large part of this book.

Some of the neutrons produced in a reactor do not create a fission. Rather they are absorbed into a non-fissionable nucleus and by some quantum wizardry produce a new, slightly heavier element. Most of the uranium in a nuclear reactor is Uranium-238 (92 protons, 146 neutrons). For practical purposes, ^{238}U does not fission. When ^{238}U absorbs a neutron, it turns into Neptunium-239 (93 protons, 146 neutrons). Elements which have more protons than uranium are called the *transuranics*. This neutron absorption process can continue producing a range of transuranics.

All the transuranic isotopes are unstable. For example, ^{239}Np decays by emitting an electron and becomes Plutonium-239 (94 protons, 145 neutrons). ^{239}Pu is fissionable. In fact, it is an excellent nuclear fuel. And in the relative absence of other plutonium isotopes, it can be turned into a bomb. One of the jobs of a reactor designer is to fission as much of the ^{239}Pu as possible while making it difficult to extract nearly pure ^{239}Pu from the reactor.

Living tissue is made up of cells. Cells are mostly water. If one of the particles created by radioactive decay enters a cell, it transfers a portion of its energy to the cell mainly by breaking the chemical bonds that hold the water molecule together. This is called *ionization*. Particles with enough energy to do this are called *ionizing radiation*. Ionization creates highly reactive, free radicals which can disrupt the cell's chemistry. The amount of energy that a particle deposits in tissue, the *dose*, is measured in joules per kilogram of tissue. The shorthand for joules per kg (J/kg) is called a gray (Gy). The assumption was that the amount of cell damage was proportional to the dose in grays. This proved untenable, so a modified dose was concocted which multiplies the dose in grays by a factor which depends on the type of particle and its energy. For photons and electrons the factor is 1.0. For alpha particles the factor is 20. This modified unit is called a sievert (Sv). If you receive a full body dose of 6 Sv ***over a short period of time***, an hour or two, you will probably die due to bone marrow failure in a few weeks. We shall see that, thanks to the effective damage repair processes with which Nature has equipped us, dose rate is far more important than total dose, when it comes to harm from radiation.

A sievert is a large amount of energy per kg tissue. We live in a sea of natural radiation. The background dose rate on this planet from natural radioactive sources varies from about 0.000003 Sv/day to more than 0.0001 Sv/day. So throughout this book we will be talking about millisieverts (mSv), one-thousandth of a sievert, and microsieverts (μSv), one-millionth of a sievert.

That's all you need to know to read this book.

Abbreviations

ACRS Advisory Committee on Reactor Safeguards
AEC Atomic Energy Commission
ALARA As Low as Reasonably Achievable
ARS Acute Radiation Sickness
BEIR Biologic Effects of Ionizing Radiation
CAPEX Capital Expense
CF Capacity factor: ratio of actual output to nameplate output.
DOE US Department of Energy
DSB Double Strand Break
EAR Expected Absolute Risk
ENSAD Energy Related Severe Accident Database
ERR Excess Relative Risk
GW Gigawatt: 1,000,000,000 watts
HBR High Background Radiation
IAEA International Atomic Energy Agency
ICRP International Commission on Radiological Protection
IPCC Intergovernmental Panel on Climate Change
LCOE Levelized Cost of Electricity
LEU19 Fuel that has been enriched in ^{235}U to just below the legal limit of 20%.
LLE Lost Life Expectancy
LNT Linear No Threshold
LWR Light Water Reactor
MW Megawatt: 1,000,000 watts
NCRP National Council for Radiation Protection
NPP Nuclear Power Plant
NPT Nuclear Non-Proliferation Treaty
NRC Nuclear Regulatory Commission
RERF Radiation Effects Research Foundation
RSS Reactor Safety Study
SIR Standardized Incidence Rate
SMR Standardized Mortality Rate
SNT Sigmoid No Threshold
TMI Three Mile Island
TRU Transuranics
UCS Union of Concerned Scientists
UNSCEAR United Nations Scientific Committee on the Effects of Atomic Radiation
VLCC Very Large Crude Carrier
WHO World Health Organization
W/S Wind and Solar Power

Chapter 1

The Gordian Knot

1.1 Electricity Poverty

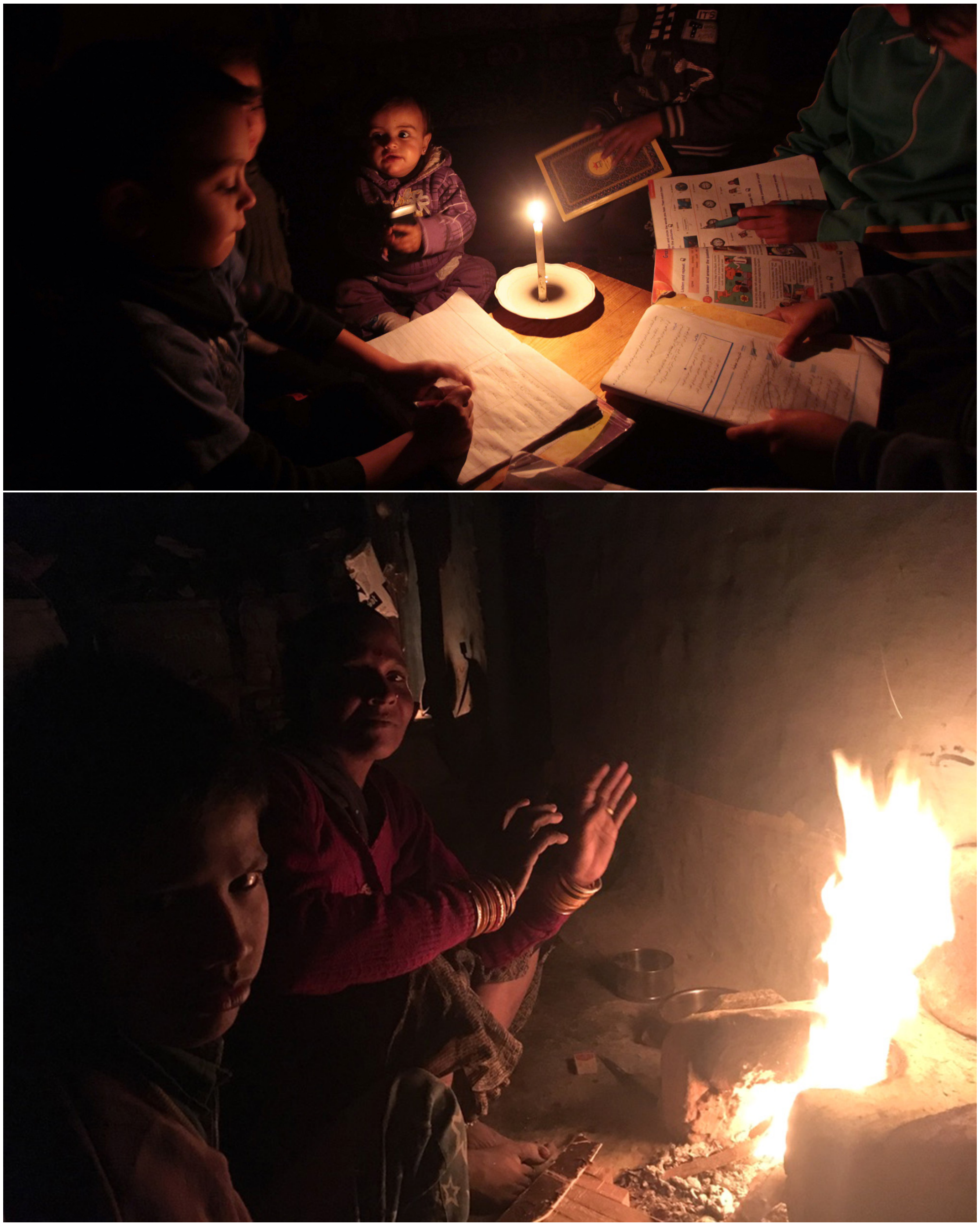
A portion of mankind is awash in electricity. For these lucky humans, darkness has been banished. They live in homes and work in offices where 70F is too hot in the summer and too cold in the winter. All the hot water they can use is available with a flick of the wrist. All the ice they can consume is available on demand. Food can be stored pretty much indefinitely. Machines wash and dry their clothes and clean their dishes. Electric powered robots are taking over manual task after manual task, freeing up people to do all kinds of mischief. Electric powered server farms store all the world's knowledge, millions of terabytes of trivial data, and very little wisdom. Electricity is the foundation of their economies and their wealth.

For these people, it is hard to imagine what life without electricity is like. Currently mankind consumes electricity at a rate of about 3,000 gigawatts(GW). But the distribution is horribly uneven as Table 1.1 shows. The USA consumes 1,500 watts per person. The Scandinavian countries considerably more. But most of Latin America is below 250 W. Most of South Asia below 125 W. Much of Africa below 25 W. The national averages mask wide disparities. Nearly a billion humans have no access to electricity at all.

	W/person		W/person		W/person
Norway	2,593	Iran	451	Pakistan	71
USA	1,478	Iraq	373	Bangladesh	62
Australia	1,187	Brazil	333	Ethiopia	56
France	918	Mexico	277	Angola	36
Russia	849	Egypt	222	Nigeria	17
Germany	779	Columbia	168	Afganistan	16
China	617	India	129	Uganda	9
Italy	534	Indonesia	115	Haiti	4
South Africa	461	Philippines	106	Chad	1

Table 1.1: Electricity consumption per person

All of us, including the people who fly around to Climate Change conferences, need to reflect on what it means to be without electricity.



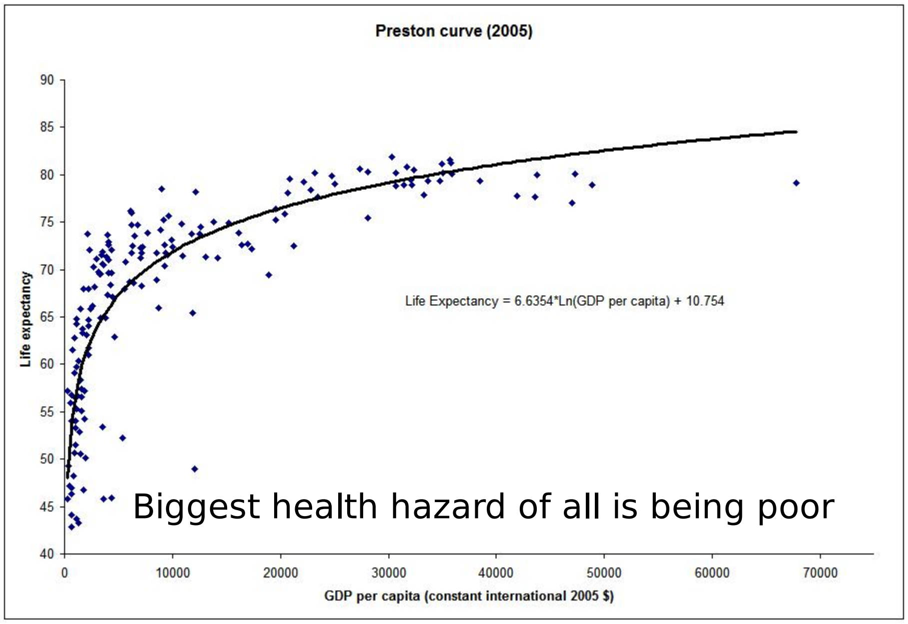


Figure 1.1: Life expectancy versus GDP. Each dot is a country. The dots hide large intra-country disparities. In the USA, a wealthy country, the difference in years of life expectancy between the top 1% in income and the lowest 1% is 14.6 (men) and 10.1 (women).

Globally the worst health hazard of all is being poor. The difference in life expectancy between the poorest and wealthiest humans is measured in decades, Figure 1.1. Wealth requires electricity. A rough rule of thumb for developing economies is every kWh per capita consumed is worth five dollars in per capita GDP.

Another way to look at this is via the United Nation's Human Development Index(HDI). The HDI is a somewhat arbitrary combination of longevity, wealth, and education. Figure 1.2 plots the HDI against electricity consumption. Unfortunately, the HDI tends to squash countries together. Looking at the HDI, you might get the impression that the quality of life in Chad is maybe half that of Norway. The table inset into the top frame of Figure 1.3 tells a different story. The top 15 countries consume something like 500 times as much electricity per capita as the bottom 15. But Figure 1.2 does make a couple of points:

1. For high electricity consumers, the curve is rather flat. These people could get by with a little less electricity without a really major impact on their lives.
2. But for the low consumers, the curve is quite steep. For these people, a little more electricity is literally a matter of life and death. Consume less does not work for them.
3. The size of the circles represents population. An awful lot of the planet's humans are in the steep part of the curve.

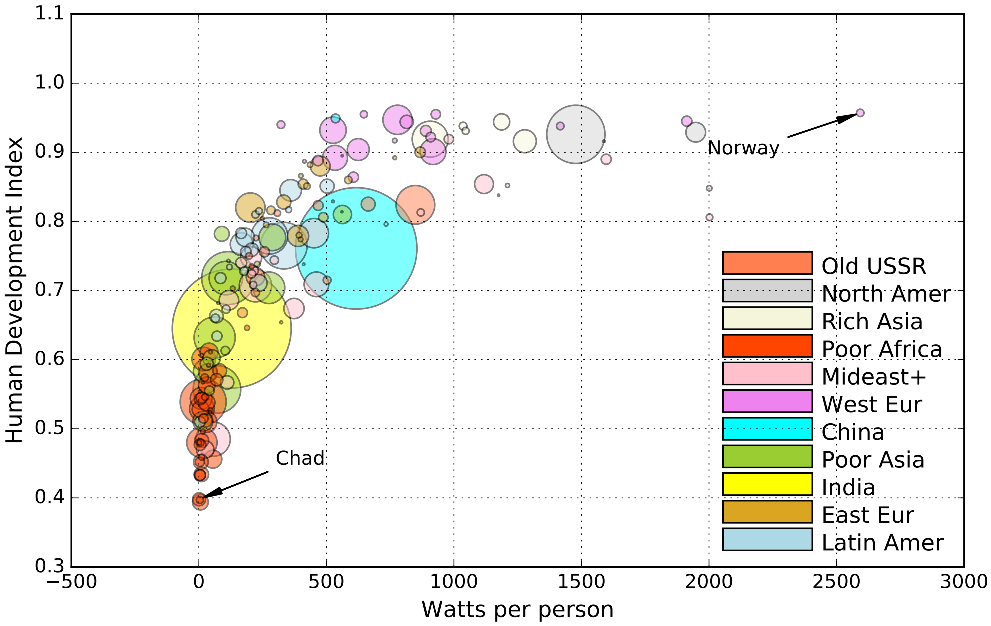
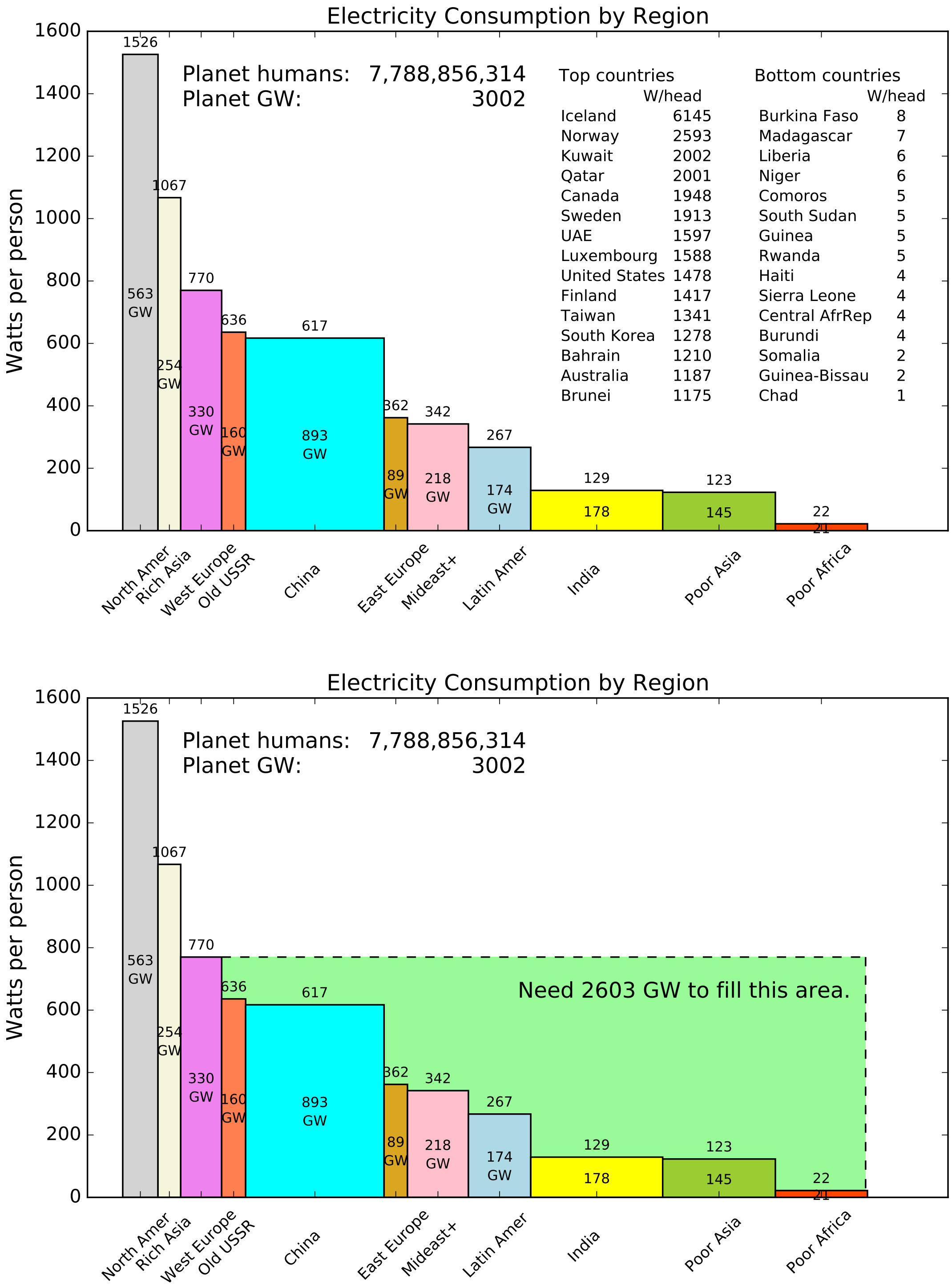


Figure 1.2: Human Development Index versus per capita electricity consumption. Size of circles is proportional to population.

If mankind is to prosper, then clean, affordable, dependable electricity must be available to all. And we must provide this power without polluting the air we breathe, without poisoning the land we live on, and without impacting the climate we depend on.

The developing countries are aggressively moving to close the electricity gap. As Figure 1.3 indicates, this will require at least 2,000 gigawatts of new capacity over the next 20 years, or 100 one GW plants per year, about 2 per week. As things stand now, most of these plants will be coal fired. According to Greenpeace as of March, 2019, 674 GW of new coal plants are planned or under construction with another 483 GW on hold.[227] In aggregate, these new coal plants will require 3 billion tons of coal annually, kill or shorten the lives of at least 400,000 people per year, and produce about 8 billion tons per year of CO2.



Top countries	W/head
Iceland	6145
Norway	2593
Kuwait	2002
Qatar	2001
Canada	1948
Sweden	1913
UAE	1597
Luxembourg	1588
United States	1478
Finland	1417
Taiwan	1341
South Korea	1278
Bahrain	1210
Australia	1187
Brunei	1175

Bottom countries	W/head
Burkina Faso	8
Madagascar	7
Liberia	6
Niger	6
Comoros	5
South Sudan	5
Guinea	5
Rwanda	5
Haiti	4
Sierra Leone	4
Central AfrRep	4
Burundi	4
Somalia	2
Guinea-Bissau	2
Chad	1

Figure 1.3: Regional distribution of electricity consumption. Width of each bar is regional population; height is per capita electricity; area is regional electricity consumption. Sources: World Bank, BP Statistical Review of World Energy, 2021

1.2 Global Warming

In this tract you will find almost no discussion of the horrors of global warming.[1] Rather I take for granted that global warming is both real and almost entirely man made. At a minimum we are facing a substantial sea level rise and a dangerous change in ocean acidity. The costs are quite likely many trillions of dollars large; but the uncertainties in the costs are even larger. The uncertainties are fat tailed which means the upper extreme, a runaway warming, cannot be ignored.[2]

In such a situation, it is simple common sense to be willing to pay an enormous price for effective insurance, if we had to. The central thesis of this book is that nuclear power, ***efficiently regulated***, can provide that insurance at zero cost. The crux of the matter, we shall see, is that little phrase "efficiently regulated".

But I do need to point out the implications of a largely decarbonized energy system. If as this book claims, nuclear power, efficiently regulated, can provide unlimited, dependable electricity at 3 cents per kilowatt-hour (kWh) or less, then all sorts of necessary changes become possible.

1. The electrification of residential and business heating.
2. The electrification of most industrial processes.
3. The electrification of most land transportation
4. The provision of carbon neutral synthetic fuels for long haul marine transportation, aviation, and other markets where direct electrification is uneconomic.

To do all this will require at least 2000 watts per person, or about triple the current European per capita electricity consumption. For example, the HYBRIT project to move Swedish steelmaking away from coal and coke will need 6.3 GW's of new power. 6.3 GW is one-third of Sweden current electricity consumption. If we combine these needs with the projected growth in population, ***we could easily see a need for 25,000 GW in the not too distant future,***

---

[1] Claims that global warming will fry the planet in 10 years or 20 years are counter-productive nonsense. Like all such doomsday pronouncements when we wake up on the day after the apocalypse, these messiahs will be revealed as fools; and the valid part of their message trashed with the preposterous. Planet heating is not a thunderclap. It is a progressive disease.

[2] The first people to raise the global warming issue after the war were people who were part of or closely associated with nuclear power. Edward Teller told the American Chemical Society in 1957 that if we continue to burn coal and oil at the current rate, the polar icecaps would melt. Later in the year he repeated that warning to a hostile audience at the annual meeting of the American Petroleum Institute.[17][p 245] In the same year, Roger Revelle, an oceanographer who figured out the net uptake of CO2 into the oceans was much smaller than previously thought, pointed out "human beings are now carrying out a large scale geophysical experiment of a kind that could not happen in the past nor be repeated in the future." But he wasn't worried. He thought we'd all swap over to nuclear energy soon enough. In the 1970's, Albert Weinberg, the inventor of the pressurized water reactor, made a nuisance of himself, going around Washington with charts showing the increase in atmospheric CO2 and his planet heating projections. But these guys were the same people who brought us the bomb. One of the reasons the counter cultural green organizations were slow to embrace global warming was they regarded it as an argument for nuclear power.[17][p 325] These priorities persist today in Germany (and elsewhere), where eliminating nuclear electricity is more important than reducing atmospheric CO2.

Figure 1.4. 25,000 large power plants. A staggering number. But not surprising. We must replace the great bulk of the entire fossil fuel industry. We need a dependable power source that is not only cheap, that is, economical in its use of the planet's resources, but expandable on a grand scale.

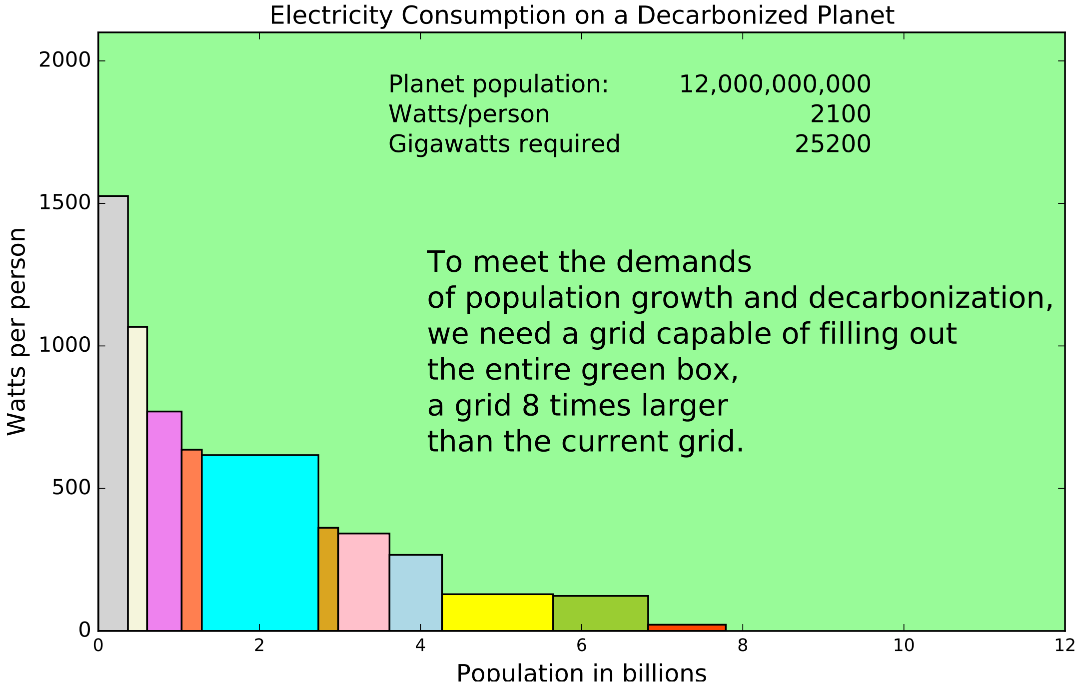


Figure 1.4: Electricity consumption in decarbonized world.

But that's not the end of it. Currently, we are over-stressing water supplies in many areas of the planet. We need enormous amounts of desalination. UNESCO in 2002 estimated the shortage then was 230 billion cubic meters per year which would go to 2000 billion m3 in 2025.[283] Desal requires 3 kWh of electricity per cubic meter of fresh water. Using the UNESCO numbers, the planet will need 685 GW for desal in 2025.[3] Capital intensive processes like desal must operate 24/7 to be economic. Desalination requires cheap, non-intermittent electricity and lots of it.

But that's not the end of it. We cannot completely stop emitting CO2. See Section A.4. CO2 capture is inevitable. But CO2 capture is both extremely capital and extremely energy intensive. To remove 20 gigatons per year, which would remove the current excess CO2 over 50 years if we stopped emitting today, would require at least 600 GW of power.[127] A more

---

[3] Most water use is for agricultural purposes. For some crops, indoor vertical farming can reduce water consumption by up to 95%. But power requirements for artificial light are roughly 10 times that of conventional green houses. Vertical farming only works if really cheap 24/7 electricity is available.

realistic number covering the CO2 we will continue to emit even in a highly decarbonized planet is 3 or 4 times this number. CO2 capture requires cheap, non-intermittent electricity and lots of it.

We can decarbonize, we can preserve our environment; but only if we have lots and lots of reliable, pollution-free, CO2-free electricity, which consumes land and other resources in as miserly a manner as possible.

1.3 Electricity's Fundamental Flaw

Electricity is an amazing form of energy. It can run motors. It can light; it can heat; it can cool. It can transmit information. It can store information. Without it there are no radios, no TV's, no computers, no cell phones, no any kind of phones. And it can do all this while producing nearly no pollution nor CO2 as it is used.

Electricity in the form we need is not found in nature. We must produce it from other kinds of energy. And this brings us to electricity's one fundamental flaw. It is exceedingly difficult and expensive to store. This means we must distinguish between *dispatchable* sources of electricity, sources which can be turned on as needed; and *intermittent* sources of electricity, sources that do not have that capability.

Dispatchable and intermittent sources cannot be compared directly. They produce two different commodities. With enough storage, intermittent electricity could be converted to nearly dispatchable; but the costs of doing so with current technology are such that, for grids that need reliable electricity, intermittent sources require close to 100% back up with dispatchable sources.[4] In most situations, the dispatchable "back up" sources end up producing most of the electricity.

Perhaps a little parable will help. I live in a very rainy area on the west flank of the Cascades in Washington state. We get 2 meters of rain per year, a layer of water taller than I. Yet my neighbors who are not hooked up to a municipal water system all have wells.

Rain water and well water are both water. But they are not the same commodity. Rain is free. A well requires drilling, piping, a pump, and then power to run that pump. Why would anybody pay for a well, the pump and the power, when they can have the rain for free? The answer of course is the well water is there whenever you need it. Rain is intermittent. It is not under your control.

With enough storage, rain can be converted to a semi-reliable source of water. But none of my neighbors have cisterns. The costs and limitations of cisterns result in their using wells instead. If I asked my neighbors, why are you using well water and not the free rain, they would correctly assume I had gone bonkers. If any of them bothered to answer, it would be with question. Do you know how much it costs to store rain?

Rain is far, far cheaper and easier to store than electricity.

---

[4] See Appendix A for back up for this claim.

There are three low CO2 sources of dispatchable electricity:

1. Geothermal.
2. Hydro.
3. Nuclear.

Geothermal power and hydropower are limited to areas with unusually favorable geology and topography. In many cases, these locations have already been fully exploited. Expanding these sources in a manner that will produce the amount of electricity that the planet needs is simply not feasible.

Humankind needs ten thousand billion watts or more of dispatchable, very low CO2 electricity. But if nuclear electricity is unacceptably dangerous or inherently too expensive, then the species must and will continue to depend on burning fossil fuels. The rest of this book explores the dangers and costs of nuclear power.

Chapter 2

Plutonium

Plutonium is the most dangerous substance known to man.[Walter Cronkite, 1977]

Much of what you have been told about nuclear power is false. This is an enormously bold statement of which you should be extremely sceptical. I face a formidable task in overcoming that scepticism.[1] So let's start with an easy one. Everybody knows plutonium is a horribly dangerous material. But if this is false, what else is?

---

[1] Not all these falsehoods are anti-nuclear. The nuclear power establishment has promulgated a very important lie, which we will discuss in Chapter 4

2.1 The Most Dangerous Substance Known to Man

Plutonium is the most dangerous substance known to man. We know this because Walter Cronkite told us so. Cronkite was the dean of network broadcasters and at the time (1977) one of the most trusted voices in America. Ralph Nader told us just how dangerous. Nader said a pound of plutonium could kill 8 billion people. (speech at Lafayette College, spring 1975). He repeated that claim many times, as have many others, over and over, sometimes mixing apples and oranges:

> a piece of plutonium the size on an orange is sufficient to kill the population of the British Isles.[215]
>
> The byproduct of breeder reactors, Plutonium-239, has a half-life of 25,000 years, yet experts suggest that a lethal dose for the whole human race need not be larger than an apple.[215]

As a whole the public accepts these claims which are reinforced by movies such as Edge of Darkness (1985) which has the principle character Jedburgh dying of radiation sickness following contact with plutonium. As a whole the nuclear establishment has made no attempt to counter these claims.[2] But....

In 1956 at the opening of the Calder Hall plutonium production facility in the UK, a young Queen Elizabeth was invited to handle a lump of plutonium and feel the warmth of the extraordinary material, which she did.[83] The shielding was a plastic bag and I presume the royal gloves. The Queen outlived almost all her contemporaries.

I need to preface this next story with a little bit of background. If enough highly enriched plutonium, called the *critical mass*, is brought together into a single piece, it will produce a short lived, chain reaction, a blue flash of neutrons and photons, which can be fatal if you are close enough to it. This happened twice in the US bomb program when mistakes were made during the bomb core assembly process. In both cases, the assemblers, Harry Daghlian and Louis Slotin, died of acute radiation sickness within a few weeks.[3]

Galen Winsor worked at the US plutonium production plant at Hanford, Washington for 15 years. The staff there regularly carried around lumps of highly enriched plutonium in their lab coat pockets. Here's Galen describing the process in a 1985 video:[4]

> Well, through the years we got pretty good at telling what a critical mass was, and I have worked in a plant where I had half a critical mass in this hand, barehanded and

---

[2] This surprising behavior will develop into a major theme of our story. Bernie Cohen and Ted Rockwell are renegade exceptions. Another was Eric Voice, who one source claims was the man who handed the Queen the plutonium. Dr. Voice volunteered to be injected with and to inhale small doses of plutonium to trace its behavior in humans. He died of natural causes at 80.

[3] Daghlian received 5900 mSv in a second or two. He died 25 days later. Slotin was hit with 21,000 mSv, and died in 9 days.[157][Ch. 2] In both cases, everybody else in the room survived with little or no after effects.

[4] https://www.youtube.com/watch?v=ejCQrOTE-XA.

Figure 2.1: Delivery of Trinity Test core pieces to assembly room, 1945-07-12.

> dressed in street clothes, and half in this hand, wearing a lab coat, and I'd put this half in a pocket on this side and this half in a pocket on this side and walk down the hall. If those two ever got together, there'd be a blue flash. They never got together because I was between them. And we'd do that every day. And each half had definite dimension characteristics, and so we'd take them down and pass them on half at a time and they'd measure it and say, "Yeah, that one passed". And then we'd pass the other half, and that one will pass too, but they were carefully put in separate bird cages, so they would not get together accidentally.

Winsor died in his eighties.

Figure 2.1 shows Sergeant Herbert Lehr delivering the plutonium core pieces for the Trinity test into the assembly room at the test site. The plutonium he is carrying in his right hand is in shock-mounted birdcages. Philip Morrison, one of the smartest physicists of all time, a man who understood radiation well, carried the core pieces the 210 miles from Los Alamos to Alamogordo in a standard Army sedan. Morrison lived to be 89.

So how can we reconcile Cronkite and Nader with Winsor and Morrison? The answer is simple. What Nader and the other claimants almost always forget to mention is that plutonium emits alpha particles. Alpha particles have almost no penetrating power. They will be stopped by a piece of paper or a few centimeters of air or a royal glove.

Lesson 1: for plutonium to be hazardous it must be ingested or inhaled.

The Manhattan Project managers understood this. They undertook a number of experiments to find out how dangerous. Their problem was the human body is terribly inefficient at absorbing plutonium. Plutonium will quickly react with air to form insoluble oxides.[5] The body has no use for these ceramics. The plutonium oxide molecule is so large that it has trouble penetrating cell membranes. 99.99% of any ingested plutonium will be excreted in a day or two.[50][p 247] The experimenters had to figure out a way around this.[6] Their solution was reprehensible.

In 1950, eighteen people, ages 4 to 69, were injected with plutonium without their knowledge. All these people had been diagnosed with terminal disease. Eight of the 18 died within 2 years of the injection, all from their pre-existing illness or cardiac failure. None died from the plutonium.

One of the involuntary subjects was Albert Stevens, a 58 year old house painter. Stevens had been misdiagnosed. His terminal stomach cancer turned out to be an operable ulcer. Stevens died at the age of 79 of heart failure, never knowing he had been injected. The researchers made every effort to maximize the damage. Stevens and the others were injected directly into the blood stream with highly soluble plutonium nitrate.

For radioactive material that is ingested or inhaled, there are two factors that can be even more important than the material's radioactive decay rate and the energy released per decay.

The uptake The fraction of ingested/inhaled material that is absorbed into the body and distributed to the various organs.

The biological half-life How long does the absorbed material stay in those organs before the body eliminates it in the normal course of events.

Plutonium has very low uptake; but once absorbed it has a biological half life of about 200 years. By shooting the Pu directly into Stevens' blood stream, the experimenters guaranteed that Stevens would carry nearly all that plutonium to his grave. There are many isotopes for which the biological half-life is far shorter than the radioactive half life. For example, the slow decaying fission product, technetium-99, has a radioactive half-life of 211,000 years. It's biological half-life in humans is about a day.

The other problem the experimenters faced is ^{239}Pu, the principle bomb isotope, has a half-life of 24,000 years. It decays far too slowly for their purposes. To inflict the dose they wanted, they had to spike the injection with ^{238}Pu. ^{238}Pu has a half life of 88 years. It emits alpha particles 300 times as rapidly as ^{239}Pu. Almost all the dose that Stevens received was from ^{238}Pu, an isotope that is an extremely tiny amount of nuclear waste. The ^{238}Pu had to be produced separately from the bomb making process in a research reactor.

---

[5] In the form of shavings, this oxidation is rapid enough to start a fire. This happened several times at the Rocky Flats weapons plant in Colorado.[157][p 236-248]

[6] Bernie Cohen, a world renowned radiation health expert, offered to eat as much plutonium oxide as Nader would eat caffeine. Nader did not accept the challenge.

Over the 21 year period between his injection and his death, Stevens' body received a cumulative dose of 64,000 mSv. According to the central hypothesis that guides our nuclear regulatory policy, known as Linear No Threshold (LNT), he should have been dead 10 times over. We know he would have died in a week or two if he had received one-tenth of that dose in a period of a few hours or less. As it was, ***his body absorbed and repaired 8 mSv/day for 21 years.***[7]

Most opponents of nuclear power believe that it is the long lived material, stuff that remains radioactive for millenia that is the real problem. In fact, it is the very short lived substances that kill because they release highly penetrating energy fast enough to overwhelm the body's repair mechanisms. These are the particles that killed Harry Daghlian and Louis Slotin. As we shall see, it's dose rate, not dose that kills. Plutonium is not only an alpha emitter, it releases its particles slowly, far more slowly than the radon that is found in just about every basement in the USA.

Lesson 2: if plutonium somehow did get into our blood stream, for which there is no efficient natural pathway, the radiation is released gradually, so gradually that the body's repair processes are usually able to cope with the damage.

That leaves the inhalation route. It turns out that

1. if you create a very fine plutonium dust,
2. somehow deliver just the right amount of this mist to the right place in everybody's lungs,
3. assume that the LNT hypothesis is correct, that the rate at which the dose is delivered is irrelevant despite the fact that the gradual plutonium dose rate will be within the capabilities of our repair processes,

then you can come up with a number which is only 4000 times lower than Nader's claim.[50][p 247] In a debate with Nader, Ralph Lapp, a radiation expert, pointed out that you could make the same claim for air. Take a tiny bubble of air, inject it in just the right way into the bloodstream, and a fatal embolism will occur. That's why nurses carefully squirt out a little bit of liquid before giving you a shot.

Nader's argument depends on an unrealizable delivery scenario. God knows we tried. During atmospheric bomb testing in the 1950's through 1963 when almost all such testing stopped, about 4000 kg of plutonium was released into the atmosphere, 10,000 times the amount that Nader said would kill us all. Fortunately the transfer of plutonium to people's innards is horribly inefficient. Best guess using International Commission on Radiological Protection (ICRP) models is that about 0.25 grams of the atmospheric plutonium ended up in human bodies.[216][p 20] The cumulative dose through 1974 per person is estimated at 0.16 mSv to the lung, 0.09 mSv to the bone, and 0.05 mSv to the liver.[19] These figures are 100 to 200 times smaller than the lifetime alpha dose to these organs from natural sources.

There are all sorts of substances that will kill people much more surely than plutonium (or air) if you concoct a Nader-like delivery scenario. They include relatively common industrial

---

[7] The repair may not have been completely effective. Ten years after the injection a radiologist noted "rather marked" degeneration in parts of his spine and several spinal discs. But he had no bone tumors when he died.

chemicals such as chlorine, phosgene, and ammonia.[49][Table III]

And let's not forget assumption (3). The Manhattan Project did do a number of much less deplorable plutonium experiments. The most important was the UPPU Club. This was a group of 26 workers who had the highest level of plutonium in their urine of all the people in the Manhattan project. They had worked with plutonium in a number of chemical forms, often with no protection at all. These men were periodically examined over the 50 year period between 1944 and 1994. Their cumulative doses ranged from 100 to 7200 mSv with a median value of 1250 mSv.

As of the end of 1994, seven of the group had died compared with an expected 16 deaths based on mortality rates of U.S. white males.[267] The UPPU group mortality rate was also less than that of 876 unexposed Los Alamos workers of the same period, The 19 living persons had diseases and physical changes characteristic of a male population with a median age of 72 years (range = 69 to 86 y). Eight of the twenty-six workers had been diagnosed as having one or more cancers, which is within the expected range. The cause of death in three of the seven dead was from cancer, namely cancer of prostate, lung, and bone. If LNT were correct, the UPPU Club would have a cancer rate 30% higher than their unexposed peers.

Lesson 3. Avoid breathing a lot of plutonium dust.

For just about all of us, this is a commandment that is impossible to break.

Plutonium needs to be handled with care. You must avoid a critical mass. It is a fire hazard. If you are machining or grinding plutonium as is required in reprocessing used nuclear fuel for solid fuel reactors, you should avoid breathing the dust. But because it is a slowly decaying, alpha emitter with very inefficient body uptake, it is one of the more easily handled toxic substances known to man.

Our fear of plutonium is totally overblown. We will run into more such fears.

Plutonium powered pacemakers

In the 1960's, cardiologists began implanting pacemakers. The best batteries at the time, mercury cell, lasted about a year, forcing an invasive, expensive operation annually. The solution was to power the pacemakers with about 150 milligrams of ^{238}Pu. Figure 2.2 shows one of the dozen different variants.

These pacemakers could last a lifetime, actually several lifetimes. The deal was the recipient had to agree to having the pacemaker removed when he died so it could be reused. Some 1500 patients received these devices, between the early 1970's and the mid 1980's.

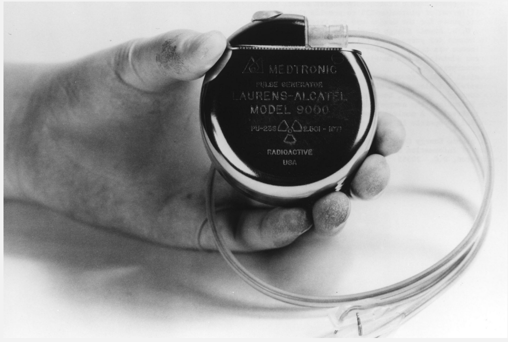


Figure 2.2: ^{238}Pu powered pacemaker.

Each of these pacemakers emitted about a trillion radioactive particles per second (1 TBq). That is about double the emission rate of all the radioiodine that was released at Three Mile Island. But in those days, people understood the difference between alpha particles and photons. Since ^{238}Pu is an alpha emitter, almost all the pacemaker emissions were alpha particles. These alphas had no chance getting through the pacemaker housing. There are a couple of photon emitters deep down the ^{238}Pu decay chain. About 0.03% of the energy from the pacemaker was photons. This produced an annual dose of about 5 mSv to the patient and 0.075 mSv to a spouse. These background level dose rates were regarded as inconsequential, correctly so as we shall see in Chapter 5,

In the 1980's, lithium-ion batteries came along that allowed a 10 year life. Better electronics allowed more sophisticated forms of heart stimulation. Doctors felt that it made sense to replace the devices about every ten years to take advantage of further improvements. It is possible that the revenue from the additional operations was not regarded as a negative. Whatever the reason, plutonium powered pacemakers fell into disuse, as did the understanding of the alpha/photon distinction.

In 2020, the Hannemann University Hospital in Philadelphia was going through bankruptcy. The liquidators discovered that the hospital had lost track of one of the devices. The Nuclear Regulatory Commission forced the liquidators to spend $15,000 over a six month period in an attempt to hunt down 0.15 grams of non-fissile material encapsulated in a titanium housing designed to be implanted in a human body for decades.

Chapter 3

Used Nuclear Fuel

> It is my personal viewpoint that it is immoral to use nuclear power without reprocessing spent fuel. By such action, our generation might well go down in history as the one that denied mankind the benefits of cheap energy for millions of years, a fitting reason to be eternally cursed.[Bernie Cohen, 1983]

There are two keys to understanding the nuclear used fuel (aka waste) problem:

1. The quantities involved.
2. The difference between photons and alpha particles.

For practical purposes, used nuclear fuel remains radioactive forever. However, the penetrating form of radiation, the photons, are essentially gone in about 500 years. After that, only alpha and electron emitters are problematic. The used fuel must be swallowed to be harmful. It's a bit like plutonium. So the rule is simple. Don't eat used nuclear fuel, even if it's 600 years old. But you have plenty of substances around the house for which the same rule applies.

95% of the used fuel is Uranium-238, If nuclear power is to play the leading role in powering a decarbonized planet, we will need to move to breeder reactors to extend our uranium reserves by a factor of 140. Breeder reactors burn ^{238}U as fuel. It would be criminally stupid to chuck away this already refined ^{238}U. We must keep this valuable resource where it is easily retrievable.

3.1 A Beautifully Small Problem

Figure 3.1 shows the dry cask storage facility for the Connecticut Yankee nuclear power plant near Haddam Neck on the Connecticut River.

Figure 3.1: Connecticut Yankee Dry Cask Storage Facility. If CT Yankee had been a coal plant and we tried to store the coal waste on the same pad, it would be a column 7000 feet high.

Connecticut Yankee (CY) was a 619 MWe pressurized water reactor which ran for 28 years between 1968 and 1996. During that time the plant produced 110 million MWh. There are 43 casks on a concrete pad, 70 feet by 228 feet.[1] These casks contain about 1020 tons of used fuel. The fuel is surrounded by 3.5 inches of steel and then 21 inches of reinforced concrete. Each cask weighs about 126 tons, of which about 25 tons is the used fuel itself. Each cask also has internal passages for natural draft circulation to remove the heat produced by the used fuel's radioactive decay. These show up in Figure 3.1 as the rectangular slots at the bottom and top of each cask.

If Connecticut Yankee had been a coal plant, it would have produced between 3,000,000 and 6,000,000 tons of toxic ash in its operating life, not to mention 110 million tons of CO2. If we attempted to store this ash on the CY fuel cask pad, we would have a column of ash about 7000

---

[1] 40 of the casks contain used fuel. Three contain other material that did not meet the standards for landfill disposal. This material will decay faster than the used fuel.

feet high. The amount of solid waste per unit power produced by a nuclear power is 10 to 20 thousand times less than that produced by a coal plant. This is by weight. Used nuclear fuel is 10 times denser than coal ash. In terms of volume, the difference is at least 100,000.

Almost all the material in these casks falls into one of four categories:

1. Cladding.
2. Uranium.
3. Plutonium and other transuranics.
4. Fission products.

Cladding About 25% of the waste is the metal tubes that encased the fuel and the tube support structure. This is non-radioactive material that has been contaminated by the fuel. If it were separated out, it would be treated as low level waste. It is not a long term storage problem.

Uranium Uranium is barely radioactive. Like plutonium, it is an alpha emitter, but at a far slower rate than plutonium. Almost all the uranium is ^{238}U. The half-life of ^{238}U is 4.5 billion years, ^{238}U emits alpha particles 180,000 times more slowly than plutonium. Like plutonium, it can be handled without any shielding at all. Unlike plutonium, you will feel no warmth, and the oxidation rate is so slow, it is not a fire hazard. By weight, uranium represents about 96% of the used fuel.

This means the fuel is potentially quite valuable. Current nuclear's energy density is 500,000 times higher than fossil fuels, 12,500,000,000 times higher than hydro, and 250,000,000,000 times higher than wind, when the wind is blowing. That sounds pretty good. But it could be a lot better. Today's nuclear technology is woefully inefficient in its use of potentially fissile material. More than 97% of the energy that could theoretically be generated from the fuel is still in the fuel when it is pulled from the reactor, Figure 3.2. We already know how to extract a large portion of this remaining energy; but due to a combination of cheap uranium and regulatory hurdles, currently this is not quite economic.[2]

Transuranics Some of the neutrons bouncing around in the reactor do not result in fission, but are absorbed by the fuel transmuting the uranium into still heavier elements, mostly plutonium. This group is known as the transuranics (TRU). By weight the TRU represent about 1% of the used fuel.

Transuranics decay by emitting alpha particles and some electrons. The great bulk of the energy is in alpha particles. Electrons have more penetrating power than alpha particles, but not much. Few can penetrate the outer layer of skin. In order for alpha particles or electrons to

---

[2] The most efficient way of extracting this energy is a fast spectrum reactor. Fast reactors have been around for 70 years. The Russians have a 600 and an 860 MW fast reactor in long term commercial operation at Beloyarsk.

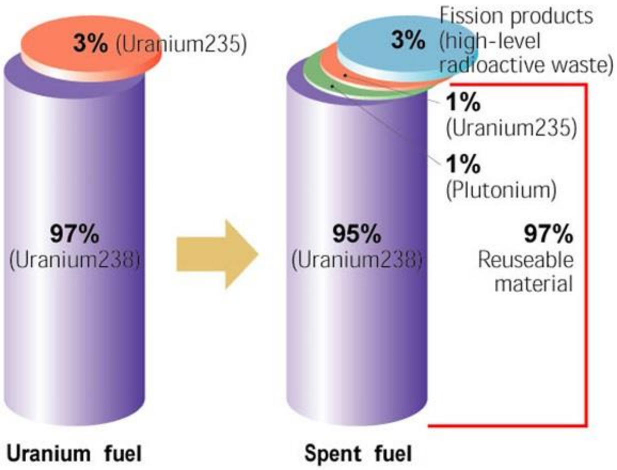


Figure 3.2: Composition of Used Fuel

do any damage, they must be ingested or inhaled.[3]

Transuranic decay tends to be very slow with some important TRU isotopes having half-lives of the order of 100,000 years. TRU's also can be quite valuable. Some such as ^{238}Pu can be used to power deep space probes. Others are either fissile or fertile and can be processed into excellent nuclear fuel, although currently this is not economic, in part because the fission product decay makes handling the used fuel so difficult.

Fission Products Fission products are the result of the nuclear fuel splitting into two pieces. They represent about 3% of the used fuel. Most fission products decay by emitting photons and electrons. The photons are the same particles that make up sun shine; but most of the fission product photons have much higher energy than the sun's rays. It is these photons that makes used fuel difficult to handle. A high energy photon can penetrate all the way through a human body. Photons are the reason the casks in Figure 3.1 are as big as they are. They provide the shielding that allows essentially unlimited access to the storage facility.

---

[3] Extremely intense amounts of high energy electrons can cause skin damage. This happened at Chernobyl to the reactor operators.

Cask hugging, Figure 3.3, is unlikely to become a national sport. But with a tiny extra bit of money, the casks could be turned into climbing walls or the pad turned into a paint ball court.

Figure 3.3: Cask Hugging at Palo Verdes. Credit: Paris-Ortiz-Wines

Three Very Different particles

Radioactive decay produces three very different particles: photons, electrons, and alpha particles, Table A. Electrons and alpha particles are charged particles; photons have no charge. Electrons and alphas interact with the electromagnetic fields within our tissue. They have little to no penetrating power. Photons do not and are highly penetrating. Electrons and alphas must be ingested or inhaled to do any damage.

Table A. Three very different particles.

	Linear Energy Transfer	Charge	Rest Mass AMU	Tissue Penetration
Photon	Low RBE = 1.0	0	0.00000	Very high depending on energy
Electron	Low RBE = 1.0	-1	0.00055	Very weak. High energy can damage skin, else must ingest or inhale.
Alpha Particle	High RBE = 20.0	+2	4.00015	Nil. Must be ingested or inhaled to cause damage. If absorbed into an organ, damage localised. Many DSB's.

The concern is damage to our DNA, because that can lead to cancer. Alpha particle damage is highly localized, clumped along the heavy particle's short, straight track. This is called high LET (Linear Energy Transfer) damage. Photon and electron damage, low LET, is far more spread out, much more like endogenous damage from our O2 based metabolism. In a nuclear power plant casualty, there is usually nil release of alpha particles; and, when it happens as it did at Chernobyl, the heavy alphas fall out very close to the plant. Almost all the radiation damage to the public in a nuclear plant release is low LET. However, if alpha particles do get inside our bodies and are absorbed into our organs, the highly localized damage is much more likely to create double strand breaks (DSB's), in which both sides of the DNA double helix are messed up. As long as one side of the helix is intact, our bodies cleverly use that strand as a template to make an essentially error-free repair. But in a DSB, error-free repair cannot be guaranteed. A few of the unrepaired cells will evade our immune system, and a few of those mutations will developed into cancer. DSB's are the problem.

Very roughly, alpha particles produce 20 times more DSB's per energy absorbed than photons or electrons. Therefore, in converting grays to sieverts, we multiply the alpha energy by 20.0. This conversion factor, dubbed RBE (Relative Biological Effectiveness), is 1.0 for photons and electrons.

3.2 The Cost of Dry Cask Storage

But what about the economics of dry cask storage? Figures 3.5 to 3.8. show a concrete example, the Hi-Store facility which would be located on a 1045 acre site in New Mexico. 110 acres of that site is enough land to hold 10,000 casks, each containing about 17.4 tons of used nuclear fuel. If the United States were to produce all its electricity from nuclear power, this area could hold at least 12 years of used fuel. In other words, every ten years, the country would need to set aside about 100 acres for used fuel storage.

Phase 1 envisions a single pad, 500 cask facility capable of storing 8680 tons of used fuel. According to the developer, Holtec, the initial cost of the facility will be 183 million dollars, exclusive of the casks which will run about $800,000 each.[116] This is a crazy number. The Holtex UMAX cask is a couple of 4.5 m high cylinders, requiring about 30 tons of steel and 30 tons of concrete. On an assembly line basis, the cost should be less than $100,000. The cask design life is 60 years.

Let's assume every 60 years, all the casks are replaced at a cost of 400 million dollars real. So we have initial costs of about 600 million, 10 million every year, and a 400 million dollar expense every 60 years. If we assume a social discount rate of 2% real and convert the present valued costs to a per MWh electricity basis under the assumption that a 1 GW plant produces 30 tons of used nuclear fuel per year, we obtain the unit costs shown in Figure 3.4 as a function of 60 year generations.

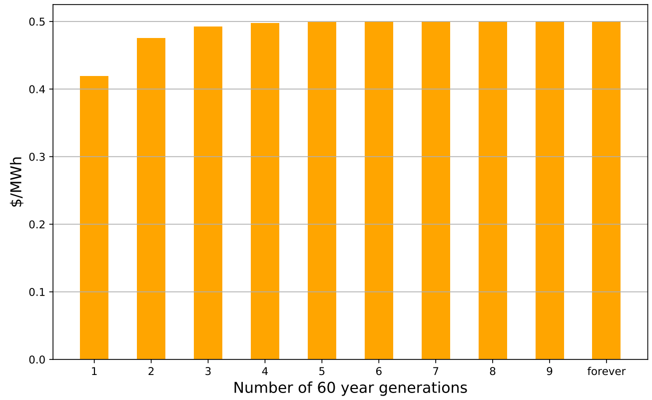


Figure 3.4: Hi-Store Unit Cost as a function of storage time

At a 2% social discount rate the unit cost levels off pretty rapidly, if your idea of rapid is something like 200 years. Under these assumptions, the cost of perpetual dry cask storage is about 0.50 $/MWh or 0.05 cents per kWh. Thanks to uranium's remarkable energy density, dry cask storage should be dirt cheap.

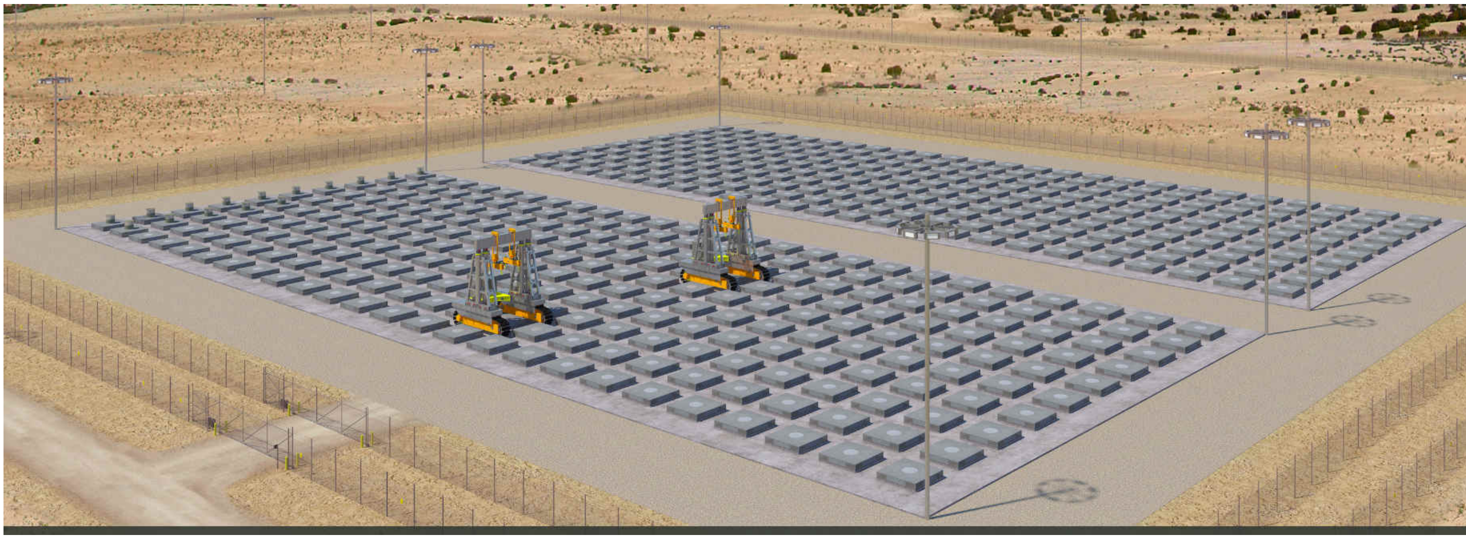


Figure 3.5: 500 cask Hi-Store pad. Hi-Store uses a vertical, below ground cask.

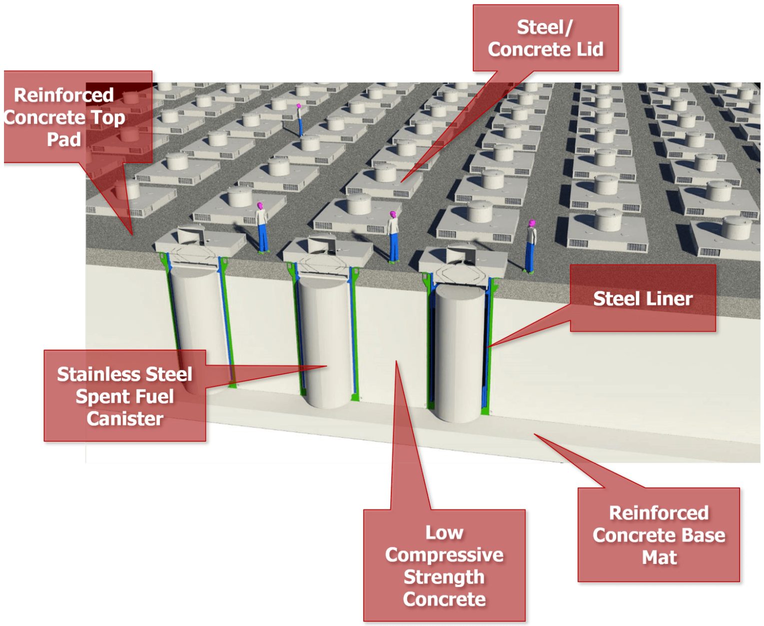


Figure 3.6: Cutaway view of the storage system

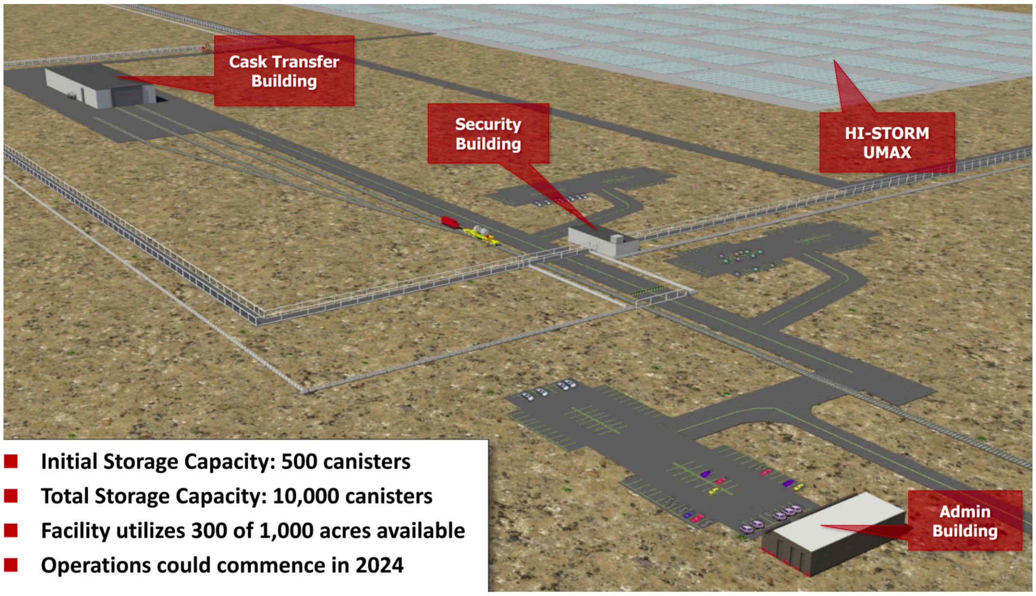


Figure 3.7: Overall view of the Hi-Store facility

Figure 3.8: Satellite view of the Hi-Store facility. If the US were to go all nuclear, the 20 pads on the right would handle at least 12 years worth of used fuel.

Nuclear waste is indeed a “beautifully small" problem. The same thing cannot be said for coal, or even natural gas.

3.3 A Surprising Antagonist

The phrase “beautifully small" is due to David MacKay whose book *Sustainable Energy without the Hot Air* is must reading for anyone seriously interested in solving the Gordian knot.

So who disagrees with Prof. MacKay’s assessment? The Nuclear Energy Institute (NEI) for one. The NEI is the well-funded lobbying arm of the nuclear power utilities. In the mid-1980’s, the NEI ran a series of expensive ads in the New York Times, the Washington Post, and other leading newspapers claiming that dry cask storage was unsafe. The ads made the argument that it would be much better to store all the waste in a single deep geologic repository. The target of the ads was Congress.

US law requires that the utilities must give the fuel back to the US government and the US government has to take it back. The original plan was the used fuel would then be reprocessed and largely reused. But reprocessing was halted by Carter in 1977. As we have seen, dry cask storage adds about 0.05 cents per kWh to the cost of electricity. The utilities decided to push Congress hard for a central repository to avoid the cost of local dry cask storage. If they had to diss local storage to do it, so be it.

But it is not only Congress that reads the New York Times. Up until this point, the opposition to nuclear electricity, which did not really get going until the mid-early 1970’s, — see Section 9.8 — had focused on the hazards of a radioactive release from a plant. But with the NEI claiming used fuel was perilous, the opposition was handed another weapon, ***nuclear waste***, which they enthusiasticly accepted. From a psychological perspective, the nuclear power establishment created the nuclear waste problem.

3.4 Suppressing Subseabed

At the same time an eclectic group of oceanographers, geologists, biochemists, and engineers, were working on another idea. Charles Hollister, a Woods Hole oceanographer, had developed techniques for coring the deep ocean abyssal plain. He discovered that large areas of the deep ocean were covered by an exceedingly fine clay, 100 meters deep. The particles were so small that the clay had the consistency of peanut butter. Packed together under pressures 500 times higher than at the surface, the permeability to water was extremely low. Some of these areas in the middle of a tectonic plate were geologically stable. One area, four times the size of Texas, 600 miles north of Hawaii, had been tranquil for 65 million years

The plan was simple. Put the used fuel in pointed canisters. Drop the canisters into the ocean. They would penetrate the seabed muck to a depth of about 30 m, be covered up by the clay, and sealed there. If and when the canisters corroded, very little would happen. Many radionuclides would bind to the clay, and the migration rate upward of those that didn't would be geologically slow. Any molecules that finally made it up to the ocean would be immediately diluted to infinitesimal concentrations.

Scientists flocked to the project, mainly to shoot it down. The initial reaction when they heard about the idea was invariably "Nuclear waste. Not in my ocean, you're not". These sceptics were welcomed to the program and to a man became converts. With DOE support, the project gained momentum. In 1975, the OECD formed the Seabed Working Group to pool talent, resources, and information. The plan was worked out in great detail. On paper everything looked great. MIT Prof. Henry Kendall, Chairman of the Union of Concerned Scientists, perhaps the initial and certainly the most influential non-industry, scientific critic of nuclear power safety, called subseabed "a sweet solution".[176] But the working group insisted on a full scale test. They proposed dropping a small number of canisters and then monitoring them for 20 years, before moving to full deployment.

That was far too slow for the NEI. It meant the utilities would have to build dry cask pads. The nuclear establishment turned against subseabed disposal. The political wheels were greased. In 1987, a bill was passed designating Yucca Mountain the ***sole*** repository for used nuclear fuel, explicitly and purposely eliminating any competition. At the same time, DOE cut off funding to the subseabed project claiming they had no money for it, despite the fact that the money the project needed was a tiny fraction of what the DOE was spending on Yucca. Subseabed disposal faded into oblivion, killed by the nuclear power establishment.[4]

3.5 Preserving Uranium Ore

At the end of the day, what should we do with the used fuel? In order to address this question, I need to call your attention to a looming problem.

Currently we have roughly 6.1 million tons of reasonably assured uranium reserves. In Section 1.2, we found we would need 25,000 one GW nuclear plants to properly support a fully decarbonized planet. If that planet were to be powered by conventional reactors, these current reserves would last less than 5 years. While more uranium will be found, clearly this is not sustainable. Fortunately, a solution exists: breeder reactors.[5]

A breeder reactor can burn not only ^{235}U and ^{239}Pu but also ^{238}U. This will extend our uranium reserves by a factor of 140.[6] Now we have at least 500 years, before we dip into thorium

---

[4] Ironically, the utilities never paid for dry cask storage. Their lawyers were able to convince the courts that the Feds had reneged on their agreement to take the used fuel back. The cost of dry cask storage was shifted to the taxpayer.

[5] Breeder reactors are not new. They go back to the dawn of the nuclear age. The Russians have had a 600 MW breeder operating since 1980 and an 800 MW breeder since 2016. China and India have active breeder programs.

[6] A good conventional reactor can generate 5.2 terajoules from a kilogram of 3.8% enriched uranium. It takes 9.5 kg of mined uranium to produce that enrichment. A breeder can produce 78 terajoules from a kilogram of

and low grade uranium ores.[7] In other words, we will need a great deal of ^{238}U in a generation or two, as nuclear ramps up.

Right now in the USA alone, there is about 90,000 tons of ^{238}U sitting in dry cask storage around the country. It would be criminally stupid to chuck away this already refined ^{238}U, which is 95% of the used fuel. We must keep this valuable resource where it is easily retrievable.

Used fuel is more than a future fuel. It is treasure trove of potentially valuable isotopes. Consider just three of the many isotopes which could be extracted from this ore.

Plutonium-238 Radioisotope Thermoelectric Generators (RTG's) are extremely long-lived, solid state, high power batteries. They are essential for deep space probes and have a large number of other potential applications. By far the best RTG fuel is ^{238}Pu. It combines an excellent power density of 570 W/kg with very low photon emissions, so low that ^{238}Pu have been used to power pacemakers that last a lifetime. But supplies of ^{238}Pu have been exhausted. There is so little of it that it is difficult to put a price on it; but one serious proposal for making ^{238}Pu would end up costing about $10,000,000 per kilogram.

Currently, ^{238}Pu is impossibly difficult to separate from the other plutonium isotopes in the ore. The easiest route is via Neptunium-237. ^{237}Np is reasonably easy to extract from the ore. If ^{237}Np is then bombarded with neutrons, it will transmute to ^{238}Pu. A gigawatt-year of used fuel contains about 10 kilograms of ^{237}Np, potentially a hundred million dollars worth of ^{238}Pu.

Actinium-225 ^{225}Ac may be the most valuable isotope in creation. ^{225}Ac is a pure alpha particle emitter. Alpha particle decay is highly localized. An alpha particle deposits almost all its energy within a radius of 1 or 2 cells. In 1993, scientists discovered that they could attach ^{225}Ac to antibodies which attach to cancer cells. This combination creates an unprecedentedly targeted cancer therapy. ^{225}Ac has a half-life of ten days, long enough for the cancer-seeking cocktail to be put together, and short enough to ensure a cancer killing burst of energy. Actinium-225 is a wonder drug.

The problem is that there is so little ^{225}Ac that less than 1 person in 5000 that could benefit from this therapy is getting it. ^{225}Ac is a decay daughter of ^{229}Th. To get an idea of what ^{229}Th is worth, in 2019 the Bill Gates company Terrapower paid 90 million dollars for 225 grams of ^{229}Th. That is $400,000,000 per kilogram. It's worth it. The Terrapower ^{229}Th will produce about 500,000 doses of ^{225}Ac annually for the next 5000 years.

^{229}Th is a decay product of Uranium-233. If we introduce natural thorium, ^{232}Th, into the fuel, the used fuel will contain substantial amounts of ^{233}U. This ^{233}U can then be milked for its ^{229}Th.

---

mined uranium.

[7] Breeders open up the possibility of extracting uranium from sea water. There is about 4 billion tons of uranium in the oceans, which is replenished at the rate of 32,000 tons per year from erosion.

Lead-212 Another isotope which is receiving strong attention as a cancer killer is Lead-212, Figure 3.9 ^{212}Pb has a convenient half-life of 10.6 hours. It decays to ^{212}Bi, which is a strong alpha emitter with a one hour half-life. ^{212}Pb is a daughter of ^{232}U. Once again by adding thorium to the fuel we can create enough ^{232}U, to be the source of millions of doses of ^{212}Pb.[8] How many ores can you call cancer killing?

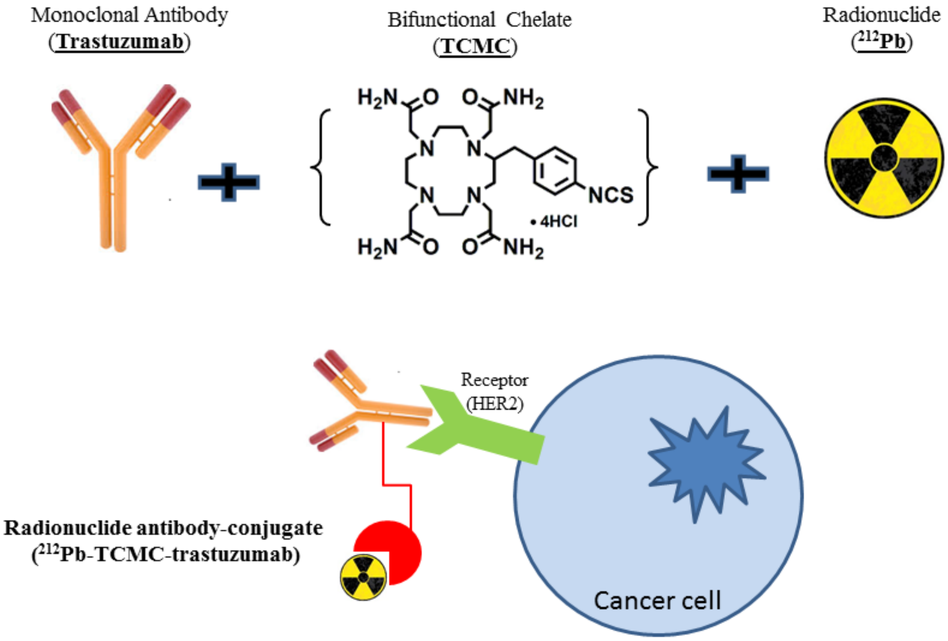


Figure 3.9: Killing a cancer cell with ^{212}Pb

---

[8] Uranium can be separated from the fuel by fluoride volatility. Even if it is uneconomic to separate ^{232}U from the rest of the uranium, ^{232}U decays to ^{228}Th with half-life of 69 years. ^{228}Th decays to ^{212}Pb. It is possible to separate the thorium from the uranium. ^{228}Th has a half-life of 1.9 years, ideal for a milking material. ^{228}Th can be distributed to the labs or even big hospitals.

Nuclear used fuel contains some 150 isotopes. Table 3.1 is a list of known potentially valuable isotopes in the used fuel.

Table 3.1: Known potentially valuable isotopes in one ton of used nuclear fuel

Isotope	Amount kg	Unit value $/kg	Value USD	Potential uses
^{238}U	950	150.00	142,500	U3O8 at $90/kg. Fertile. Preserve for breeder reactors.
^{235}U	10	40000.00	400,000	Primary fission fuel
^{233}U	?	50000.00	?	Route to ^{225}Ac. Requires thorium in fuel.
^{137}Cs	6	0.00	0	Prolific photon emitter. Well-logging. Medical.
^{90}Sr	4	6.50	0	Prolific electron emitter. RTG fuel.
^{239}Pu	5	50000.00	250,000	Fission fuel
^{237}Np	2	800000.00	1,600,000	RTG fuel. Best route to ^{238}Pu
^{238}Pu	1	10000000.00	0	Superlative RTG fuel. Deep space probes, pacemakers, etc.
^{243}Am	1	50000.00	50,000	RTG fuel. Fast Fission fuel
^{147}Pm	1	46000.00	46,000	RTG Fuel
^{244}Cm	0.5	50000.00	25,000	RTG fuel. Alpha spectrometers. Neutron source. Fast fission fuel.
^{241}Am	0.1	728000.00	73,000	Fire detectors. RTG fuel.
^{232}U	?	?	?	Decays to cancer killing ^{212}Pb. Requires thorium in fuel.
Total			2,586,000	

Prior to 1990, actinium was thought to be worthless. We have no way of knowing what future scientific developments will transform an exotic nuisance into an unimaginably valuable commodity.[9] We don't know. All we can do is preserve the ore for our descendants, and let them decide what to do with it.

---

[9] In the US any such development is stymied by the lack of clear title to the used fuel. The utilities are obligated by law to give the used fuel back to the government. The government won't take it back. A preposterous situation. Who is going to pay to extract valuable isotopes from an ore that effectively nobody controls?

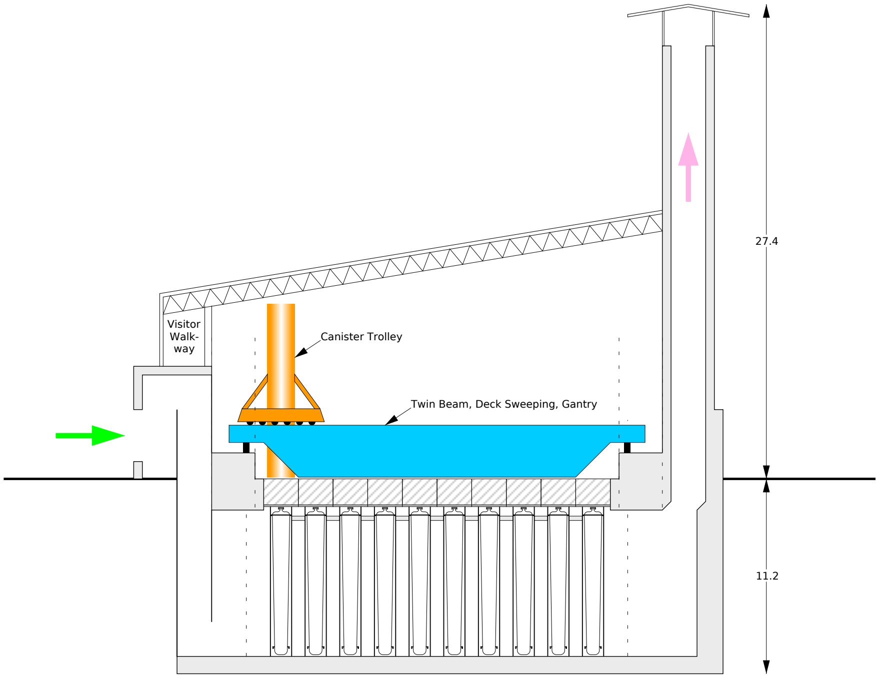


Figure 3.10: Section of Vault

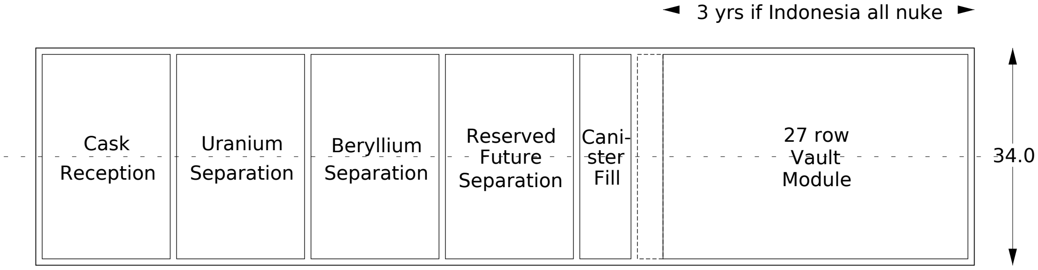


Figure 3.11: Conceptual Plan of Indonesian Used Fuel Recycling and Storage Center

The best way to do that is a vault. Figures 3.10 and 3.11 sketch a used fuel storage vault proposed for Indonesia. The vault combines extraction and storage. The used fuel from the power plants comes in at the left end of Figure 3.11. After separating out the currently valuable isotopes, the ore is put into canisters. The canisters in turn are lowered into a forest of tubes in the right end of the building. The building will grow rightward with time. Currently, Indonesia consumes 30 GW of electricity. At this rate, if Indonesia went all nuclear, every three years she would need to add a 48 m long vault module.

The vault is cooled by natural circulation. No power is required. Air enters at the left side of Figure 3.10 and exhausts out the stack at the right side. A vault is more compact than dry casks since there is no need to shield each canister separately. The vault is served by a gantry crane. This crane moves canisters from the canister fill cell to the tubes. Importantly, the crane can pull the canisters out of the tubes and return then to the extraction modules in the left end of the building.

Vaults are not new. France, a country that produces most of its electricity with nuclear power, stores all its nuclear ore in a vault that is about the size of a hockey rink. The Russians have a similar facility, the Mining and Chemical Complex (MCC), at Zheleznogorsk, Figure 3.12. Vaults become the centerpiece of a bustling, vibrant, high tech industrial park. The economic activity at MCC supports a small city.

Figure 3.12: Zheleznogorsk Mining and Chemical Complex

Used nuclear fuel needs to be recognized for what it is, a potentially valuable ore. Our job is to preserve it for our descendants. A vault is the best way to do that.

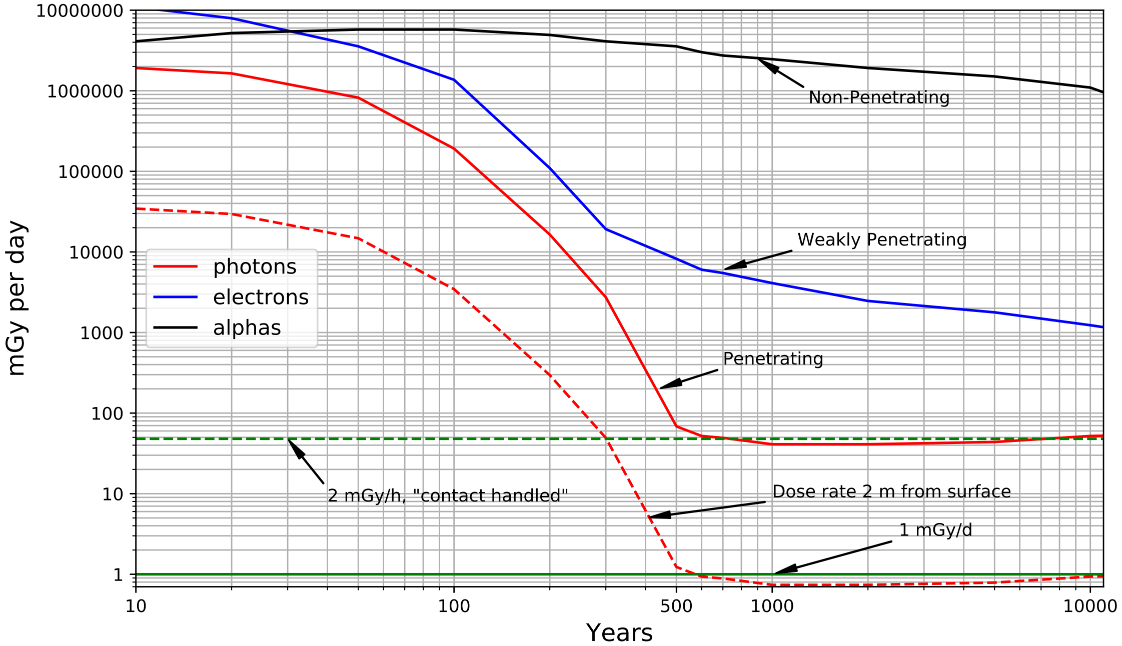


Figure 3.13: Dose Rate at Fuel Element Surface, based on reference [200][Figure 5-13]

3.6 Yeah, but for how long?

It's all very well to talk about indefinite vault or dry cask storage, but there's got to be an end to it. How long do we have to keep the stuff around?

Figure 3.13 puts some numbers on the decay process. The key feature of Figure 3.13 is that photon decay is relatively rapid. By year 600, 99.999% of the photon emitters are gone, relative to end of year 1.[48][p 27] In fact, the photon dose rate is so low that, according to DOE rules, the used fuel elements can be *contact handled*, handled without any shielding at all. ***After year 600, the spent nuclear fuel must be swallowed in order to do any damage.***[10] This led to Ted Rockwell's suggestion of slapping a DO NOT EAT sticker on the casks, and forgetting about them.

---

[10] The swallower's main problem would be uranium's chemical toxicity. Only 1% of the fuel is plutonium, and 99.997% of the plutonium will be excreted in a day or two. About 20% of the uranium will be absorbed into the blood and about 70% of that will end up in the kidneys. Kathren and Burklin estimate that ingesting 5 grams of uranium over a short period will result in a 50% chance of death due to kidney failure.[126]. Others put this number as low as 0.15 grams. Cohen calculated that it would take 225 grams of 600 year old fuel to give you a 50% chance of fatal cancer from the radiation.[48][p 31] This amount is based on the Linear No Threshold hypothesis, which, as we shall see, is grossly conservative at low dose rates.

But that would be a waste. A better plan is:

1. Keep the material in vault/dry cask storage until the photon emitters have mostly decayed away, no more than 600 years. If the US were to generate all its electricity from nuclear, a 600 year decay time means she would have to devote at most 21 square miles — about the size of Manhattan — to dry cask storage. More to the point, it is one-tenth the size of the Riverside East Solar Zone in the Mohave. This area is based on the Histore system, Figure 3.5, which needs one acre to store 580 tons of used fuel. More compact solutions exist.
2. Extract the valuable medical, industrial and RTG fuel isotopes.
3. Extract the remaining uranium and transuranics and burn them as nuclear fuel.[11] This will reduce the waste volume by about a factor of 15. Far more importantly, it will extend our uranium reserves by a factor of 140.[12]
4. The remaining material will be low level waste. It can be diluted and landfilled.[13]

The answer to the how long question is: at most 600 years.

---

[11] Technical aside. We may be able to burn the so-called spent fuel as is. The reason why the fuel could no longer be used in a conventional *slow* reactor, is that the fission products were absorbing to many neutrons. The chain reaction could no longer be sustained. In a fast reactor, the fission products ability to absorb neutrons is much smaller. The spent fuel is perfectly good fuel for a fast reactor the first time through. But sooner or later, some fission product removal is required. We cannot just keep recycling the fuel and allow the fission products to build up.

In molten salt reactors, quite a bit of fission product removal happens automatically. The gaseous fission products bubble out and the insoluble fission products plate out by themselves. Idea is to provide a removable mesh to take advantage of this. On paper, this should be enough to keep the process going forever.

But the amount and location of the plate out is a guess at his point. We need tests. But we can't test without a license. And we can't get a license because we are not sure what the fission products are going to do. Catch NRC.

[12] Because the material is so valuable, it will almost certainly pay to do the extraction well before all the photon emitters have decayed away. The residue will need to be returned to storage until they can be handled without shielding.

[13] After the first 50 years, a single isotope, Cesium-137 is responsible for practically all the photon dose. The NRC upper limit for ^{137}Cs containing material to be landfilled is 170 TBq/m3. The NRC limit is exceedingly conservative. At the Hanford federal reservation in Washington, reactors were used to produce weapons grade plutonium between 1944 and 1986, Section 11.1. The ^{137}Cs in the spent fuel left over in this process is already well below the NRC requirement.

If an economic method for extracting ^{137}Cs is developed, handling the remaining fuel becomes far easier. Separating cesium from used fuel is something we know how to do.[141]

3.7 Geologic Disposal

The nuclear power establishment's knee jerk solution is deep geologic disposal. Even then the material is a lurking, barely contained danger, requiring careful, multi-million dollar studies of the hazard, studies which in the end cannot even agree on which isotopes we should worry about. See Appendix C, which is a little more technical than the rest of the book.

Mined repositories are non-starters economically. The Finnish Onkalo repository is being pushed as a success story. Coincidentally Onkalo has a capacity that's almost the same as Hi-Store Phase I. But Onkalo's initial cost is somewhere north of 3.5 billion dollars. That's about 1.33 $/MWh. And before disposal, the fuel needs to cool for 40 to 60 years. So the Finns also need to pay for a generation or more of dry cask storage.[14]

Much worse, expensive geologic repositories send exactly the wrong message to the public and send it very clearly. In doing so, they inspire some of the most pretentious prose since the Victorian Age. Here's a sample.

> Onkalo is constructed with the desire that its contents never be retrieved. It is a place that confronts us with timescales that scorn our usual measures. Radiological time is not equivalent to eternity, but it does function across temporal spans of such breadth that our conventional modes of imagination and communication collapse in consideration of them. Decades and centuries feel pettily brief, language seems irrelevant compared to the deep time stone-space of Onkalo and what it will hold. The half-life of uranium-235 [sic] is 4.46 billion years: such chronology decenters the human, crushing the first person to an irrelevance.[152][Ch 12]

None of the uranium at Onkalo was created by man. We just dug this rock up, and now it's being undug. And the four billion year half-life of ^{238}U means that it is a completely innocuous material. But by being buried in such an ostentatiously expensive manner, this lowly rock is elevated to a supernatural level in the same way the pyramids proclaim to one and all that these few, miserable bones are the relics of a god. (Two can play the pretentious game.)

To claim that used fuel is a potentially valuable, easily handled, toxic material and then spend billions of dollars to put it 100's of meters underground is completely contradictory. The public is not fooled. If the material is as claimed, nobody would be stupid enough to waste my money that way. These people must be liars. This is extremely dangerous stuff. How can we possibly be sure a little of it won't leak back to the surface over thousands of year?[15] Should I trust their claims that the repository is safe? The answer is pretty obvious.

The nuclear establishment's insistence on deep geologic disposal is so counter-productive, it begs the question of why? We will come back to this puzzler in Chapter 9.

---

[14] The intention is to make the used fuel as inaccessible as possible. This is equivalent to throwing diamonds down a volcano.

[15] Or maybe a drill crew drills into the repository and pulls the perilous material back to the surface. You can always concoct a screw up that defeats your barriers.

Chapter 4

Lies, Damned Lies, and Probabilities

> Preliminary results suggest there will never be a major accident in a nuclear power plant. The odds on a major catastrophe were one in one billion to one in ten billion years for a given reactor.[Dr. Herbert Kouts, Head of AEC Division of Reactor Safety to Associated Press, 1974-01-14]

> If another accident were to occur, I fear the general public will no longer believe any contention that the risk of a severe accident is so small as to be almost negligible.[Hans Blix, IAEA Director General to the IAEA Board of Governors, 1986-05-12]

> Nothing can replace the knowledge that when all else fails, the consequences of the worst realistic casualty are tolerable.[Ted Rockwell, 2008]

One of the lies about nuclear power that you have been told is that the probability of a sizable release of radioactive material is so low that you can just assume it won't happen.

This is a very stupid lie, in part because it is obviously false. It was proven false at Three Mile Island, again at Chernobyl, and again at Fukushima. Based on past performance, in a nearly all nuclear grid, we can expect a significant release every few years.

It is also stupid because it is unnecessary. No one was measurably hurt from radiation at Three Mile Island. If there was any radiation health impact from Fukushima, it will be so small that we will not be able to reliably identify it.[276] A risk that is so low that you can't see it is hardly a risk at all. Chernobyl killed about 50 people and may have shortened the lives of 1500 more, Section 5.6.14. In the meantime, we have experienced over 80,000 deaths from other sources of energy, and that's before you count the health impact of pollution, Section 5.1.

Finally, it is a stupid lie because it is so expensive. Once the industry and the regulators promulgated this falsehood, they had to try to make it true. But eliminating all releases is impossible. ***There is no limit to the amount of money you can spend attempting to do the impossible.*** Or more precisely, the limit is the point at which you price nuclear out of the market. We reached that limit pretty quickly.

This chapter focuses on this lie and other abuses of probability by nuclear regulators and their customers.

4.1 Core Damage Frequency Numbers

A favorite habit of nuclear regulatory bodies is estimating Core Damage Frequency (CDF). Core damage is the polite name for core meltdown. Usually, the numbers that they come up with are based on *fault tree analysis*. In fault tree analysis, one tries to imagine all the failures that could result in core damage, somehow put probabilities on all these events that lead up to the casualty, and then combine these individual probabilities into the probability that a meltdown actually occurs. This assumes

(a) we can imagine all the event chains that can generate core damage,
(b) we have probabilities for all these events including any interdependencies.

Both (a) and (b) are false.

Unsurprisingly, the results vary all over the place. Early on the AEC continually threw out the figure of one in a million reactor years.[1] However, the 1974 Reactor Safety Study — often called the The Rasmussen Report — ended up with 1 in 17,000 reactor-years after several unexplained, last minute major upward revisions.[2]

More recently, the NRC has gone back to 1 in a million style numbers. In January, 2012, the NRC issued a report called State of the Art Reactor Consequences Analysis (SOARCA) Report, NRC NUREG 1935. SOARCA comes up with numbers for CDF from STSBO (Short term Station Black out) of three per ten-million reactor years and three per million reactor-years from LTSBO (Long term Station Black Out).[3] The use of short-term and long-term is confusing. Short term actually means “immediate" and “long-term" means the plant has a little time to prepare for the black out. In fact we have had at least 4 “long term" SBO’s in 14,500 reactor-years (Daichi 1, 2, 3, 4), three of which resulted in a melt down.

14,500 reactor-years is a sizable sample. Here’s a much simpler approach, based only on the casualty data and requiring no fault tree analysis. Let’s assume we have had six instances of core damage in 15,000 reactor-years. This is a optimistic assumption. According to the World

---

[1] The rank and file bought this. Mike Derivan recalls his feelings when he first watched the TV reports on Three Mile Island.

> I sat there with total disbelief as he discussed potential core meltdown. Disbelief because if you were a trained operator in those days it was pretty much embedded in your head that a core meltdown was not even possible; and here that possibility was staring me right in the face.[65]

Derivan was the Shift Supervisor at Davis-Besse, a similar plant to Three Mile Island. 18 months prior it had a very similar failure to TMI. The same valve failed open. The plant was at low power at the time and Derivan managed to figure out what had happened, which the TMI staff did not. The Davis-Besse casualty was not communicated to the other plants. If it had been, the name Three Mile Island would mean nothing to almost everybody.

[2] In May, 1973, Rasmussen himself claimed the study was coming up with one in a million numbers.[279][p 59] I have found no explanation for the factor of 60 change.

[3] Westinghouse comes up with roughly similar numbers, but accurate to two decimal points. They claim a core damage frequency of 2.41e-7 per reactor year for the AP1000. AP1000 Design Control Document, Chapter 19, Probabilistic Risk Assessment.

Nuclear Association, as of late 2012 we had 14,500 commercial reactor years and the following casualties: TMI (1 core damage), Fukushima Daichi (3 cores damaged), Greifswald 5 (1 core damage), Chernobyl (1) plus some 10 incidents of core damage in military or research reactors. The WNA could have added Fermi 1 (1966), Chapelcross (1967), St Laurent (1969), Lucens (1969), Bohunice (1969) and Vandellos 1 (1989). So the actual commercial experience is arguably 6 to 12 in 15,000 years. If we take a Bayesian approach with this data, we find that the the probability that the casualty rate is less than 1 in a million years is 0.000,000,000,000,016.[4] The probability that the casualty rate is less than 1 in a hundred thousand reactor-years is 0.000,000,014, about one chance in a hundred million.

The NRC and reactor vendor claims are transparently bogus. Based on actual experience to date, we can expect a major casualty every 3000 reactor-years. For the current fleet, that's about one in every ten years. If the world were to go full nuclear, then we are talking about a major casualty every year or so. Even if new technology cuts this by a factor of five, which we have no right to assume until the technology proves itself, we can expect a major casualty every five years or so.

Nuclear power's claim to safety can not depend on clearly bogus core damage frequency numbers. It is based on two empirical facts:

a. Nuclear power casualties are indeed rare, roughly one in every 3000 plant-years, far rarer than fossil fuel related casualties, as we will see in Section 5.1.
b. The fatalities associated with a major nuclear plant casualty are of the same order of magnitude as a major fossil fuel casualty, or less. We will investigate this claim in Chapters 5 and 6

4.2 Problematic Probabilistic Risk Analysis

Estimating Core Damage Frequency is an example of Probabilistic Risk Analysis (PRA). PRA is the cornerstone of the NRC's approach to nuclear safety analysis. But the core damage frequencies that PRA has generated are obviously bogus. This section examines why PRA numbers are bogus and explores the corrosive implications of a safety system that is built on bogus numbers.

---

[4] For the geeks, we assume

1. That Core Damage occurs according to Poisson process with an unknown casualty rate.
2. We assume that the unknown casualty rate is distributed according to a gamma density.
3. Prior to any data, we assume we know nothing about the occurrence of core damage, and use a non-informative prior.
4. We then update our prior according to Bayes Rule with the actual Core Damage data to arrive at our posterior distribution.

PRA probabilities are unreliable to meaningless PRA in the nuclear context is usually dealing with extremely rare events, often events that have never happened. In such cases, we have no data on which to base a probability. But PRA says we must have a probability. So we concoct them. There are two ways to do this:

Build a Model These models need to make a whole range of arguable assumptions. Almost invariably, one or more of these assumptions is crucial to the probability that emerges from the model. The problem becomes:

1. Create a model and set of assumptions that cranks out the target probability.
2. Convince the NRC guy that the model and the assumptions are acceptable.

What comes out of this process is a negotiated number. Different negotiators will end up with different numbers. This is inherent in a situation where we do not have the data needed to come up with an objective probability. The problem is compounded by the multiplicative nature of probabilities. It only takes one incorrectly low number in a chain of probabilities to render the output meaningless.

Make the numbers up Even with models, there will still be blanks. To fill in these blanks, PRA uses the aptly named Delphi Method, a polite way of saying “guess". The Delphi Method is based on asking a group of “experts" what they think the probability of an event is, often an event that has never happened. Sometimes the answers differ by a factor of 1000 or more.[279][p 71] You mush all the guesses together and come up with a distribution, from which you grab a statistic, say the mean, which you treat as if it were an objective probability, as if you had all sorts of data on the event in question. Pick the right experts and you can come with just about any target number.

PRA is supposed to be objective, but there is nothing objective about unsupported opinions.

Often the NRC’s and the plant’s probabilities don’t match. If an inspection reveals a fault, the NRC bins the problem: green, white, yellow or red. The increase in Core Damage Frequency associated with the failure is calculated by the operator using his PRA model and by the NRC using the Standardized Plant Analysis Risk (SPAR) model. Figure 4.1 compares the two numbers for five of the yellow and red faults.[150] The y-axis is logarithmic. None of the numbers match within a factor of ten. In one case, the NRC number is 800 times higher than the plant’s number. These analyses represent a tiny, well defined portion of the tree by two groups supposedly following the same rules. Both sets of numbers are meaningless.

The Event Tree is a Fractal Bush To implement PRA, we need to enumerate all possible casualties and then create a tree of all the possible events that could lead up to this casualty. If such a tree exists, it is a fractal bush, which no matter how detailed could be made more

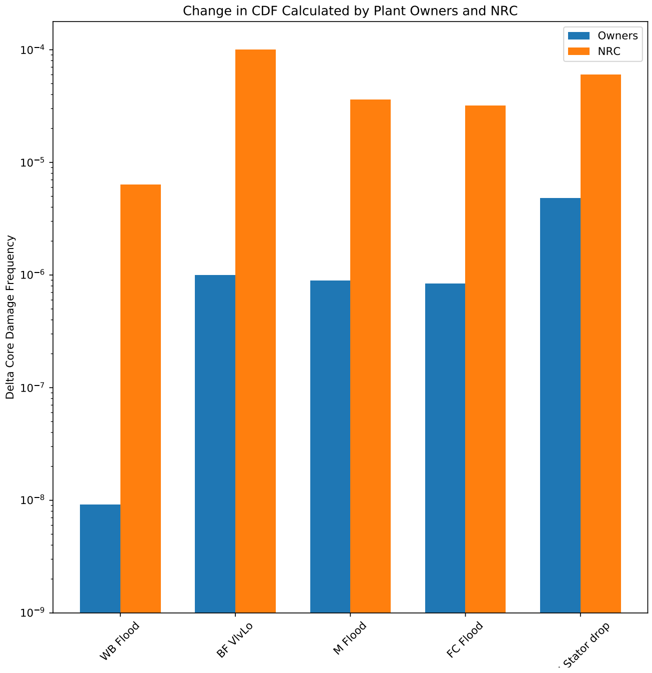


Figure 4.1: NRC vs plant estimate of increase in CDF due to fault

detailed. And if we could somehow come up with this bush, we would not only have to assign probabilities to the infinite number of branches, but also to all the possible interdependencies which are factorial in the number of branches.

This is manifestly impossible. In practice, the tree is a tiny subset of all the possibilities, which miniscule subset is chosen by the applicant, and perhaps expanded a little by the NRC. The result is completely unrepresentative of the real world.[5] It should come as no surprise that almost all nuclear casualties to date involved a series of events that were not in the PRA tree.

In March, 1975, a workman accidentally set fire to the sensor and control cables at the Browns Ferry Plant in Alabama. He was using a candle to check the polyurethane foam seal that he had applied to the opening where the cables entered the spreading room. The foam caught fire and this spread to the insulation. The whole thing got out of control and the plant was shut down for a year for repairs. Are we to blame the PRA analysts for not including this event in their

---

[5] Prior to the Three Mile Island release, a key weapon in pruning the bush down to a manageable tree was the “single failure criterion" which was interpreted to mean we don’t have to consider sequences of events involving multiple failures. This defied experience in which the vast number of major casualties involve a chain of failures the non-occurrence of any of which would have avoided the actual outcome. TMI gave birth to the Interim Reliability Evaluation Program which was supposed “to identify high risk accident sequences and determine regulatory initiatives to reduce these high-risk sequences". What in the world was PRA doing up to this point? In any event, the IREP goal explicitly admits we are only looking at a very small part of the bush.

fault tree? (If they did, what should they use for the probability?) Not if we are rational. The blame should be for focusing on the fault tree instead of picking a non-flammable sealant and insulation.

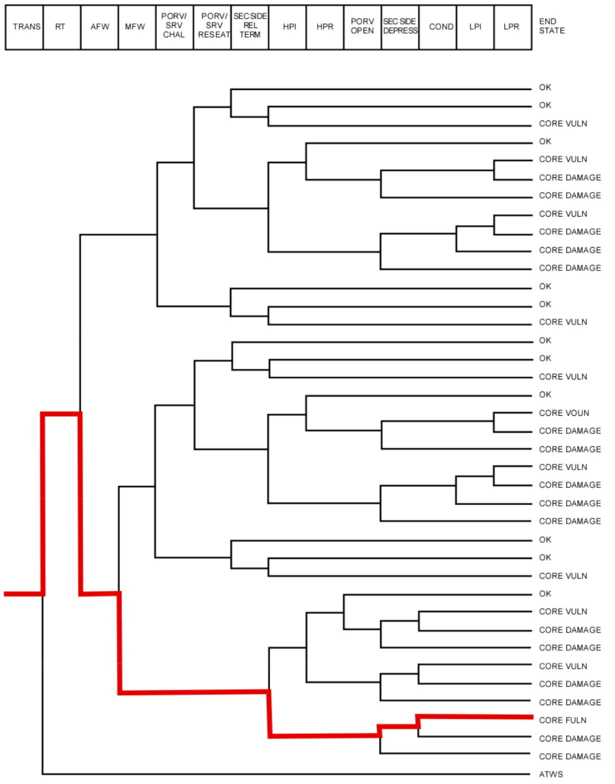


Figure 4.2: Davis Besse Loss of Feedwater Event Tree

Here's another example. On June 9, 1985, the Davis-Besse plant experienced a complete loss of feedwater. That's a major problem. The casualty sequence included 12 different equipment failures and one operator error. He hit the wrong pair of poorly marked buttons. Figure 4.2 shows NRC's diagram of a tiny portion of the PRA event tree, with the red line supposedly representing the sequence that actually happened.[55] At each node, the lower branch is Fails, the upper branch is Works. PRA requires that we put probabilities on all these branches. According to this figure, there were 39 possible sequences.

But this post-hoc drawing is not representative of this casualty. The 12 failures identified by the investigation team have been turned into three. The operator error isn't even shown, in part because how do you put probabilities on human screw ups. And failures don't have to be binary. Partial failures are not uncommon. In this case, a pressure relief valve called a PORV worked twice, then failed open, then later closed itself. A semi-realistic event tree of this casualty would require a drawing the size of large table. A semi-realistic event tree of all possible casualty sequences would require a drawing the size of a football field. And there is no way a drawing of any size is going to come up with trustworthy probabilities.

PRA more important than the design Despite the impossibility of doing a meaningful PRA, Probabilistic Safety Analysis has become the principal focus of the applicant and the NRC. Events that are not in the fault tree are ignored. The focus is not on a robust, well-engineered design but making the number, convincing the NRC that the PRA proves that the design meets the target probabilities. People who are good at this make great salesmen, lawyers, and politicians. They tend to be lousy engineers. Good engineers when presented with a bogus number have this nasty habit of saying this looks like a bogus number. To get through the process, the applicant needs to put the salesmen in charge. The wrong people get promoted, and this starts a vicious circle in which like picks like in the promotion process.

It also creates a cottage industry of PRA experts, hired guns who claim to know the secrets of getting through the process. When these people are not out selling their magic potion, they are spending their time on various industry groups, strengthening PRA, making sure that PRA is more firmly ingrained into the regulatory process, producing still more consulting fees.

Here's a proposition for these experts in probability. I will bet $10,000 that the next significant release involves a chain of events that was not in the plant's PRA event tree. Any takers?

PRA breeds complexity One way of making the number is to add layers of backup or redundancy. Double or triple the number of pumps or valves. Tack on safety system after safety system. This is often call Defense in Depth. As long as you assume independent failures, with enough layers and redundancy, you can make any target probability. But you also make the system exponentially more complex. You add new failure modes and factorially more interdependencies, some of which you will not catch. And you multiply the number of individual failures which put the system in a non-normal state.[6]

PRA favors fragile complex designs over robust simple designs.

And then a common mode casualty comes along and wipes out your redundancy. In August, 1984, the Indian Point plant lost all its emergency cooling water pumps. The pumps were in the same space which became flooded and all the motors shorted out.[7] Much the same thing happened at San Onofre, 1982-02-27, at Cooper, 1984-04-04, at LaSalle, 1985-05-31, at Hatch, 1985-12-21, at Columbia, 1998-06-17, and most importantly at Fukushima.

“Adding provisions to solve a non-problem merely provides additional paths to failure." Ted Rockwell.[219] Zirconium sheets covering the stainless steel core spreader in the Fermi plant were a last minute safety add to handle an event that was later determined to be impossible. But they also added a new failure mode that apparently no one thought much about. In operation some of the zirconium pulled off the steel, balled up, and clogged some of the coolant channels which

---

[6] One consequence is more costly shutdowns. If we add a fourth pump to get more redundancy, we increase the probability of a pump failure. But under NRC rules if any of the pumps are down, the plant must shutdown until it is fixed.

[7] The flooding required three valves in series to fail. The valves were rarely tested. PRA would proscribe a fourth valve. A much better solution would be frequent tests of a two valve system. And if you're depending on pump redundancy, don't put them in the same space.

overheated portions of the core. The plant was shut down for four years to try and correct this.

Bogus Probabilities will be Misused In a light water reactor, the used fuel elements are transferred from the core to a spent fuel pool where they are allowed to cool under water for about four years. The water provides both shielding and cooling. The original plan was that after cooling for four years the fuel elements would be sent to a reprocessing facility or a centralized air cooled repository. But in the US, both reprocessing and a repository got hung up in political wrangling and neither materialized. The obvious fallback was on-site dry cask storage, Section 3.1. But dry cask storage adds about 0.03 to 0.06 cents per kWh to the cost of the electricity.[10]

Most spent fuel pools are outside containment and many are elevated. They could be damaged and drained either by a screw up, a natural event such as an earthquake, or terrorist attack. If the fuel elements overheat to about 600C, the gas pressure inside the elements will burst the cladding and cause a release. Therefore, the original plan called for *open-racking*. The fuel elements were spaced far enough apart so that, even if the pool drained, air cooling by natural circulation would keep the elements below the temperature at which the cladding would rupture. It was a good plan.

But when the spent fuel pools started filling up, the NRC approved *dense-packing*, which quadrupled the capacity of the pools by encasing each bundle of fuel elements in a neutron absorbing shield to avoid criticality. The problem is NRC's own study indicated that air cooling would no longer keep the elements intact if the pool were drained.[18] The NRC justified dense-packing by doing a PRA which came up with a probability of pool draining of less than one in one million per pool year. I have no idea how they arrived at this probability. The NRC itself admitted than the probability does not take into account terrorist attacks.

So now we have some 35,000 tons of used fuel sitting in vulnerable spent fuel pools waiting for something bad to happen and cause a major release in order to put off spending about 0.05 cents per kWh for a few years. Absolutely nuts, but with bogus probabilities you can defend just about anything.

PRA means we don't have to test. Glory be. PRA was concocted by the 1974 Reactor Safety Study (RSS). Their job was to show that the worst case in the Brookhaven Study (WASH 1400) had such an extremely low probability, we don't have to worry about it. They were given this job after Brookhaven National Laboratory, despite intense pressure from the AEC, refused to come up with this probability, honestly saying: "a quantitative determination of reactor accident probabilities cannot be made at this time due to the paucity of input data."[85][p 77] At the time, the RSS results were considered fraudulent by almost all statisticians.[8] The RSS was reviewed by the Lewis Panel, a group of prominent physicists, almost all of whom consulted to the US government. As they politely put it, "Based on our experience with problems of this

---

[8] The RSS made extensive use of expert guesses to produce subjective probabilities, as did NUREG-1150, a 1991 update of the RSS. The NRC still condones this oxymoronic practice in PRA's.

nature involving very low probabilities, we do not now have confidence in the presently calculated values of the probabilities."[147] In other words, your probabilities are bogus. Steven Hanauer, one of the key NRC organizers of the RSS, earlier wrote in 1971, “I do not consider the numerical results [from fault tree analysis] to be reliable.[85][p 146] Even the NRC itself agrees. In 1979, the Commission announced

> In the light of the [Lewis] Review Group's conclusions on accident probabilities, the Commission does not regard as reliable the Reactor Safety Study's numerical estimate of the overall risk of reactor accident.[54]

Despite this, PRA was pounced on by the industry and NRC and became not just part of the regulatory process, but the centerpiece of this process. The reason was it relieved the industry of the need to do full scale casualty tests. The PRA paperwork might be horribly expensive, but it was a hell of a lot cheaper than building a plant just to put it through a series of rigorous stress tests.

PRA is indeed the cornerstone of NRC regulatory policy. That's because it means we don't have to do the tests that would confirm or deny the validity of the applicant's claims. In the rest of the engineering world when dealing with hazardous activities, the rule is Test then License. At NRC, the rule is Don't Test but License Anyway. PRA is the essential cover for this nonsense.

For new nukes, PRA is a Catch 22 If existing nuclear technologies can't produce meaningful event trees and probabilities, think where that puts nuclear technologies for which we have no operating experience. We need a PRA before we can get a license. But in order to do a PRA, we need all sorts of probabilities. To get the data to do a meaningful PRA, we need some operating experience and a set of casualty tests. But we can't test without a license. Catch PRA.

One of the new contenders is Nuscale. Nuscale is not really a new technology, just a scaled down Pressurized Water Reactor; but the scale down allows them to rely on natural circulation to handle the decay heat. No AC power is required to do this. The design also uses boron, a neutron absorber, in the cooling water to control the reactivity. The Advisory Committee on Reactor Safeguards(ACRS), an independent government body, is concerned that in emergency cooling mode some of the boron will not be recirculated into the core, and that could allow the core to restart. Nuscale offers computer analyses that they claim show this will not happen. ACRS and others remain unconvinced.

The solution is simple. Build one and test it. But under NRC rules, you cannot build even a test reactor without a license, and you can't get a license until all such questions are resolved.

PRA is a stupid lie PRA is an embodiment of the nuclear power establishment's philosophy that any major casualty is unacceptable where major casualty is defined as any unplanned release of radioactive material. The perception is that nuclear has to be perfect or at least claim to be perfect for political reasons. Since we can't actually say a large release is impossible, we use PRA to produce astronomically low probabilities and use those to imply that it is virtually impossible, or in the industry jargon "not credible".[9]

This is a stupid, self-defeating lie. Radioactive releases are inevitable; and when they do happen, public trust is lost for a very long time, if not forever. While we should take reasonable measures to make casualties like large radioactive releases rare, the real issue is what are the consequences of the casualty. How many people were killed? How many were injured? And most importantly, how does this compare with the alternatives?

Real Safety Analysis focuses at least as strongly on the consequences as the casualty itself. In dealing with the latter, the underlying principle is: if it can happen, it will happen. This avoids made up probabilities. It avoids a lie that is certain to backfire. And now we can go about the process of designing plants which have reasonably low — albeit unknown — probability of major casualties and, when those casualties occur, reasonably low consequences.

Put another way, if we really believed the PRA numbers, there would be no need for that horribly expensive containment vessel. Fortunately, the USA industry, unlike the Russians in the 1970's, Section 5.6.14, did not believe their own PRA numbers. So they paid for the containment and at TMI it worked.

If prior to TMI the nuclear power establishment had said

> We are working hard to make casualties such as core meltdown very rare. But sooner or later we will have a major casualty at a nuclear plant, and, when that happens, we have taken a series of measures including the containment vessel to insure that over time nuclear will result in far fewer deaths and injuries than coal, or gas, or oil.

Then when TMI happened, the establishment would have been able to say:

> Damn, we had a major casualty. Lost a brand new plant. We will learn from it just like the airlines learn something from every crash, and use that info to make such casualties rarer.
>
> But thank God, the casualty was almost entirely contained and nobody was hurt. Nuclear remains by far the safest source of electricity. This slide shows the up to date numbers.

No lies. No loss of trust.

---

[9] Airlines take the opposite approach. They say "We are so certain there will be a deadly casualty that it's worth installing two expensive orange boxes on every commercial aircraft. These boxes are designed to survive a crash that kills everybody on board. The only purpose of these boxes is to help us figure out what caused the horrific casualty so we can make intelligent fixes." The public applauds this attitude.

Which people are stupid? Why would anybody promulgate a lie that was guaranteed to be exposed? Nuclear power was born in a strange period where secrecy was the norm. The early developers of nuclear power came of age in an era where there were all sorts of information the public could not be trusted with. Only a privileged few were capable of understanding things like nuclear energy. It was short step for these technocrats to conclude that the public was incapable of evaluating the risks and benefits of nuclear electricity.

On November 29, 1955, the first meltdown of a nuclear reactor occurred. This took place during an aggressive test of the EBR-1, the world's first breeder reactor at a remote Idaho test facility.[10] A reactivity spike occurred. Power zoomed up to 10 MW, ten times the reactor's max capacity. Then the reactor was scrammed but it was already shutting itself down, as damage in the core destroyed the core's geometry. No personnel were harmed and the accident was undetectable outside the building.[157][p 120-121] But the core was completely trashed.

The AEC decided to cover the incident up. The Greatest Generation, the people who had been through World War II and won it, did not understand enough about risk to be trusted with the news of a low harm set back, which provided valuable information. Of course, the news leaked out and that was the beginning of the loss of trust.[11]

It's not the public that is stupid. It's the other way around. If the nuclear power establishment were as smart as they think they are, they would have learned the obvious lesson a long time ago. But to this day they continue to pump out bogus and misleading probabilities.[12] Will they learn the lesson when the next major release occurs?

---

[10] The EBR-1 was a successful experiment that proved that a reactor could produce more fissionable fuel than it consumed. This is called *breeding*. But the EBR-1 also had displayed a troubling anomaly. In certain situations, an increase in temperature increased power. This was not supposed to happen. Nobody knew why. In November, 1955, the reactor was about to be shut down. The decision was made to do a risky series of tests to get to the bottom of the matter.[101] They purposely stopped the coolant flow while turning up the power. It was during this experiment, the reactor core was destroyed. But the information gained led to the solution. It turned out the reactor was built in such a way that as the core heated up, the fuel rods bowed inward increasing reactivity. Once this was recognized, it became trivial to avoid this mistake.

[11] Ray Haroldsen was a member of the EBR team. Here's how he remembers the reaction.

> Our phones began to ring as newsmen inquired about the details of the meltdown. Our director, Harold Lichtenburger, responded to the calls by explaining that we were under orders not to respond to any questions for reasons of national security. The result was that the news media became hostile and started making up their own stories of what had happened. The news media had, in past times, painted our actions as brilliant. Suddenly we were accused of hiding our incompetence under the protection of national security. We changed from being heroes to villains in the media overnight.[101][p 82]

[12] Recently (2020) Oklo, designer of an untested micro-breeder reactor somewhat similar to the EBR-1, came up with a figure of once in 57 billion years, about 4 times the age of the universe. I think this is the first time we've seen “billion" in this context since Herbert Kouts' unfortunate claim in 1974.

Chapter 5

Radiation Harm and LNT

> EPA policy is to assess cancer risks from ionizing radiation as a linear response. Therefore, use of the dial-painter data requires deriving a linear risk coefficient from significantly non-linear exposure data or abandoning EPA policy.[EPA, 1991]

The overriding safety concern about nuclear electricity is the health hazard associated with a release of radioactive material. We have been told over and over that any such release is a catastrophe. But we live in a sea of radiation. Depending on where you are reading this, in the last minute your body has absorbed between 1 and 10 million particles with enough energy to produce cell damage. Life evolved in an environment where the natural level of radiation was 5 times higher than it is now.[122] If radiation is so harmful, why are we here?

The answer is life evolved a system, an extraordinarily clever system, for handling this onslaught.[1] The system is so automatic that we are unaware of it. For many hazards, evolution developed sensors and responses, so we can react to a danger. Too much heat will destroy tissue. So we developed nerves that sense temperature and send a signal called pain to the central nervous system that tells us "stop touching, get away". But there's no getting away from radiation. So evolution went with a system that repairs radiation damage without our needing to do anything. This system can be overwhelmed if the dose rate is high enough. But we shall see that the dose rates required to do this are very difficult to reach even in a radioactive release as large as Fukushima.

Unfortunately, to make this argument we will have to slog through study after study. This chapter gets repetitious and boring and more than a little distressing. I claim this is not my fault. Blame the promoters of something called LNT, the main subject of this chapter. It's the least of their sins. I suggest once you can't take any more, fast forward to Section 5.9 where we can start moving ahead again.

---

[1] This repair system may have allowed the development of oxygen based metabolism. As we shall see, oxygen based metabolism produces roughly 300 times more DNA damage in the form of Double Strand Breaks than normal background radiation. Could O_2 based metabolism have developed without a DNA repair system? Of course, to handle such levels of damage the repair system needed to further evolve to a level where the fact that it is not fazed by radiation dose rates many times normal background levels should not be surprising.

5.1 Killing People Statistically

5.1.1 Lost Life Expectancy

It is quite common to come across statements like “coal kills 30,000 Americans a year" or “nuclear has prevented 1.84 million deaths".[129] But what do these statements really mean? In a strict sense, they are not just false; they are nonsensical. Every human is going to die. The number of deaths is equal to the number of people born. Nothing we can do can change that. What we can change is the timing. Coal pollution shortens lives. Nuclear based reduction in pollution defers deaths.

How much life shortening takes place depends on the cause and the population involved. War tends to shorten the lives of young people, mainly men, at least they did before indiscriminate bombing of civilian populations. The average age of American soldiers who died in Vietnam was 23. These young men had their lives shortened by more than 50 years on average.

At the other extreme, consider the Fukushima evacuees. The panicked, disorganized evacuation killed at least 1600 people. Prior to the tsunami, there were eight hospitals and 17 nursing care facilities located within 20 km of the plant. The estimated number of hospital inpatients is 1240. The estimated number of elderly in nursing facilities was 980. On March 12, a day after the tsunami the Japanese government ordered a mandatory evacuation from anywhere within 20 km of the damaged plant. It took about 48 hours to complete the evacuation. Most of the nursing care patients were taken to Minamisoma, 26 km northwest of the plant. Soon the hospitals were full. Some of the patients were dumped in a meeting room at the Soso Health care office. Other were forced to stay in busses for long hours. 27 patients with severe medical problems were bussed north more than 100 km to Iwaki City. 10 died in route, two shortly thereafter. No significant radiation contamination was found in the patients including those who had waited 48 hours for evacuation.[243] In fact, Minamisoma turned out to be a higher dose rate area than the locations from which the people were moved. A totally avoidable, tragic mess predicted by John Dunster of the UK Health and Safety Executive in 1979:

> There is no politician would not prefer a dead body to a frightened voter.[281]

But for our unfeeling purposes, we focus on the change in life expectancy. Most of the deaths were from this group of elderly people in very poor health.

> Around 90 percent of those who died of indirect causes were aged 66 or older, according to the Reconstruction Agency statistics.[202]

For these people, what would be something between a lark and a real pain in the butt for a young, healthy person was fatal torture. A generous upper bound on the average loss in life expectancy for these poor people might be 5 years.

5.1.2 Sure Deaths and Statistical Deaths

We can divide mortality into *sure* deaths and *statistical* deaths. *Sure* deaths are fatalities that are clearly attributable to the cause in question. They tend to be immediate. *Statistical* deaths are fatalities that can only be seen in an increase in mortality rates. Our cavalier use of "saving lives and "preventing deaths" is excusable when we are talking about *sure* deaths. If a train hits a school bus and 30 kids die, then when I write "the collision killed thirty children" no one is misled.

But when we are talking about statistical deaths, this usage can be quite misleading. In fact, it is meaningless. When I say coal kills 30,000 Americans a year what I'm really saying is that exposure to coal pollution will shorten the lives of 30,000 people a year. This statement begs the question: by how much? Is it a day, is it a month, or is it like those school kids something like 70 years? If it's a day, should society devote any resources at all to trying to further reduce this number? If we are shortening the lives of 30,000 Americans by 70 years annually, that's an entirely different matter. The number 30,000 by itself is meaningless.

Often the only data we have to work with is mortality tables. A mortality table is an estimate of the probability of death by age. We must try to construct the mortality tables with and without the cause of death we are interested in. Once we have the with and without tables, it is a straight forward matter to calculate the average reduction in life associated with this cause. This is usually labeled LLE for the klutzy Lost Life Expectancy. According to Cohen, the LLE associated with coal pollution is around 23 days for the average American.[51]

There's a great deal of uncertainty in this particular figure. But at least we have a meaningful number upon which we can base policy, and decide how much resources, if any, to devote to reducing this number. And we can compare this number with the LLE of other causes of death in helping to make this decision.

5.1.3 Energy Related Sure Deaths

It is indisputable that nuclear is the safest source of dispatchable electricity when it comes to sure deaths. According to the Energy-related Severe Accident Database(ENSAD), the planet is experiencing roughly 2500 sure fatalities per year from energy-related casualties resulting in 5 or more deaths.[2] The ENSAD database contains 1870 such casualties totaling some 81,000 fatalities, Table 5.1.[31]

Exactly one of the those casualties is nuclear. Chernobyl (Section 5.6.14) resulted in about 50 sure deaths including 15 fatal cases of thyroid cancer which were clearly caused by the release.

After Fukushima, thyroid cancer was a big concern. The Japanese implemented a thorough, systematic screening system using the latest ultra-sound techniques. 48% of the 300,000 kids

---

[2] ENSAD is maintained by the Paul Scherrer Institut. It excludes a very large number of industrial casualties resulting in 1 to 4 deaths.

Table 5.1: ENSAD Energy Casualties with at least 5 deaths, 1969-2000

	Casualties	Fatalities
Coal	1,221	25,107
Oil	397	20,218
Natural Gas	135	2,043
LPG	105	3,921
Hydro	11	29,938
Nuclear	1	31
Total	1,870	81,258

registered small nodules or cysts, far higher than expected from normal screening. This raised all kinds of fears. But when a control program was instituted in Aomori, Yamanashi, and Nagasaki prefectures, 56% of the kids screened registered small nodules or cysts.[284][p 17] Adjusted for age, the numbers were the same. So far there is no evidence of elevated thyroid cancer from the Fukushima release. As a result of the screening, 126 kids underwent surgery and 125 were postoperatively diagnosed with cancer. Yamashita et al comment:

> The mean tumor diameter of operated thyroid cancers in Fukushima (14 mm) and the rate of distant metastasis (2%) are in contrast with a past report of childhood thyroid cancer in Japan. According to that study, the average tumor diameter and the rate of lung metastases was 40 mm and 19% respectively, which indicates that before the screening in Fukushima, childhood thyroid cancers were usually detected at a more advanced stage.[284][p 17]

It is likely that the intensive screening and early detection increased the life expectancy of the Fukushima kids.

This table does not include the fatalities at Fukushima caused by the evacuation, which we will argue was unnecessary and criminally imprudent. Nuclear power has been around since 1960. Table 5.2 is an incomplete list of the energy related casualties with the most sure deaths over that period. Chernobyl, the only commercial nuclear power casualty on the list, is 64th. Nuclear power was responsible for about 50 of these 50,000 deaths.[3]

Nuclear produces very roughly one-tenth of the world's electricity. On a per terawatt-hour basis, nuclear is more than 100 times safer than the dispatchable competition when it comes to sure deaths.

---

[3] I have identified six other casualties at commercial nuclear power plants which killed a total of 32 people. The worst of these was at Balakavo, Russia in 1985, when a high pressure steam valve failed or was incorrectly opened during maintenance killing 14. None of these deaths involved radiation.

Table 5.2: Major Energy Related Casualties, 1960-, Sure Deaths

	Date	Name	Type	Dead
1	1975-08-07	Banqiao Dam	dam failure	26000
2	1979-08-11	Machchhu Dam	dam failure	5000
3	1987-12-20	Donna Paz-Vector	tanker/ferry col	4386
4	1993-10-09	Vajont, Italy	dam failure	1917
5	1993-03-27	Gouhou, Qinghai	dam failure	1250
6	1980-09-18	Indian Dam	dam failure	1000
7	1965-05-06	Laobaidong	mine explosion	684
8	1984-11-19	San Juanico LPG	tank farm explos	600
9	1994-11-02	Egypt oil	pipeline exp?	580
10	1989-06-04	Ufa gas pipeline	pipeline fire	575
11	1984-02-25	Brazil oil	pipeline fire?	508
12	1995-06-29	South Korea oil	pipeline fire?	500
13	1963-11-09	Miike	mine explosion	465
14	1960-01-21	Coalbrook,	mine explosion	435
15	1972-06-06	Wankie, RH	mine explosion	426
16	1965-05-27	Dnanbad 1	mine explosion	375
17	1975-12-27	Dnanbad 2	mine explosion	372
18	2014-05-13	Soma Turkey	mine explosion	301
19	1985-07-19	Stava Dam	dam failure	269
20	1992-03-00	Kozla TK	mine explosion	263
21	1965-06-00	Yamano	mine no cause	237
22	2005-02-14	Sunjiawan	mine explosion	214
23	2015-08-12	Chuondongbei	gas well blowout	191
24	1999-10-07	Jebba, Shiriro,	dam flood	190
25	1990-08-26	Dobrnja, Yugosla	mine explosion	180
26	1980-04-22	Tacloban/Don Jua	tanker/ferry col	176
27	2015-08-12	Tianjin	mine explosion	173
28	2005-11-27	Donfeng	mine explosion	171
29	1988-07-06	Piper Alpha	rig fire	167
30	2004-11-28	Chenjiashan	mine fire	166
31	1983-07-28	Guavio Dam, Colu	dam Rlandslide	160
32	1991-04-21	Muchonggou	mine fire	159
33	2000-09-21	Sanjiaohe	mine fire	148
34	2004-10-20	Daping	imine fire	148
35	1966-10-21	Aberfan coal tip	mine flood	144
36	1991-04-10	Agip Abruzzo	tanker/roro coll	142
37	2001-06-20	Chengzihe	mine fire	124
38	1980-03-27	Alexander Kiella	rig failure	123
39	2005-08-07	Daxing	mine explosion	123
40	1972-02-26	Buffalo Creek	tailings flood	114
41	2009-11-21	Xining	mine explosion	108
42	1961-07-07	Dukla Czech	mine explosion	108
43	2007-03-19	Ulyanovskaya	mine explosion	108
44	1984-07-10	Meishan, TW	mine fire	103
45	1983-03-00	Armutcuk TK	mine fire	103
46	1984-12-05	Haishan TW	mine fire	93
47	1989-11-00	Seacrest	rig failure	91
48	1972-05-02	Sunshine ID	mine explosion	91
49	2010-05-08	Mezhdurechensk	mine explosion	91
50	2010-11-21	Heilongjiang	mine explosion	87
51	1982-02-14	Ocean Ranger	rig failure	84
52	2005-07-11	Shenlong	mine explosion	83
53	2013-03-29	Gyama Tibet	mine explosion	83
54	1968-11-20	Consol 9 WVa	mine explosion	78
55	1976-10-20	George Prince/Fr	ship collision	78
56	2009-02-22	Tunlan	mine explosion	77
57	1978-10-12	Spyros	ship explosion	76
58	2009-08-17	Sayano-Shushenka	hydro failure	75
59	2010-06-17	Amaga Columbia	mine explosion	73
60	1984-06-20	Haishan Mine	mine explosion	72
61	1972-05-11	Tien Chee	tanker/cargo col	72
62	2006-02-19	Pasta de Conchos	mine explosion	65
63	1983-09-12	Hlobane Colliery	mine explosion?	64
64	1986-04-26	Chernobyl	reactor fire	57
65	1988-06-02	Borken Hessen	mine explosion	57
66	2006-05-19	Xinjing	mine flood	56
67	2006-07-15	Liuguatun	mine explosion	54
68	1993-05-13	Middelbult Colli	mine fire?	53
69	1978-11-01	Benito Juarez	pipeline fire?	52
70	1971-01-11	Texaco Caribbean	ship collision	51
71	1979-01-08	Betelgeuse	tanker fire	50
Total				51549

5.1.4 Statistical Deaths from Cancer

The health concern for nuclear power is statistical deaths, or far more precisely the impact on life expectancy of a release of radioactive material. And the Lost Life Expectancy we are talking about is cancer. Radiation can damage a cell's DNA. Evolution has provided us with multiple repair mechanisms to deal with this damage. But if the repair system is over-stressed, the repair can be incomplete, resulting in aberrant cells which eventually lead to cancer.

Cancer is an old folks disease, which reduces its life shortening capability. For the US, most estimates put the Lost Life Expectancy associated with dying of cancer at around 12 years.[238][4] This is on the high side planet-wide; but it is the number I will use.

People often confuse statistical deaths with sure deaths. When they see a statement such as "coal kills 30,000 Americans per year", they equate it to something like 30,000 Americans killed in car crashes. But a car crash tends to kill young people with an average Lost Life Expectancy of perhaps 50 years per victim. Commercial aircraft fatalities more closely mirror the population age distribution. The LLE per passenger-death is around 40 years. So if we must equate statistical cancer deaths to sure deaths, a ratio of around 40 to 12 might be roughly appropriate. Divide the number of statistical deaths by 3.3.

LLE claims all statistical deaths are not equal. A statistical death is a premature death. A two month old infant dying in her crib is a premature death. An 80 year old Fukushima nursing home patient dying a few months early due to an unnecessary, botched evacuation is a premature death. Are they the same? Statistical deaths claims they are. LLE disagrees.

But LLE is not biased against old people. LLE is the judgement that all life years are equal.[5] This is an ethically defensible position and consistent with a societal goal of maximizing life-years. But LLE also claims that a young, productive life-year is the same as keeping a frail, elderly person alive for another year. Caveat lector.

---

[4] This is the LLE given that you die of cancer. Since about 30% of Americans will die of cancer, cancer costs Americans on average about 3.6 years of life expectancy.

[5] This assumption allows us to add individual LLE's to obtain group LLE's.

5.2 The Linear No Threshold Theory

Almost all nuclear plant radiation regulations and most radiation casualty analyses are based on the Linear No Threshold (LNT) hypothesis. LNT is based on three assumptions:

1. Cell damage is linear in the dose as measured in millisieverts.
2. All that counts is the accumulated dose over time. Dose rate is irrelevant.
3. Mortality and disease including cancer are linear in the amount of cell damage.

LNT has a number of immediate corollaries:

A. There are no damage repair mechanisms. That's why damage just builds up. If there are repair mechanisms, then the time required to repair becomes important. It makes a big difference whether the damage rate is higher or lower than the repair rate.

B. For a single person, absorbing 5000 mSv in a short time, (say an hour or two) is the same as receiving 5000 mSv evenly spread out over 50 years. In the jargon, the former is called an *acute* dose, the latter a *chronic* dose. This is a bit like saying taking one aspirin tablet per day for a year is the same as taking 365 tablets in a day.[6] Conversely, if in fact dose rate is important, then LNT's focus on cumulative dose is dangerous. Early regulation, implicitly assuming a repair period of one day, imposed daily limits of 2, then 1 mSv per day.[7] Now under LNT we have annual limits; for example, 50 mSv per year for nuclear workers. It is possible for some one to abide by the current "much stricter" limits, and violate the early limits by a factor of 25. There is a good reason why your aspirin bottle shows a daily limit, not an annual limit. For radiation, annual limits make no physiological sense.

C. Applied to a population, 5,000 people receiving 1 mSv is the same as 1 person absorbing 5000 mSv. By this logic, you can take all the radiation received by 5000 people in a sun tanning session and focus it on a single person and get the same effect. By this logic, 5000 people drinking a glass of wine in a day is the same as one person drinking 5000 glasses of wine in a day.

D. Dilution is not an effective mitigation measure. There is no point in decreasing individual doses by one thousand or one million if it means increasing the population affected by a like amount. If you have a necessary task which could be done with 10 people receiving 11 mSv or one person receiving 100 mSv, LNT says do the latter.

E If LNT is valid, casualties such as Chernobyl have or will shorten the lives of 20,000 or more people.[8] Massive, costly, disruptive, deadly evacuations can be justified every time a nuclear plant casualty threatens. And when a major release does occur, much of the evacuated area will be deemed uninhabitable for years. If LNT is valid, the cost of any sizable radiation release in uninsurable. If LNT is valid, unaided private investment in nuclear will never happen.

---

[6] A standard adult aspirin tablet contain 325 mg aspirin. The 50% lethal mammal dose is 1.75 g/kg or about 130 grams for an adult. 365 tablets taken quickly (119 g) has almost an even chance of killing you.

[7] As we shall see, this assumption turns out to have a lot of support from the most recent science.

[8] The Union of Concerned Scientists LNT based estimate is 26,000, Table 6.6.

> If LNT is not valid, the Lost Life Expectancy at Chernobyl, under a series of very conservative assumptions, was roughly equivalent to 210 sure deaths, Section 6.6. Almost all the currently restricted zone is safely livable and has been for more than 30 years.[9] If LNT is not valid, the dangers of evacuating elderly patients at Fukushima were far, far worse than any health risks associated with staying where they were. The massively disruptive evacuation and the 1600 plus evacuation related deaths could have been avoided. See Section 6.7. If LNT is not valid, nuclear power is unequivocally orders of magnitude safer than fossil fuels. If LNT is not valid and this is factored into reasonable regulations, nuclear electricity can easily compete with coal and other fossil fuels without public subsidy.

So the all important question is: what is the evidence for LNT? We have six sets of relevant information:

1. The survivors of Hiroshima and Nagaski.
2. Medical radiotherapy experience
3. Experiments on animals
4. Laboratory tests on cells and simple organisms.
5. Cancer incidence in populations which have been exposed to elevated levels of radiation occupationally or from a release.
6. Cancer incidence in areas of high background radiation.

Let's do a quick survey, or at least as quick as we can. But first we have to set the stage. That means we must go back to the end of World War II.

---

[9] In fact, the restricted zone was reoccupied as early as the summer of 1986 by illegal "self-settlers". The explosion occurred in April, 1986. In fall of 1986, two of the four units at the plant were restarted, Section 5.6.14. The last unit was restarted a year later. Up to 4000 people worked at these plants for the next 20 years.

5.3 The Rockefeller Foundation and the Genetic Scare

On August 20, 1945, Ernest O. Lawrence wrote to the Rockefeller Foundation (RF) thanking them for their critically important help in developing the atomic bomb. Lawrence said "that if it had not been for the RF, there would have been no atomic bomb".[142] Lawrence was probably right. In their support of theoretical physics in the 1930's, the RF had funded just about all the Manhattan Project greats. Much worse, they had single handedly funded Lawrence's cyclotron program, which turned out to be crucial in developing the bomb.

Foundation President Raymond Fosdick was not happy. On the 29th, he wrote to Warren Weaver, the RF's Director for Natural Sciences, saying "his conscience was deeply troubled".[86] Fosdick and Weaver decided to make amends and do whatever they could to control nuclear weapons, starting with ending weapons testing. Here's what Fosdick told the Rockefeller Trustees later that fall.

> Whether the release of atomic energy in the long run will result in good or evil for the race, no one can now say; but whatever the consequences, the Foundation and its related boards cannot escape their share of the responsibility, indirect as it may be. The atomic bomb is the result of influences which, for the most part unintentionally and unwittingly, we helped to set in motion. ... The towering question which faces the world now is whether the new energies can be controlled. It is, I know, the hope of all of us that the Foundation may be able to make some contribution, however slight, to this end.[89]

Fosdick and Weaver got right to work. In late 1945, the Foundation set up Herman Muller at Indiana University with a generous grant.[10] In 1927, Muller had shown that X-rays could produce mutations in Drosophila fruit flies. In 1930, Muller had claimed that the mutation frequency "is exactly proportional to the energy of the dosage observed" despite the fact that his own data did not support linearity, and in 1927 and 1928 papers he discussed the implications of the non-linear response.[32][page 206] This claim was based on his theory that a single change in a gene, which Muller called a 'point mutation' or a 'hit', caused the big changes that Muller

---

[10] Why Indiana? Muller was an abrasive character who turned people off wherever he went. He bounced from Rice, to Columbia, to Texas University where he dabbled in Communism and eugenics. After a suicide attempt in 1932, he moved to Germany and then the USSR. He spent 5 years in Russia; but, because he was on the wrong side of the Lysenko argument that genes were malleable by the environment, was lucky to get out alive. He moved to Edinburgh and then Amherst during World War II. At the end of the war, Amherst informed him that he was being fired. Frantic letters to colleagues produced nothing.

The Rockefeller Foundation money was unexpected salvation. But finding a place to spend that money proved a problem. The combination of Muller's personality and his Communist past made him unwelcome just about everywhere. Indiana was an exception.

Ironically Muller ended up a bit of a Cold War hawk. His time in Russia had soured him on Communism and taught him to be suspicious of some of the more extreme disarmament proposals.

observed in his flies. We now know that the large doses, 2750 mSv or more in periods of an hour or less, that Muller was basing his judgement on induced massive gene deletions in the flies.[87][11]

In 1946, despite his rocky academic career, Muller was awarded the Nobel prize. Five weeks before he received his award, Muller received a manuscript from Ernst Caspari, a fruit fly researcher he knew well. Caspari had been given the job of confirming that Muller's linear, dose rate independent rule extended down to dose rates 2500 times lower than had been tested at the time. He irradiated a group of flies at 25 mSv/day for 21 days. He meticulously maintained a control group under exactly the same conditions, except for the radiation. The test was female sterility. To Caspari's consternation, ***there was no difference between the irradiated females and the non-irradiated,*** Table 5.3. This should have been a bombshell.

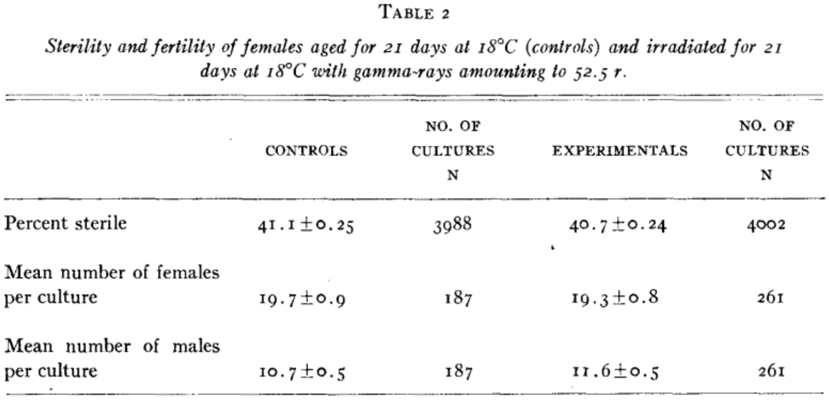


TABLE 2

Sterility and fertility of females aged for 21 days at 18°C (controls) and irradiated for 21 days at 18°C with gamma-rays amounting to 52.5 r.

	CONTROLS	NO. OF CULTURES N	EXPERIMENTALS	NO. OF CULTURES N
Percent sterile	41.1 ± 0.25	3988	40.7 ± 0.24	4002
Mean number of females per culture	19.7 ± 0.9	187	19.3 ± 0.8	261
Mean number of males per culture	10.7 ± 0.5	187	11.6 ± 0.5	261

Table 5.3: Caspari Table 2. 52.5 r is 525 mSv. Gamma-rays are photons.[38]

Caspari worked in Curt Stern's lab. Muller wrote to his buddy Stern admitting he could find no problem with Caspari's work, only asking that it be repeated. Yet a few days later in his Nobel acceptance speech, Muller claimed:

> They leave, we believe, no escape from the conclusion that there is no threshold dose, and that the individual mutations result from individual hits, producing genetic effects in their immediate neighborhood.

The RF made sure Muller received plenty of publicity, funding speaking trips all over the world.[12]

In 1954, the Foundation contracted with the National Academy of Sciences (NAS) to perform a review of the biological effects of radiation. Under this contract, the NAS set up the Biological

---

[11] In fact, Nobel Laureate Barbara McClintock discovered this in 1931. Her results were never refuted, simply ignored.

[12] When Caspari finally published his results in 1948, he treated them as an anomaly, something to be studied further.[38] Caspari did comment that, if his results were proved correct, they would be consistent with the sigmoid response seen in the killing of bacteria and Drosophila eggs by radiation.

Effects of Atomic Radiation Genetics Panel (BEAR). Warren Weaver was put in charge of the Genetics committee. Weaver stacked the committee with laboratory biologists, most of whose work was done on fruit flies, and much of that work was funded by the Foundation. Radiotherapists who had worked with humans need not apply.

Muller was the prominent member of the Genetics committee, arguing strongly for linearity which would be an abrupt departure from the prevailing position that there was a *tolerance* dose below which there was no detectable harm, a position which was consistent with Caspari's results, which the Panel simply ignored. The Panel held that genetic damage was unrepairable and therefore the damage was not only linear, it was cumulative in dose. Dose rate was irrelevant.

The key decision by BEAR to accept LNT was made at a February 6, 1956 meeting with little or no debate.[33][page 13][13] Later that year, the BEAR I panel issued a report claiming "from a genetics point of view" all doses of radiation are harmful.[14] The New York Times immediately ran a front page story with the headline "SCIENTISTS TERM RADIATION A PERIL TO THE FUTURE OF MAN".[15] The paper carried a series of articles amplifying and at times exaggerating the Panel's findings. The Foundation's plan was going well.

But there was a problem. Starting in 1946, the US government had funded the same National Academy to do a study of birth defects in children born to atom bomb survivors. The leader of this study was James Neel. Over 10 years, 70,000 pregnancies were studied. In 1956, the NAS published the results.[181] ***There was no evidence of any damage to children conceived after the bombs were dropped.***[16]

The Genetics committee was aware of the Neel study which issued periodic reports on its progress. But they chose to ignore it, preferring censored, fruit fly data over human data. As

---

[13] At the meeting, Weaver made sure everybody understood what was at stake. He told the group that he would "try to get a very substantial amount of free support for genetics, if at the end of this thing, we have a case for it. I am not talking about a few thousand dollars, gentlemen. I am talking about a substantial amount of flexible and free support to geneticists". The Foundation was quite prepared to use the geneticists' cupidity to induce scientific misconduct, if that's what it took to stop nuclear weapons testing.

At the end of the meeting, Weaver asked the committee to estimate the number of adverse genetics effects over 10 generations from the parents receiving 100 mSv over 30 years, using LNT. Three of the 12 members refused. The 9 estimates varied by a factor of 2000. Panelist James Crow, a Muller mentee, was chosen to collate the results. He threw out the three lowest estimates reducing the range to a factor of 750. But in a 1956 Science article summarizing their work,[274] the panel claimed the variation was a factor or 100, a flat lie. The article also dishonestly claimed that only six members had offered estimates, and neglected to say that 3 members had refused to make an estimate on the grounds that there was not enough information to do so. To preserve this deception, the Panel voted not to share the six estimates with the public.

[14] Later in the year, several biologists pointed out that the BEAR I panel had provided no real documentation supporting LNT and asked for it. The BEAR II panel elected to ignore this request and focus on areas requiring funding (to them). The BEAR II Panel informed the then President of the NAS, Detlev Bronk, of this decision. Bronk did not object. Bronk was also the President of the Rockefeller Institute and on the Foundation's Board of Trustees.

[15] Arthur Sulzberger, publisher of the New York Times, was also a member of the Board of Trustees.

[16] There has been a series of follow up studies extending into the 1990's.[182] They have confirmed and strengthened the original results.

Muller put it, “We should beware of reliance on illusionary conclusions from human data, such as the Hiroshima-Nagasaki data, especially when they seem to be negative". But after publishing the full report, Neel took his data to Europe, where he found a much more receptive audience. British scientists generally accepted the Neel study and it became part of a major WHO report, despite aggressive threats from Muller.[17] The Genetics committee defense by dismissal was not working.

Fortunately, a better solution soon appeared. In May, 1957, a fruit fly biologist, E. B. Lewis, who had studied under a Muller protege published a paper in Science, claiming a relationship between radiation dose and leukemia.[146] And the relationship was linear and cumulative, just like Muller's fruit fly model. We will take a look at Lewis's methods shortly.

Lewis's paper created an avalanche of favorable publicity, including a gushing editorial by Science's editor-in-chief, Graham DuShane. DuShane was quite clear about why he was so pleased with the paper: “Thanks to Lewis, it is now possible to calculate — within narrow limits — how many deaths from leukemia will result in any population from any increase in fallout or other source of radiation."

The National Academy switched its focus to cancer. The Biological Effects of Atomic Radiation Genetics Panel label was quietly dropped and replaced with the Biological Effects of Ionizing Radiation (BEIR). As Muller predicted, the Rockefeller Foundation stopped funding fruit fly research. The theory of genetic harm to humans from radiation lived on mainly in low budget horror flicks. But the genetic hypothesis that harm was linear and cumulative with dose somehow survived.[18]

---

[17] The acrimonious correspondence shows that Muller was much more worried about funding than pushing LNT.[34] Neel was challenging the whole idea of using fruit fly data to predict human response. If Neel was right, Muller's funding would dry up.

[18] Linear and cumulative are not really two separate assumptions. Each implies the other, Section 6.3.

5.4 The Atom Bomb Survivors

5.4.1 Introduction

For regulatory purposes, the single most important source of cancer radiation risk data has been the the survivors of Hiroshima and Nagasaki. About 120,000 people have been tracked, including 86,000 for which it was deemed possible to estimate the dose received. This population has a number of important characteristics:

1. They were exposed to an acute dose. Most received most of their dose in a few seconds. The dose rates have been put at 1000 to 6000 mSv per second.[120] Dose rates to the public in a nuclear power plant release rarely exceed 0.00001 mSv/second, one hundred million times less.
2. Most of the dose was from photons but a few percent of the dose was from neutrons.
3. At least early on, there was a very high uncertainty with respect to the individual doses. We shall see some examples.
4. The database has continued to be unstable despite the long passage of time. The 2004 version known as lss07 had 61,000 people in the 0 to 5 mSv dose category and 6500 unknowns. The 2012 version (lss14) has 38,500 people in the 0 to 5 mSv dose category and no unknowns. This was the result of using Accelerator Mass Spectroscopy to recompute the dose distribution.
5. Usually the data is presented in the form of ERR (Excess Relative Risk). $ERR = (R - B)/B$ where R is the mortality rate of the irradiated population and B is the mortality rate of the baseline population. This is a statistical nightmare especially at low dose. R and B are nearly equal numbers, both of which have a lot of scatter. Taking the difference drastically magnifies any statistical fluctuations. We will avoid this by showing the absolute mortality rates.

5.4.2 Early History and Leukemia

It took a while to set up the tracking system. The Atomic Bomb Casualty Commission (ABCC) was set up in 1947. The ABCC was funded by the AEC, and at least at the start was an American dominated organization. For ten years, the focus was on genetic effects. But when the results came up negative, Section 5.3, attention turned to cancer, and in particular leukemia. A registry for tumors was not set up until 1958.

The early returns on leukemia are interesting. The following table reproduces Table VII from the UNSCEAR 1958 report except that I have converted the dose in rem to mSv. The lettered footnotes are in the original.

This table makes a number of points.

1. The dose for many of these people was enormous.[19]

---

[19] The highest doses are clearly wrong. No one can survive an acute dose of 13,000 mSv.

Table VII. Leukemia incidence for 1950 - 57 after exposure at Hiroshima[a]

Zone	Distance from hypocentre (metres)	Dose mSv	s Persons exposed	L Cases of leukemia	$\sqrt{L}$	N[b] Total cases per 10^6	N_x Rad.cases per 10^6	N_x per mSv
A	under 1,000	13,000	1,241	15	3.9	$12,087 \pm 3,143$	11,814	0.091
B	1,000 - 1,499	5,000	8,810	33	5.7	$3,946 \pm 647$	3,473	0.069
C	1,500 - 1,999	500[c]	20,113	8	2.8	398 ± 139	125	0.025
D	2,000 - 2,999	20	32,692	3	1.7	92 ± 52	-181	-0.9
E	over 3,000	0	32,963	9	3.0	273 ± 91	Control	

---

[a] Prior to 1950 the number of cases may be understated rather seriously

[b] The standard error is taken as $N\sqrt{L}/L$

[c] It has been noted that almost all cases of leukemia in this zone occurred in patients who had severe radiation complaints, indicating that their dose were greater than 500 mSv.

Table 5.4: UNSCEAR 1958 Table VII Leukemia Incidence

2. There was a tremendous uncertainty in the individual doses.
3. The Zone A and B exposures increased leukemia incidence by a factor or 40 and 14 respectively. Leukemia is a rare disease. As of 1957, 12 cases has been diagnosed among the 66,000 people in Zones D and E. Pretty clearly, almost all the leukemias in Zones A and B were caused by radiation.
4. The response was highly non-linear in dose. If we take the average zone doses at face value and use the Zone E rate as background, the excess incidence per mSv is 0.091 for Zone A, 0.069 for Zone B, 0.025 for Zone C and -0.9 for Zone D. Since the grouping and averaging by zone washes out a lot of the non-linearity, we can be sure the actual numbers were even more non-linear.
5. The 32,692 people in Zone D had a ***lower*** leukemia rate than the 32,963 people in Zone E. The zone with the higher average dose had less disease than the zone with the lower. 66,000 people is a large sample.

So how did UNSCEAR interpret this?[20]

> In zones A (13,000 mSv), B (5000 mSv) and C (500 mSv), the values of P_L were calculated to be 0.09, 0.07 and 0.07 [sic] times 10^{-6} respectively. This finding was taken to support the suggestion that the extra leukemia incidence is directly proportional to radiation dose, and conversely to argue against the existence of a threshold for leukemia induction.[256][para 31, page 165]

P_L is the extra probability of leukemia occurring per dose per year since exposure, the last

---

[20] Again I've converted rem, an antiquated dose unit, to mSv in the quotes.

column in Table VII. So 0.091, 0.069 and 0.025 (without the typo) are equal? What about the Zone D numbers?

> Contrary to previous findings, the present findings indicate that P_L decreases markedly as the dose falls, that therefore leukemia incidence is not a linear function of dose, and that a threshold for leukemia induction might occur. In fact according to Table VII, a dose of 20 mSv is associated with a decreased leukemia rate. It is to be emphasized again, however, that estimates of dose employed in the present and previous analyses are much too uncertain to permit drawing conclusions relative to the vital points in question. The calculations are made only to illustrate how variable the results may be when inadequate data are utilized.[256][para 33, page 165]

In other words, the uncertainties are such that the numbers can be ignored; but they support LNT even when it looks like they don't. This is Wonderland stuff.

But wait a minute. How did Professor Lewis, working from essentially the same data come up with a linear relationship between dose and leukemia? At the heart of Lewis's argument is his Table 2 reproduced here as Table 5.5.

Table 5.5: Lewis's Table 2: Incidence of Leukemia combined populations of Hiroshima and Nagasaki

Zone	Distance from hypocenter m	Estimated population of exposed survivors (Oct, 1950)	Number of confirmed cases of leukemia	Percentage of Leukemia
A	0 - 999	1,870	18	0.96
B	1000 -1499	13,370	41	0.30
C	1500 -1999	23,060	10	0.043
D	2000 and over	156,400	26	0.017

There are some differences in the population. The UNSCEAR table refers only to Hiroshima survivors. Lewis combined Hiroshima and Nagasaki. But semi-quantitatively the results are somewhat similar, with one very striking difference. ***Lewis has lumped Zone E and D together while UNSCEAR did not.*** In so doing, Lewis hid the glaring non-linearity in the data.

Lewis knew what he was doing. To defend his decision to include Zone D into his control group, he feels compelled to say "the average dose is under 5 rem [50 mSv] and is thus so low that zone D can be treated as if it were a 'control' zone."[146][page 125] But if there is no difference between 50 mSv acute and zero, the relationship cannot be linear.[21] The widely acclaimed and

---

[21] According to LNT, 50 mSv results in a 0.5% chance of cancer. By putting these people in his control group, Lewis is contradicting LNT.

enormously influential Lewis paper was not only deceitful, it was inconsistent. The UNSCEAR explanation might be gibberish; but at least they did not hide the data.

We shall run into the duplicitous trick of mushing together low dose groups to hide non-linear and sometimes beneficial responses again and again. For example, Figure 5.1 compares how UNSCEAR presented the updated bomb survivor leukemia data in 1994, with the US National Council on Radiation Protection (NCRP) presentation in 2001. As we shall see, doses to the public in a nuclear plant release are almost never over 50 mSv (0.05 Sv), and almost always less than 15 mSv. Yet the NCRP, following Lewis, prefers to view the data from so far away that the all-important 0 to 50 mSv range is nearly invisible.

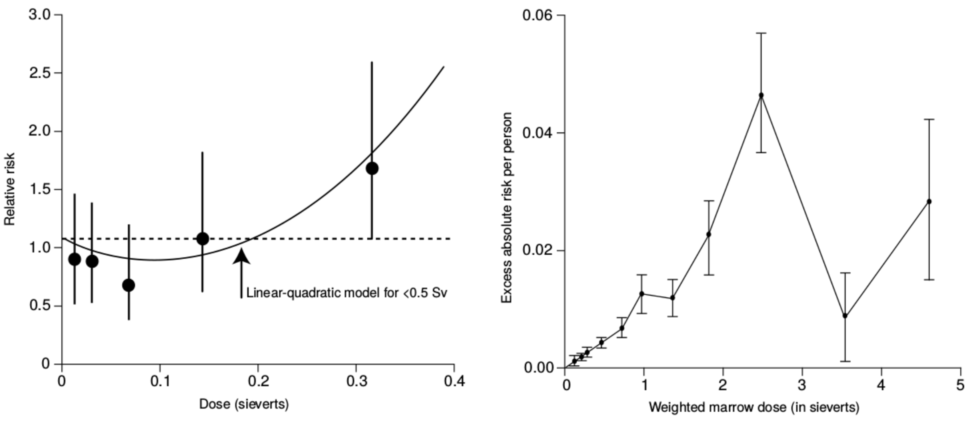


FIGURE 1a

Mortality from Leukemia in Hiroshima and Nagasaki—Data as Presented by UNSCEAR

FIGURE 1b

Mortality from Leukemia in Hiroshima and Nagasaki—NCRP Version of the Same Data

Source: UNSCEAR 1994, p. 257.

Source: NCRP Report No. 136, p. 146.

In Figure 1a, taken from UNSCEAR 1994, the threshold below the dose of about 200 mSv (millisieverts) and the hormetic effect at lower doses are clearly seen. In Figure 1b, taken from NCRP Report No. 136, the x-axis for this dose range is so compressed that the threshold and hormetic effects are concealed, and the report states: "There is statistically significant upward curvature in the dose range 0 to 3 Sv."

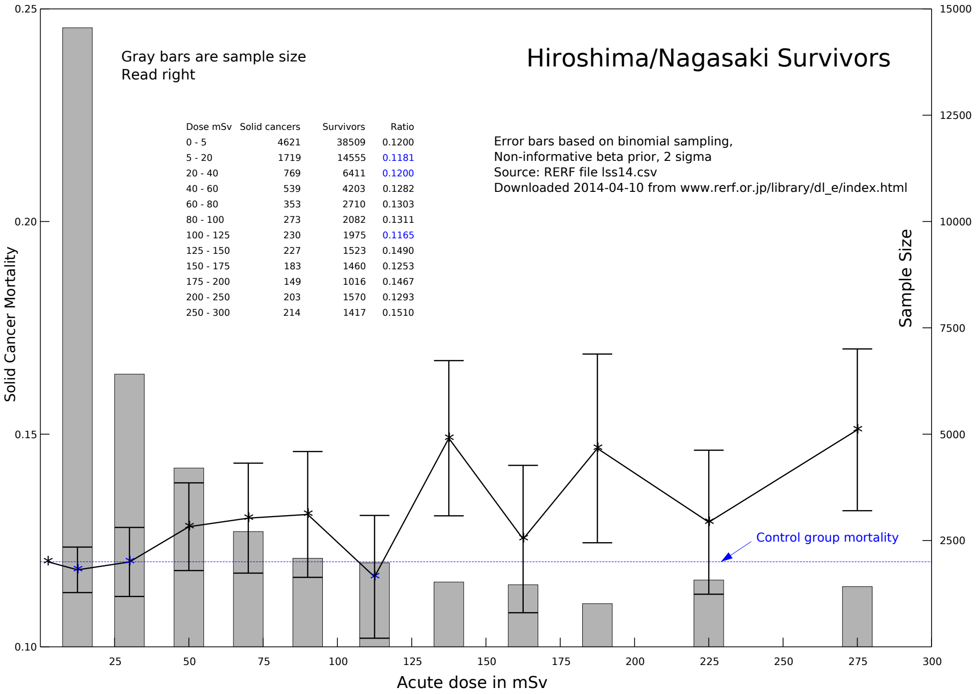
Figure 5.1: Two Views of the Bomb Survivor Leukemia data: left UNSCEAR, 1994, right NCRP, 2001

5.4.3 The RERF and Solid Cancers

In 1975 the ABCC was dissolved and replaced by the Japan U.S. Radiation Effects Research Foundation (RERF), jointly funded by both governments. A great deal of work has gone into dosimetry. After major revisions in 1986 and 2002, the RERF claims "the radiation dose of each A-bomb survivor has been estimated with a high degree of accuracy".[88][page 1] Elsewhere high degree of accuracy is put at a relative one standard deviation error of 30%. But then in 2012, the size of the dose rate cohorts changed drastically.

The RERF usually presents its results in terms of colon dose. RERF assumes that the people were irradiated in a manner such that colon dose is representative of whole body dose. So for our purposes colon dose and whole body dose are the same.

On 2014-04-10, we downloaded lss14.csv from the RERF website.[22] Table 5.6 displays the result of ratioing solid cancer deaths to the number of subjects in each dose category. Figure 5.2 plots the data for the under 300 mSv groups. The data does not look linear, especially at the low end. These raw numbers show no significant increase in mortality below 100 mSv. In fact, these raw numbers show a decreased mortality in the 5-20 mSv and 20-40 (barely) mSv dose categories relative to the 0 to 5 mSv control group.



Dose mSv	Solid cancers	Survivors	Ratio
0 - 5	4621	38509	0.1200
5 - 20	1719	14555	0.1181
20 - 40	769	6411	0.1200
40 - 60	539	4203	0.1282
60 - 80	353	2710	0.1303
80 - 100	273	2082	0.1311
100 - 125	230	1975	0.1165
125 - 150	227	1523	0.1490
150 - 175	183	1460	0.1253
175 - 200	149	1016	0.1467
200 - 250	203	1570	0.1293
250 - 300	214	1417	0.1510

Figure 5.2: RERF Solid Cancer Mortality, 0 to 300 mSv

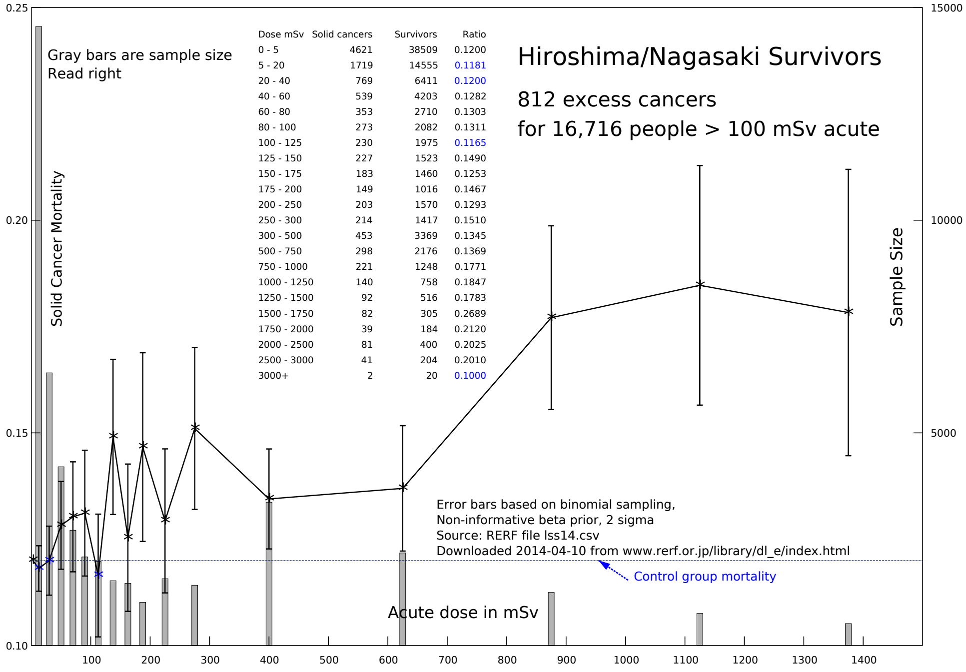
---

[22] This report makes use of data obtained from the Radiation Effects Research Foundation (RERF), Hiroshima and Nagasaki, Japan. RERF is a private, non-profit foundation funded by the Japanese Ministry of Health, labour and Welfare (MHLW) and the U.S. Department of Energy (DOE), the latter in part through DOE Award DE-HS0000031 to the National Academy of Sciences. The conclusions in this report are those of the authors and do not necessarily reflect the scientific judgement of RERF or its funding agencies.

Ozasa et al, Figure 4 show positive ERR's (Excess Relative Risk defined in Section5.4.1) in these two dose categories.[203] The main reason is the young age of the 5 to 20 mSv cohort which was a whopping 0.5 years lower than the 0 to 5 mSv cohort as Table 5.6 shows. Cancer is a very strong function of age. Statistically older people have much higher cancer mortality rates than younger. The average age of the entire population is only 29 so this is a massive difference. Why would children be much more likely to be in the 5 to 20 mSv dose group than older people? We have found no discussion of this in the RERF reports.

The survivors were interviewed 10 or more years after the fact. They were being asked details about just where they were in the most traumatic experience that anyone could possibly imagine, an event that in many cases left them unconscious and badly injured. Even if they answered all the questions as honestly as they could, to expect accuracy under these circumstances is unrealistic. And to expect honesty may also be unrealistic. Sasaki et al noted a strange blip in cancer rates in females who were 20 to 30 years old at the time of the bombing.[226] Sasaki suggests a possible explanation is that this group under-reported their dose to avoid harming their marriage prospects.

Figure 5.3 plots the data for everybody under 1500 mSv. This is the kind of big picture that RERF likes to show us. From this distance the behavior in the 0 to 40 mSv range, where almost all the data is, is lost in the jumble; and the points in the 100 mSv plus range, of almost no applicability to nuclear power plant releases, are strongly emphasized.



Gray bars are sample size
Read right

Dose mSv	Solid cancers	Survivors	Ratio
0 - 5	4621	38509	0.1200
5 - 20	1719	14555	0.1181
20 - 40	769	6411	0.1200
40 - 60	539	4203	0.1282
60 - 80	353	2710	0.1303
80 - 100	273	2082	0.1311
100 - 125	230	1975	0.1165
125 - 150	227	1523	0.1490
150 - 175	183	1460	0.1253
175 - 200	149	1016	0.1467
200 - 250	203	1570	0.1293
250 - 300	214	1417	0.1510
300 - 500	453	3369	0.1345
500 - 750	298	2176	0.1369
750 - 1000	221	1248	0.1771
1000 - 1250	140	758	0.1847
1250 - 1500	92	516	0.1783
1500 - 1750	82	305	0.2689
1750 - 2000	39	184	0.2120
2000 - 2500	81	400	0.2025
2500 - 3000	41	204	0.2010
3000+	2	20	0.1000

Hiroshima/Nagasaki Survivors

812 excess cancers
for 16,716 people > 100 mSv acute

Error bars based on binomial sampling,
Non-informative beta prior, 2 sigma
Source: RERF file lss14.csv
Downloaded 2014-04-10 from www.rerf.or.jp/library/dl_e/index.html

Figure 5.3: RERF Solid Cancer Mortality, 0 to 1500 mSv

5.4.4 Summary

In summary,

1. The REFR data is based on acute doses while almost all nuclear safety issues involve chronic doses.[23] If you accept the fact that the body has repair mechanisms, then the two are quite different in their health implications.
2. The data base has been disturbingly unstable mainly due to the difficulty of estimating the dose received by each individual. It seems likely that some biases have crept in, including assigning higher doses to children than older people. Given the uncertainties small biases can flip the results all over the place.
3. The raw data is non-linear showing little or no increased mortality up to about 50 mSv. RERF itself admits:

   > The estimated lowest dose range with a significant ERR for all solid cancer was 0 to 0.2 Gy [roughly 0 to 200 mSv].[203, page 229]

   This is an artfully worded way of saying there was no statistically significant increase in solid cancers in the people who received less than 200 mSv acute.
4. Even after RERF massaging, Ozasa et al come to the conclusion that the data are non-linear in the dose range 0 to 2000 mSv.

   > Although the linear model provided the best fit in the full dose range, statistically significant upward curvature was observed when the dose range was limited to 0-2 Gy [0 to 2000 mSv] (P=0.02).[203, page 234]

   An acute dose of 2000 mSv is far above the range of interest for the public in a nuclear power plant release.

In short, there is little evidence for LNT in the bomb survivor, solid cancer data, even if you believe that dose rate is unimportant.

Postscript Nagasaki and Hiroshima recovered as quickly as the cities that had “only" been fire bombed. Both became major shipbuilding centers. Shipbuilding was a pillar of the Japanese post-War recovery.

---

[23] Any dose response curve implicitly assumes an acute dose. How can such curves be applied to chronic dose profiles? The next chapter suggests a work around.

Dose range	range mGy	midrange	subjects	all solid cancers	ratio	deaths	ERR	ave age
1	0 - 5	2.5	38509	4621	0.12000	22270	0.00000	29.050
2	5 - 20	12.5	14555	1719	0.11810	8266	-0.01579	28.499
3	20 - 40	30.0	6411	769	0.11995	3735	-0.00040	29.319
4	40 - 60	50.0	4203	539	0.12824	2404	0.06870	28.478
5	60 - 80	70.0	2710	353	0.13026	1614	0.08550	29.365
6	80 - 100	90.0	2082	273	0.13112	1273	0.09272	30.161
7	100 - 125	112.5	1975	230	0.11646	1135	-0.02952	29.092
8	125 - 150	137.5	1523	227	0.14905	956	0.24209	31.115
9	150 - 175	162.5	1460	183	0.12534	863	0.04454	29.558
10	175 - 200	187.5	1016	149	0.14665	603	0.22213	29.626
11	200 - 250	225.0	1570	203	0.12930	972	0.07751	30.032
12	250 - 300	275.0	1417	214	0.15102	880	0.25855	29.878
13	300 - 500	400.0	3369	453	0.13446	2046	0.12053	29.772
14	500 - 750	625.0	2176	298	0.13695	1327	0.14126	29.612
15	750 - 1000	875.0	1248	221	0.17708	734	0.47572	27.792
16	1000 - 1250	1125.0	758	140	0.18470	486	0.53916	27.375
17	1250 - 1500	1375.0	516	92	0.17829	315	0.48581	27.103
18	1500 - 1750	1625.0	305	82	0.26885	213	1.24048	28.025
19	1750 - 2000	1875.0	184	39	0.21196	113	0.76633	26.087
20	2000 - 2500	2250.0	400	81	0.20250	269	0.68753	26.788
21	2500 - 3000	2750.0	204	41	0.20098	137	0.67487	25.221
22	3000+		20	2	0.10000	9	-0.16665	4.750
Totals			86611	10929	0.12618	50620		29.033

Table 5.6: RERF Solid cancer mortality from lss14.csv

5.5 Radiotherapy and LNT

In the explosion at Chernobyl (see Section 5.6.14), over a hundred plant workers and first responders received doses of 1000 mSv or more. 134 were treated for Acute Radiation Sickness (ARS). 28 of these men died. ARS kills by messing with the immune system. The blood forming cells in bone marrow stop or cut production depending on the dose. The immune system can't function, and deadly infections follow. If the dose is less than about 5000 mSv, the bone marrow will normally recover. It typically takes about 3 or 4 weeks for the marrow cells to resume production. If the victim survives for more than about 30 days, then a full recovery can be expected.

Table 5.7 shows short-term death rates of the 134 Chernobyl ARS victims against dose.[260][page 58]

Dose Range	Mortality	Frequency
800 to 2100 mSv	0 out of 41	0.00
2100 to 4100 mSv	1 out of 50	0.02
4200 to 6100 mSv	7 out of 22	0.32
6100 to 16000 mSv	20 out of 21	0.95

Table 5.7: Chernobyl ARS deaths as a function of acute dose

The Chernobyl ARS doses were acute doses. The dose rates were in the sieverts per hour range or higher. At these rates, if you received less than 2000 mSv, you almost certainly survived; if you received more than 6000 mSv, you almost certainly died.

But the important point for now is the non-linearity of the death curve. Figure 5.4 plots the Table 5.7 data. Below about 4000 millisieverts and above about 6000, the curve is quite flat. This reflects the fact that a probability/frequency cannot be smaller than 0.00 nor larger than 1.00. To put it another way, a smooth dose-response curve must have a slope of zero at 0.00 probability and a slope of zero at 1.00 probability. In between, the curve can be fairly steep. In the Chernobyl data, the curve rises by 0.3 in the 2000 to 4000 mSv interval and another 0.6 in the 4000 to 6000 mSv interval. This sigmoid behavior can be modelled by a logistic curve such as the red line in Figure 5.4.

It is difficult to see in Figure 5.4, but the logistic curve is always larger than zero, except at zero. Using logistic curves to fit dose-response relationships is standard practice except for radiation. LNT would have to fit this data with something like the blue dashed line. If an undergraduate attempted to do this in an introductory biology course, he would be rewarded with an F.

As Figure 5.4 indicates, if the response curve is non-linear, there must be a region in which the slope of the curve is higher than if it were linear.[24] This is gospel as far as radiotherapists are concerned. Here's a quote from the Royal College of Radiologists,[194].

---

[24] LNT is often defended on the grounds that it is conservative. But in fact it is only conservative at the low end. And then only if dose rate is unimportant.

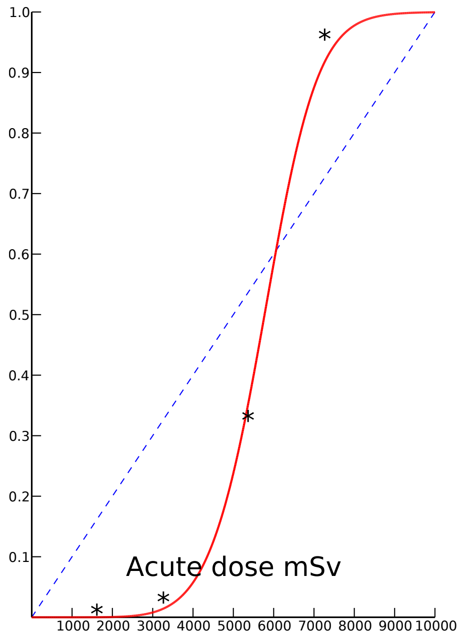


Figure 5.4: Chernobyl ARS deaths as a function of acute dose

> Dose-response relationships for tumour control are steep and a 4-5% dose increase might lead to a 10% increase in probability of tumour control.

This is essential to radiotherapy. It means that, if the doctor can locate his dose so that the edge of the tumor is in the steep part of the curve, he can do a lot more damage to the tumor than to the surrounding healthy tissue.

The final point to notice about Figure 5.4 is the *relative* difference between LNT and a non-linear response curve can be reasonably small in the middle and upper portion of the dose range while at the same time be massive at the low end. At 5000 mSv, the two curves differ by less than a factor of two. At 1000 mSv, the two curves differ by a factor of 30,000.

The Chernobyl acute dose fatality rates have plenty of support in other casualties. For Hiroshima, where the population was malnourished and under extreme stress before the bomb, 50% lethality was achieved at about 3000 mSv. But for acute doses below 1000 mSv, clinical symptoms are not usually observed.[276]

As does the non-linearity. Figure 5.5 shows the results of a survey of acute hairloss in atom bomb survivors. The curve is clearly non-linear. The dip at the high end is almost certainly the result of dose over-estimation for these people. For our purposes, a grey is 1000 mSv.

Another fundamental principle of radiotherapy is *fractionation*. The doses required to kill

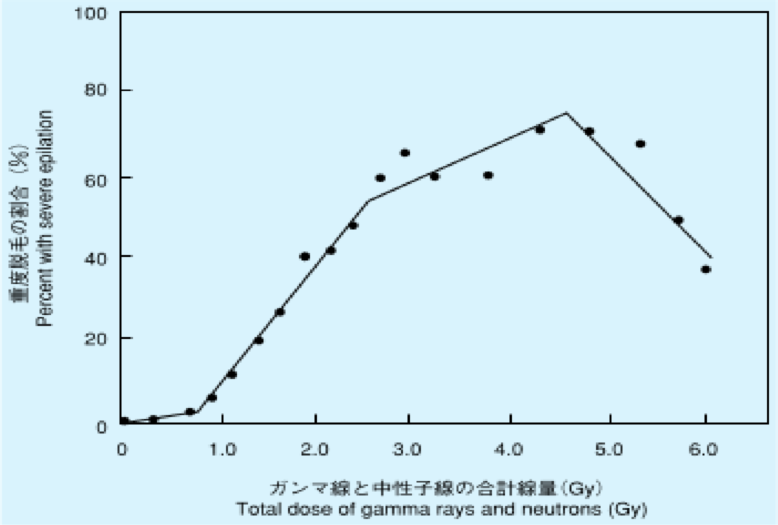


Figure 5.5: RERF survey of acute hairloss of atom bomb survivors, 1 Gy = 1000 mSv

tumors are enormous. Radiotherapists discovered early on that if they administered a dose in fractions, that is, dispensed say 20% of the dose on day 1, 20% on day 3, and so on the results were much better than if the full dose was administered in a single session. The reason was that this gave the cells a chance to recover from the damage and normal cells tend to be better at recovering than cancer cells. According to LNT, fractionation should not make any difference. No honest radiologist believes in LNT.

5.6 Occupational and Other Exposures

5.6.1 The UK Radiologist 100 year Study

In 2001, the British Journal of Radiology updated their long-term study of mortality among British radiologists covering the period 1897 to 1997.[21] Table 5.8 of Standardized Mortality Rates (SMR) is taken from the study's Table 2.

The radiologists were divided into four groups based on the date they joined one of the two British radiology societies. The data shows a near doubling in cancer mortality rate for the radiologists that joined before 1920. Early on radiologists calibrated their X-ray machines by sticking an arm into the beam. If this caused a reddening reaction, similar to sunburn, then the machine was set up properly.[156][p 238] It's estimated that the reddening dose was 600 mSv.[286] But the cancer SMR's drop off sharply for the later cohorts when limits were imposed, and are well below 1.00 for the post-1955 group.

Strikingly the non-cancer SMR's are generally well below one. The 0.86 SMR for the total

		Relative Mortality Rates					
	Measured against	1897-1920	1921-1936	1936-1954	1955-1979	All 1920+	Total
All causes	all UK men	0.95	0.80	0.76	0.50	0.72	0.77
	all Social class I	1.03	0.93	0.99	0.69	0.91	0.94
	all UK physicians	0.97	0.92	1.00	0.68	0.91	0.92
All Cancers	all UK men	1.27	0.76	0.66	0.46	0.63	0.73
	all Social class I	1.45	0.93	0.88	0.61	0.82	0.93
	all UK physicians	1.75	1.24	1.12	0.71	1.04	1.16
All Non-Cancers	all UK men	0.89	0.81	0.78	0.49	0.73	0.77
	all Social class I	0.96	0.92	1.00	0.70	0.92	0.93
	all UK physicians	0.86	0.86	0.95	0.64	0.86	0.86

Table 5.8: Standardized mortality rates for British Radiologists

group relative to all physicians is significant at the $p < 0.001$ level The net result is that even the pre-1920 group has an overall mortality rate lower than all physicians. Since 80% of these radiologists died from non-cancer causes, the decreased SMR for non-cancer cancelled the 75% excess cancer mortality. The authors spend a great deal of time discussing the cancer numbers but their only comment on the non-cancer figures in the abstract is:

> Non-cancer causes of death were also examined in more detail than has been reported previously. There was no evidence of an effect of radiation on diseases other than cancer even in the earliest radiologists, despite the fact that the doses received by them have been associated with more than a doubling in the death rate among the survivors of the Japanese bombing.

The second sentence is a flat lie. There's no other way to put it. In any event, the results of this study argue strongly against LNT.

In 2004, Wakeford made a sweeping review of radiation health studies.[270] Wakeford has no doubts about LNT. In his introduction, he explicitly assumes it is true. After explaining that dose measured in sieverts is a measure of cell damage, he immediately makes the jump “The equivalent dose therefore is a measure of the risk of cancer developing in the human tissue in which the energy of the particular radiation is deposited." He then goes on to cite study after study which he claims support LNT. Here's how Wakeford summarizes Table 5.8.

> Recently, Berrington et al presented results of 100 years of observation of British radiologists, which showed a significant 41% increase in cancer mortality rate over that for all medical practitioners combined for radiologists registered with a radiological

Dose (mSv)	Observed	Expected	Ratio
Less than 10	11836	11877	0.997
10 to 20	2920	2937	0.994
20 to 50	3693	3726	0.991
50 to 100	2082	2067	1.007
100 to 200	1380	1366	1.010
200 to 400	914	855	1.069
more than 400	501	496	1.010

Table 5.9: Deaths all causes from Muirhead, Table S2

> society for more than 40 years, and a significant trend of this rate with time since first registration.

Wakeford wrote in 2004. The only radiologists with more then 40 years registered were in the group that registered before 1964. This group is heavily weighted toward the period when there was no concern about radiation. Sometimes cherry picking is worse than a lie.

5.6.2 UK Radiation Workers

In 2009, Muirhead et al updated the ongoing study of 174,000 UK radiation workers for which we have dose numbers.[173] They divided the sample into less than 10 mSv, 10 to 50, 50 to 100, and more than a 100. The more than a 100 group was only 6% of all the workers but had 50% of the collective dose. Muirhead applied linear regression to this data and found a weak positive correlation (0.093, CI of -0.08, 0.28). The authors comment

> There was borderline evidence of an increasing trend in total mortality with increasing dose from a one-side test (P = 0.049); the corresponding evidence from a two sided test was weak (P = 0.098).[25]

Table 5.9 taken from Muirhead's Supplementary (aka unpublished) Table S2 gives us an idea of just how weak this trend is. The ERR below 50 mSv is 0.995, just below 1.000. The average ERR above 50 mSv is 1.019.

---

[25] At least these authors reported the results of the two-sided test. The standard LNT practice is to assume the correlation coefficient can't be negative. As Cardis et al explains: “Since the main objective of radiation epidemiological studies is generally to test for increased risk in relationship to radiation exposure, one sided P-values and corresponding 90% confidence intervals are usually presented."[37] In other words, we arbitrarily toss out the low tail of our uncertainty to make the results look more significant. And we use a 90% confidence interval when 95% is the standard in most other fields and most journals.

But these linear regression P-values and confidence intervals make a far more fundamental assumption. They only apply if the relationship is linear.

Nowhere in the analysis do the authors consider the possibility of a non-linear response. For them a positive correlation equates to linear. But in their own data, there is no evidence of an elevated ERR until you get above 50 mSv. There is weak evidence of a decreasing effect between 0 and 50 mSv.

Table 5.9 compares this group of radiation workers with itself. The *Expected* column took the total number of deaths in the cohort and distributed it among the dose categories according to the number of workers in each category. They had to do this because if they had compared the workers death rates with the death rates of all UK workers in the same Social class, you come up with an Standardize Mortality Rate (SMR) of 0.81. In other words, the overall death rate of the 174,000 person group was 81% that of UK workers in the same social class. The authors toss this staggering difference off as Healthy Worker Effect.

Some argue that Table 5.9 is strong support for LNT. At best it is a weak argument for a positive correlation between dose and mortality above 50 mSv. And combined with the massive difference in this groups SMR and that of non-radiation workers, we could be looking at a reduction in hormetic effects on either side of 20 to 50 mSv.

5.6.3 The 15 Country Radiation Workers Study

The 2009 UK radiation workers study was preceded in 2007 by a 15 country study of radiation workers by Cardis et al.[37]. The authors start out by admitting that “Most [rad worker] studies to date showed little evidence of dose related increase in all cancer mortality".

To rectify this unsatisfactory situation, the decision was made to pool all the studies in the hopes that the additional statistical power would reveal the real truth underlying the numbers. But simply adding up a bunch of negative studies was not going to get a positive response. The authors threw out two cohorts, Idaho National Lab and Ontario Hydro, which they admit showed “strong and statistically significant negative correlation between radiation dose and cancer risk". This was done because the 15 Country Study was stratified by socio-economic status, and the information to perform that stratification was not available from INL and Ontario Hydro.

They also excluded a group of Canadian, U.K, and U.S. workers who had been exposed to substantial amounts of neutron radiation on the grounds that the doses were not adequately measured. This group tended to be both high dose and low cancer mortality rate, 88% that of the included workers. The authors lamely admit “The reasons for this are unclear and include a possibly stronger healthy worker effect and/or different smoking behavior relative to other radiation workers." What is really unclear is why the dose measurements for this group which were accurate enough for earlier studies are no longer accurate enough to be included.

The case control shipyard study was also not included, presumably because these were not nuclear workers, even though the doses were on average higher than the 15 country average. But strangely a far less controlled cohort from the Portsmouth Naval shipyard was included.

The authors also introduced a set of bias adjustment factors based in part on questionnaires.[247] This was to correct for differing calibration standards and dose measurement procedures in different countries. In many cases, these adjustments were of the same order of magnitude as the measured dose rates.

The Cardis paper is a hard read, but the biases are transparent. After explaining the use of a one sided test and a 90% confidence interval as noted above, the authors go further. Their linear model is of the form $1 + \beta Z$ where Z is the cumulative dose β is the slope in Excess Relative Risk per sievert. This leads to the following paragraph.

> The linear excess relative risk model has computational restrictions, *since the relative risk cannot be negative.* Hence the parameter β is constrained to be larger than minus one divided by the maximum dose, and in some cases estimates and/or lower confidence bounds for β cannot be obtained; these are designated simply as < 0 throughout this paper. Log-linear models, in which the relative risk is assumed to be of the form $\exp(\beta Z)$, were also fitted to the data, and resulting estimates of the relative risk at 100 mSv compared to 0 mSv are presented in this paper where β could not be estimated under the linear model. *Linear and log-linear models give essentially the same results for low dose and low risks.*

The emphasis is mine. It is hard to know where to start with this one. But here's a possible translation.

> We are defending a linear model. But sometimes the linear model comes up with a negative relationship between harm and dose. When this happens, we toss the linear model and apply a transformation which always yields a positive relationship. Then we claim that there is no real difference between a straight line and the exponential function.

How this passed peer review is beyond me.

There are all kinds of interesting patterns in the data which go unexplored. I'll just mention two. The all cancers except leukemia slope for nuclear power plants is -0.01 ERR/Sv while that for other "mixed" facilities is +1.23. "mixed" facilities are bomb making, fuel enrichment, and reprocessing. There is little radiation in fuel enrichment, so the doses in this group must be from bomb making and reprocessing. Why the big difference? If I had to make a guess, the non-power plant doses were received in a much spikier manner. But we don't know. What we do know is that for the nuclear plant workers there was no evidence of increased mortality with increased dose.

The data was stratified by duration of employment at the nuclear facility. People who were employed in nuclear facilities for more than 10 years fared much better than people employed for less than ten years. The authors claim without argument this is evidence of a "strong healthy workers effect". Since we don't know what the people with shorter employment were doing when they were not employed by the nuclear facility while we do know, thanks to the stratification, they had the same socio-economic status, this claim seems unsupported, What we do know is that people with longer employment but the same cumulative dose experienced lower average dose rates.

Fortunately, the authors summarize some of their results graphically in their Figure 1, our Figure 5.6. This figure breaks things down into all cancers excluding leukemia and leukemia excluding Chronic Lymphocytic Leukemia (CLL). The data shown has all the biases mentioned above. The key feature of Figure 5.6 is that the confidence limits dwarf the data.

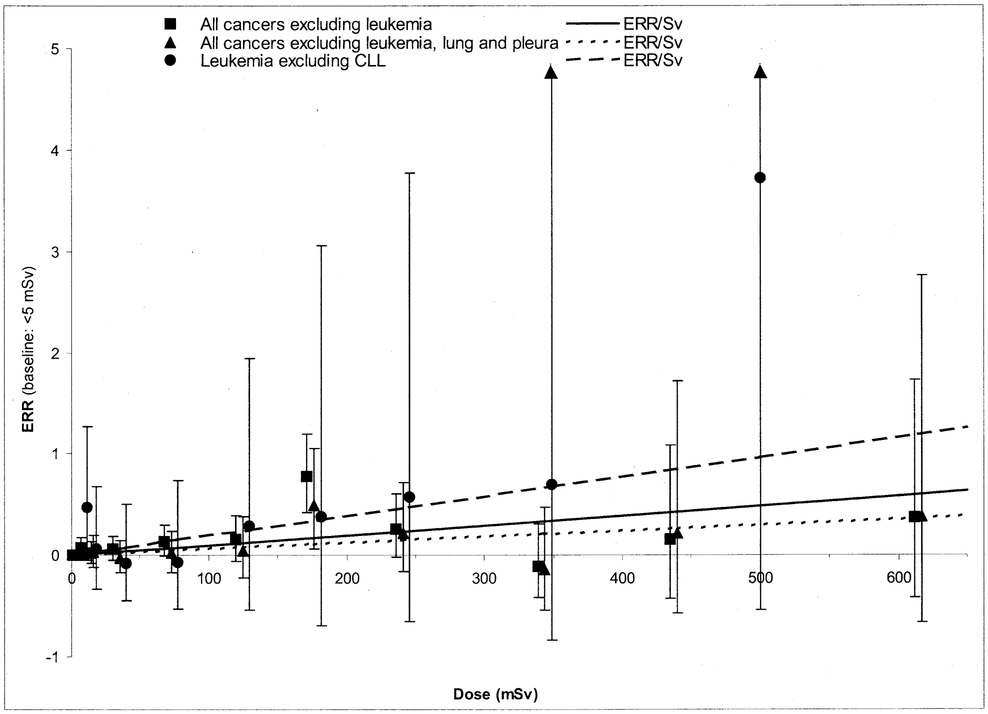


Figure 5.6: Cardis et al, Figure 1

And these are 90% confidence limits. The attempt at statistical precision failed, presumably due to the additional scatter associated with combining the disparate cohorts, despite the authors' best efforts to correct for the country-wide differences and biases. The various squares and triangles do exhibit a weak positive correlation at least above 100 mSv, but there is little evidence of linearity. And the leukemia numbers show a strongly non-linear pattern with a drop between 0 and 30 mSv to negative levels, and then climbing back above zero at about 100 mSv, and rising faster than linearly above 300 mSv.

The authors conclude with a oft-quoted line from BEIR VII saying current evidence is "consistent with the hypothesis that there is a linear no threshold relationship between exposure to ionizing radiation and the development of cancer in humans".[26] They continue

> Results presented here are consistent with the BEIR VII conclusions. The study, however, cannot address effects at very low dose rates of the order of tens of mSv [sic]. Further the power of the study is inadequate to investigate the shape of the dose response, even in the dose range under study.

The second and third sentences contradict the first. The second sentence is describing a 407,391 person study in which 90% of the subjects received less than 50 mSv over multi-year periods. The third sentence contradicts their earlier statement that not-reported-here analyses "did not reveal significant departures from linearity for any of these causes of death". What do the authors really believe?

At the end of the day, the 15 Country Study was able to come up with a weak and statistically insignificant correlation between cumulative dose and cancer incidence. Even that nearly meaningless result disappeared when Canada withdrew a 3088 worker Canadian cohort which Cardis et al had used, citing problems with the recorded doses.[46] This should have come as no surprise. This cohort of people had an excess relative risk six times that of the 15 Country average. Something had to be fishy. When the Canadian cohort was removed, the excess relative risk for the entire group was not significantly different from zero, even if you circularly assume LNT.

In a later paper by the Cardis team, we find

> INWORKS did not include data from Canada, a cohort for which the excess dose rate per Gy estimate was considerably [sic] larger than observed in most countries, ...[213][page 5]

But the Cardis paper was never withdrawn.

---

[26] Periodically, the National Academy of Science issues a report on the Biologic Effects of Ionizing Radiation (BEIR). BEIR VII published in 2006 is the most recent[251]. In the guts of the report, written by scientists, the support for LNT is often quite qualified. In the Executive Summary and press releases written by communications specialists, the support for LNT is far stronger.

With respect to nuclear workers, here is what BEIR VII actually said:

> In most of the nuclear industry workers studies, death rates among worker populations were compared with national or regional rates. In most cases, rates for all causes and all cancer mortality were substantially lower than in the reference populations.[251][p 194]

BEIR VII then decreed that "occupational studies are not currently suitable for the projection of population based risks."[251][p 206]

5.6.4 The INWORKS Study

Despite all the manipulation, the 15 Country Study had crashed and burned; but Cardis et al were not ready to give up. They continued their study of nuclear workers under the moniker INWORKS.[144, 213] By this time, they knew their data base pretty well. In particular, they knew that workers in weapons and mixed facilities were showing more harm than workers at power only nuclear plants. They made some adjustments:

1. They excluded the data they had already collected from 12 of the 15 countries because "of the limited resources and consequent need for efficiency in project coordination." The three countries that survived this project coordination process were France, UK, and the USA. The three countries selected just happened to be the only three countries in the 15 that had nuclear weapons programs. In the authors' words

   > INWORKS was not intended to assemble the largest number of nuclear workers possible, but rather to assemble those cohorts that were most informative with regard to quality and completeness of exposure and follow up data.[213][p 5]

   Once again the American shipyard workers did not qualify.
2. Unlike their earlier work, there is no breakdown between nuclear weapons workers and power plant workers.

After this pruning process, they were left with 308,297 people over the period 1943 to 2005. Table 5.10 shows the results for leukemia mortality.

Table 5.10: INWORKS leukemia (no CLL) by dose category.
This table is extracted from Table A.2 in the appendix to reference [144]

		0 - 5	5 -50	50 - 100	100 - 200	200 - 300	300 +
	Mean dose	1.0	17.2	70.0	137.9	241.2	407.5
Leukemia excluding CLL	Deaths	281	174	37	22	14	6
	RR	1.00	1.01	1.30	1.19	2.30	1.70
	90% CI		0.86-1.19	0.97-1.73	0.82-1.73	1.46-3.62	0.85-3.36

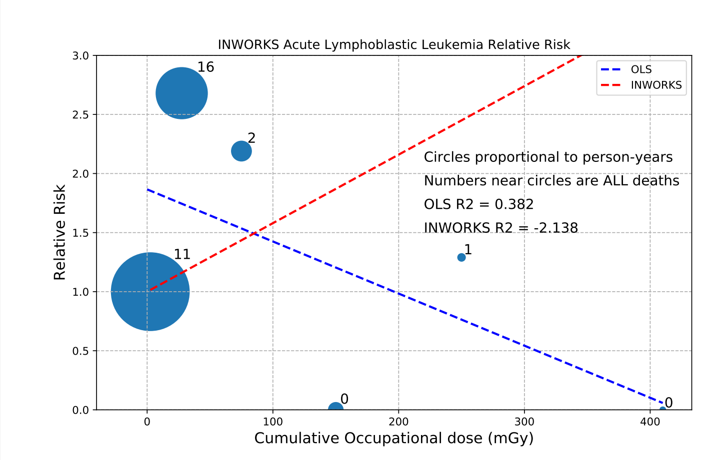
1. Only the 200-300 mSv category Relative Risk is significant. But this "significance" is based on a ***one-sided, 90% confidence interval***. If the authors had used a conventional, two sided 95% confidence interval, none of the results would have been significant.[27]
2. The number of leukemia deaths is quite small. In a group of 300,000 people, we are talking about 669 (531 after tossing out CLL) deaths. It is not surprising that the confidence intervals would be quite wide.

---

[27] Another trick was to exclude chronic lymphocytic leukemia (CLL) from the collection of disease they decided to focus on. By excluding CLL, they threw out 20% of the leukemia deaths. They admit that the "association between CLL and dose was negative".

3. The results are strongly non-linear. In the 0 to 50 mSv range, there is no evidence of an increase in leukemia. The authors admit that a pure quadratic model fitted the data better. But decided to go linear anyway with no justification.[28]

To see how easy it is to manipulate the data, consider Acute Lymphoblastic Leukemia (ALL). INWORKS claims the risk of ALL from radiation is linear in cumulative dose. The Relative Risk increases at a rate of 5.8/gray. This figure plots their ALL data.



The red dashed line is the INWORKS result. Normally, if someone postulates a linear relationship between two variables, he will use Ordinary Least Squares (OLS) regression to test that hypothesis. According to OLS, the blue dashed line, ALL incidence is a decreasing function of cumulative dose. So how did INWORKS turn that around and come up with the opposite result? First they forced the y-intercept to 1.0. Second, they “combined" the two zero death bins with the 1 death 250 mSv bin. This “combining" effectively expunged these two bins, which together had four times as many person-years as the unerased bin.

Of course, the data is not linear. The OLS R2 is a lousy 0.38. The INWORKS R2 is an off-the-charts -2.1. Totally meaningless.

Thanks to Ken Chaplin for pointing this out.

---

[28] Their Table A2 from which Table 5.10 was extracted was not even in the paper. You had to dig it out of a separate, unpublished appendix. In their summary, all they talk about is risk per gray.

> Doses were accrued at very low rates (mean 1.1 mGy per year). The excess relative risk of leukemia was 2.96 per Gy.

In other words, the summary claims with no support all the doses were chronic, and assumes LNT even though their leukemia data is clearly non-linear.

Figure 5.7 shows the most recent update of solid cancer.[214] INWORKS only shows one-sided 90% confidence intervals. I've added the more conventional, one-sided 95% CI's. Based on a 95% Confidence Interval, none of the bins are significant. In most journals this would have disqualified them from publication, unless it was called a Null result.

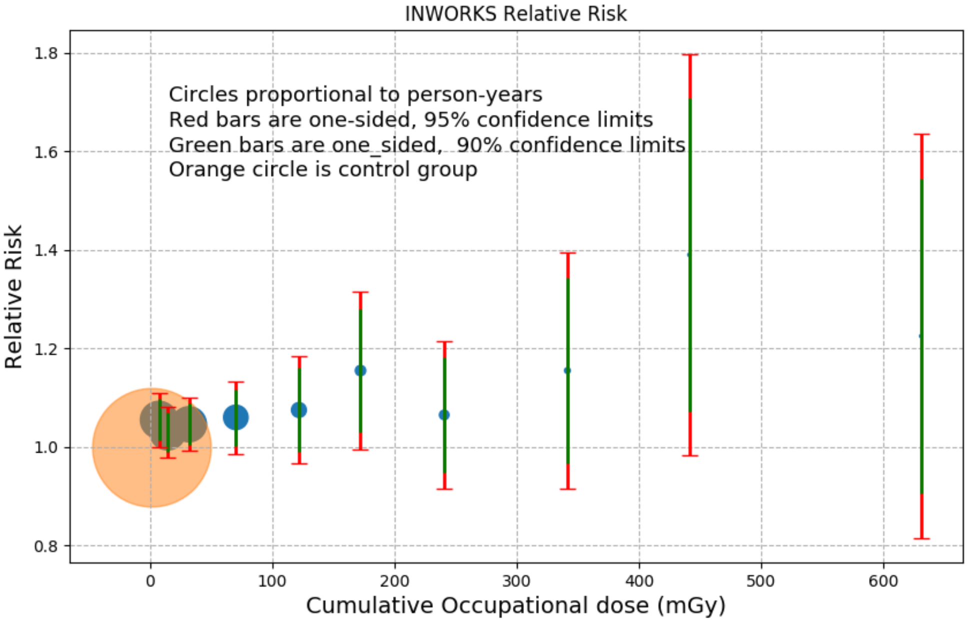


Figure 5.7: INWORKS 2023 solid cancer. Reference [214] Based on Supplementary Figure B. The origin is meaningless. The “zero" dose could easily be 100 mGy for a Rocky Flats worker, and 20 mGy for a Hanford worker.

INWORKS subtracts the local background radiation from the dosimeter readings.[29] Almost all the workers were at the very low dose end. The median total occupational dose was 2.1 mGy over decades; but a few people had doses as high as 1217 mGy. This means for almost all their sample, the background dose was far larger than the occupational dose that INWORKS shows us. A median occupational dose, 20 year worker at Rocky Flats, where the background dose is at least 5 mGy/y, would end up in the same bin as a median dose Hanford worker (background about 1 mGy/y) who received 20 mGy over 20 years. ***INWORKS is not measuring total cumulative dose, which they claim is the all important explanatory variable.***

---

[29] Passive dosimeters do not turn off when their owners leave the plant. They are measuring the background rate all the time.

To avoid the Healthy Worker Effect, INWORKS used the 0-5 mGy cohort as their control group. The 5-10 mGy group (less than 0.2 mGy/y occupational), — a tiny fraction of background — saw a 6% jump in solid cancer, relative to the control group. That's a slope of 850% per gray. At this harm rate, the species went extinct a very long time ago. Something else is clearly happening here. People with near zero occupational dose in nuclear plants have desk jobs. They tend to be higher educated, higher income with different smoking, drinking, and eating habits than the blue collar people. INWORKS ignores these differences.

From 5 to 300 mGy, there is essentially no further increase in solid cancer. So 0.6 mGy to 7.2 mGy over 20+ years causes an impossible jump in cancer; but an additional 250 mGy has nil effect? If this section is linear, it is linear with near-zero slope.

Above 300 mGy, there is a weak but statistically insignificant increase in cancer. But a straight line is only one of the many curves you could put through this data, and one that does not fit it well at all.

But the key question here is: how did these high end people get their dose? Was the dose spread more or less evenly over 20+ years? Or was most of the dose incurred in a handful of sharp spikes? INWORKS refuses to tell us; and they refuse to allow us access to the data. The actual INWORKS dose data is not available "for reasons of ethics and permissions from different agencies". Another basic principle of science unapologetically violated. This too should have prevented publication.

But we can be confident that the high end doses were not received evenly. That's not how it works. In a properly functioning nuclear power plant, more than 80% of the plant dose is associated with refueling, a two or three week period every two or so years, and even then the doses do not add up to anything like the INWORKS high end. An individual rarely receives more than 5 mGy during a refueling outage. Something very unusual happened to the 0.3% of the people at the high end.

Mixing nuclear weapons workers going back to the war years with nuclear power plant workers is problematic. The weapons programs ran under the threat of annihilation. Corners were cut; mistakes were made. See UPPU Club, Section 2.1. The dose profiles for the high dose weapons people were likely very spiky. But the authors simply assume with no support that all the doses were in their word "protracted".

If INWORKS wants to make the case for LNT, they must rule out dose rate dependence. You cannot rule out dose rate dependence, if you make no attempt to ascertain the dose rates. This is consistent with their circular reasoning. To make the case for LNT, they show us only cumulative doses, which makes sense only if LNT is valid.

The INWORKS study only raises questions.

1. Why did they reject 12 of the 15 countries' data?
2. Why did they reject the American shipyard study?
3. Why did they not show us power plant workers and weapons workers separately as the 15 Country Study did?
4. Why do they show us only occupational doses when they claim the only thing that counts

is total cumulative dose?

5. Did they pick an appropriate control group?
6. Why don't they use conventional statistics?
7. Why don't they make their data available?
8. How can they argue that dose rate is irrelevant if they don't show us the dose rates?

The failure to adjust for non-occupational doses which for almost everybody was much larger than the occupational dose, the strange rejection of 12 of the 15 countries' data, the failure to look at the dose profiles, the very weak statistical significance, even when using an unconventionally weak test produce an uncompelling story.

I apologize for all the time I have spent on the 15 Country Study and the subsequent INWORKS efforts. The reason is that these papers have played and are playing a prominent role in the defense of LNT. The NRC and the EPA invariably cite these studies whenever LNT is questioned. They are the best that the defenders of LNT have to offer.

5.6.5 The Radon Saga

Introduction

Radon, a heavy inert gas, is a daughter product of the the spontaneous decay of ^{238}U. ^{238}U decays very slowly, and Radon-222, the isotope of interest, has a half life of 3.8 days. Radon is not a nuclear reactor safety concern. Radon is not a fission product. And even if a major casualty spread some ^{238}U around the release rate of radon would be very low. Outdoors any radon concentrations would be extremely dilute. Radon was a non-factor at both Fukushima and Chernobyl.

But radon is germane to the validity of LNT. Radon is an unusual form of background radiation in that it can be trapped in buildings and other confined spaces and build up, creating hot spots in which the radiation levels are orders of magnitude higher than the surrounding background. Thus, radon offers a wide range of exposure over large populations. Radon has become the chosen battlefield of the pro-LNT forces.

Radon and its daughters are primarily alpha emitters. Radon has to be inhaled to be dangerous; but once inhaled it can be taken into the lungs, and result in lung cancer. The impact of radon on miners was first documented in Germany in the 16th century, although the cause was unknown. It resurfaced among American uranium miners after World War II. Miners in poorly ventilated mines were exhibiting clearly elevated lung cancer rates. Radon exposure is usually measured in decays per second per cubic meter of air, Bq/m3, known as the radon activity. In poorly ventilated uranium mines, the radon activity can be 10,000 to 50,000 Bq/m3.[35] 10,000 Bq/m3 is roughly 600 mSv/y.[30] About the same time, people became aware that radon could build up in houses, especially basements. Radon became front page news.

By the late 1950's, LNT was the established religion. In order to evaluate the residential risk of radon, the miner mortality rates were linearly extrapolated down to zero. This was done with almost no discussion.

Bernie Cohen's Radon Studies

The first (and at the time just about the only) person to challenge this extrapolation was Bernie Cohen. Dr. Cohen was a well-established radiation researcher at the University of Pittsburgh. In the late 1980's through the 1990's, under his direction, the University of Pittsburgh undertook a massive study of USA radon exposure. They collected county by county data on radon exposure and lung cancer mortality.[52] They eventually ended up with data for 1600 counties. Most of Cohen's homes had a radon activity of 25 to 150 Bq/m3, very roughly 100 times less than the bad mines. The biggest problem facing Cohen was smoking. Smoking is a far stronger cause of lung cancer than radiation. So he collected county by county data on cigarette sales and stratified his sample accordingly.

---

[30] The studies were poorly controlled for smoking and not controlled at all for diesel exhaust in a confined space. Diesel exhaust contains a bunch of carcinogens.

To Cohen's surprise, the results were unambiguous. Not only was there no evidence for LNT, but there was strong evidence that low levels of radon exposure decreased lung cancer, Figure 5.8. He tried to disprove the result by stratifying the data by every possible confounding factor he could think of. He ground through some 54 factors, but the general result stood. Unlike INWORKS, Cohen made his raw data available to everyone.

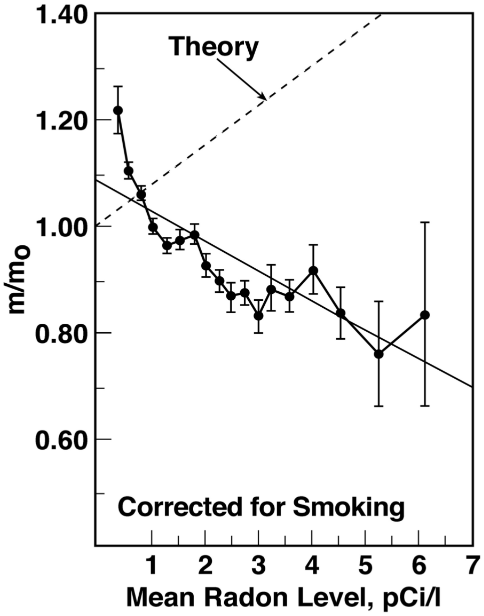


Figure 5.8: Mortality rate versus radon exposure, reference [52]. 1 pCi/L is 37 Bq/m3.

Cohen's results have been challenged most vigorously. He was attacked for grouping individuals by county, a procedure that strictly speaking is only valid if the response is linear. But this is precisely what LNT assumes. A non-LNTer can attack Cohen on these grounds but an LNTer cannot.

Van Pelt attacked on the grounds that Cohen had not stratified by altitude.[263] Van Pelt suggested that increasing altitude might decrease lung cancer by reducing free oxygen radicals in the cells. Van Pelt redid Cohen's results stratifying by altitude. This removed some of the “negative bias" but not all. Van Pelt became a supporter of Cohen's results.

In 2004, NCRP Scientific Committee 1-10 came up with its definitive response.[104] Their basic argument is that there are high levels of uncertainty about county by county smoking incidence. Therefore, there could be an undetected confounding smoking factor that invalidates Cohen numbers. They did their own adjustment for smoking and redid Cohen numbers. Heath et al summarize their results:

> Both Cohen's analysis and ours show an overall pattern of decreasing mortality with rising radon levels. In both sets of data, however, that decrease is largely confined to radon levels below about 100 Bq/m3, rates above about 175 Bq/m3 being too uncertain to permit interpretation due to the limited number of counties with such dose rates.[31]

In other words, after their correction for smoking, they still found a negative correlation. In the authors' view, we are left with two choices: either

1. "a negative confounding relationship between smoking prevalence and radon levels across counties",
2. "a protective effect of radon exposure against lung cancer".

Heath et al opt for (1) without even speculating on what this undetected factor is that secretly and systematically depresses smoking below the sales statistics more in high radon counties than low. They are OK with this because (2) simply can't be true. The Heath paper has been widely heralded as "the respectable end to Cohen's radon debate."

In fact, Heath's re-analysis of Cohen's results, a self-professed attempt to shoot down Cohen, strengthens Cohen's case. Both Cohen's and Heath's results contradict LNT.

European Case Control Studies

A much stronger challenge to Cohen's results came from a series of *case control* studies, that is, studies that tracked individual people. On the European side, these studies were collected together by Darby et al.[61]. Darby examined 7148 cases of lung cancer and 14,208 controls. Her results are summarized in Table 5.11. Radon exposure is almost always measured in Bq/m3. One issue is how to convert this to dose in mSv. ICRP uses a method that has nothing to do with absorbed dose but is based on equating risks using ICRP LNT factors. This method assumes LNT twice, so it is completely circular for our purposes. There have been some dosimetric measurements of absorbed dose as a function of Bq-h/m3. There is a wide spread but, based on these measurements, Chen argues for an annual dose to the lung of 50 mSv for 100 Bq/m3.[40] I've use this factor in the last column of Table 5.11. Darby et al are examining pretty high lung doses.

Table 5.11 does not look particularly linear to me. But Darby et al make a series of carefully parsed statements: "the results are consistent with a linear dose-response relationship", adding "Models with no effect up to a threshold dose and then a linear effect did not fit significantly better than a linear effect with no threshold; in such models the upper 95% confidence limit for a possible threshold was 150 Bq/m3 measured radon". (Does this mean the non-linear fit was

---

[31] Cohen agreed with this. His view was that mortality bottomed out at about 150 Bq/m3 and then started rising, based on fitting a non-linear curve to his data.[52]

Bq/m3	Relative Risk	Lung dose mSv/y
less than 25	1.00	9
25 to 49	1.06	20
50 to 99	1.03	36
100 to 199	1.20	68
200 to 399	1.18	136
400 to 799	1.43	271
more than 800	2.02	600

Table 5.11: Relative Risk of Lung Cancer from Darby Table 2

Bq/m3	Relative Risk	Lung dose mSv/y
less than 25	1.00	6
25 to 49	1.13	19
50 to 74	1.09	36
75 to 99	1.16	44
100 to 149	1.24	68
150 to 199	1.22	136
more than 200	1.37	340

Table 5.12: Relative Risk of Lung cancer from Krewski, all subjects, Table 2

better?) Finally, “The linear relationship remained significant even when we limited analysis to measured concentrations of less than 200 Bq/m3 ($P=0.04$)". Meaning, I think, that, if they went any lower, P would be greater than 0.05, and that statement would no longer be true. You can be sure that, if they could have made the same statement about 100 Bq/m3, they would have. 200 Bq/m3 is roughly 100 mSv/y to the lung.

So what we have here is at best weak support for LNT, but only above about 40 mSv/y to the lung.

American Case Control Studies

At about the same time Krewski et al were collecting American case control data.[136] They ended up with a total of 3662 cases and 4966 controls from a rather diverse group of seven studies. Some of these studies were in high radon areas (Winnipeg, mean 131 Bq/m3; Iowa, mean 125 Bq/m3), and some in low (New Jersey, mean 25 Bq/m3). In about half the cases, the radon concentrations were “imputed" that is, the radon concentrations were measured for 12 months in the subject’s current home, and those concentrations assumed to be representative of 20 plus years of exposure, ***even if the subject had changed residences***. If the data is limited to those subjects who occupied only one or two houses and for which 20 years of actual radon concentration measurements were available, they ended up with 1910 cases and 2651 controls. Table 5.12 summarizes the Krewski results.

Bq/m3	Relative Risk	Lung dose mSv/y
less than 25	1.00	6
25 to 49	1.00	19
50 to 74	1.31	36
75 to 99	1.22	44
100 to 149	1.27	68
150 to 199	1.40	136
more than 200	1.32	340

Table 5.13: Krewski Lung cancer Risk, no imputed subjects, Figure 1.B (Jack dose)

The data is roughly linear and the regression slope is 0.11 per 100 Bq/m3, almost exactly the same as the 0.12 obtained by extrapolating the miner lung cancer data downward. The match is near perfect. Of course, there is tremendous spread in the data, so the confidence intervals are very wide. Krewski et al are surprisingly cautious in their overall statements. They never explicitly claim linearity: “These results provide direct evidence of an association between residential radon and lung cancer risk, a finding predicted using miner data and consistent with results from animal and in vitro studies." But they used a linear model and it worked. The community was in no doubt. Krewski et al had confirmed LNT. Papers with catchy names like “Residential radon and lung cancer: end of the story?" appeared in peer reviewed journals.

But if we limit Krewski’s sample to those subjects for which we actually have 20 years of radon measurements and who have not moved residences more than once, a rather different picture, Table 5.13 emerges.

The Table 5.13 data is strongly non-linear. But, if you do try to fit a straight line to it, you get a slope of 0.18 per 100 Bq/m3, well above that for the combined sample. Krewski et al mention the higher slope, but do not discuss the apparent non-linearity. So which is better; the sample for which we have actual radon measurements, or the combined sample including the cases for which we don’t?

The Worcester Study

Just when Darby and Krewski — properly interpreted — had confirmed LNT for radon, along comes the 2008 Worcester Study.[249] This study involved 200 lung cancer cases and 397 matched controls all participants in the same health maintenance organization in the Worcester, Mass area. Smoking was stratified into 9 categories. The sample size is much smaller than the other studies but the sample was much more carefully controlled. They included adjusting for how much time was spent in different parts of the residence. The calibration process for the detectors was standardized and strict. It ended up revealing a bias in the detectors as they aged. Overall the sample is much more homogeneous than the wider studies. Table 5.14 summarizes the results.

It is hard to imagine a more non-linear result. The authors claim this “came as a complete

Bq/m3	Relative Risk	Lung dose mSv/y
less than 25	1.00	6
25 to 50	0.53	19
50 to 75	0.31	36
75 to 150	0.47	62
150 to 250	0.22	100
more than 250	2.50	

Table 5.14: Thompson Lung Cancer Risk from Table 3

surprise". And they go to great lengths to try to reconcile their results with Krewski et al.

1. They point out that their sample is almost all at the low dose end of the Krewski sample. Worcester is a low radon area.
2. They point out their results are much closer to a sub-sample of Krewski from the two low radon area (New Jersey and Connecticut) sub-studies included in the pooled study.
3. They point out that even in the pooled data, Krewski et al *unadjusted* risks were less than 1.00. They suspect there is something basically different in the process of adjusting for confounding factors that resulted in the very different results.

But for our purposes, what's important is that there is no evidence for LNT in either the Worcester data nor the non-imputed Krewski data.

Laboratory results: the Columbia University Alpha Hit Experiment

In 1999, researchers at Columbia University decided to try to get to the bottom of the radon controversy in the lab. Radon is an alpha emitter which can get lodged in the lung if it is inhaled. By an exceedingly clever experiment, they were able to irradiate the nuclei of tens of thousands of mouse cells with exactly 0, 1, 2, 4, or 8 alphas, alphas which had the same energy as radon decay.[168] They then counted the number of oncogenic transformations, mutations which could lead to cancer, which occurred. Figure 5.9 summarizes their results.

The number of mutations for a single hit are not statistically different from the sham control (zero hit) results. But if a cell was hit twice, the number of mutations jumped to 6 times the control results. ***What we have here is a black and white contradiction of Muller's single hit theory.***[32]

The authors comment

> The BEIR VI estimates (and others) of the risks of domestic radon exposure were made by extrapolating risks from underground miners who received radon doses that

---

[32] If the probability of a single hit is linear in the dose and it takes n hits to cause cancer, then the probability of cancer, P is given by $P = (a \cdot d)^n$ where $a \cdot d$ is the probability of a hit for dose d. For any n other than 1, the slope of this dose response curve is zero at zero dose. For example, if it takes two hits to get the process started, as the Columbia results suggest, the dose response curve at the low end is quadratic.

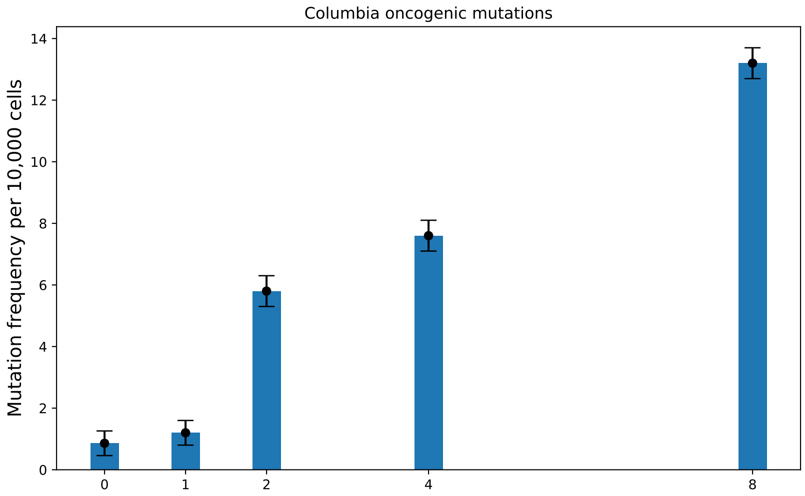


Figure 5.9: Columbia University alpha particle mutations

> were on average many times larger than those of people in most homes. The problem inherent in this extrapolation is that, at these high exposures, the cells at risk in the bronchial epithelium of miners may be traversed by several α particles during a short period, whereas for individuals exposed in homes at normal domestic radon levels, it is unlikely that any cell at risk will be traversed by more than one α particle in a lifetime.[168][page 19]

Columbia is not exactly a hot bed of anti-LNT sentiment. At least one of the authors, David Brenner, is a strong supporter of LNT. These remarkable results have been pretty much ignored.

The WHO 2009 Radon Handbook

None of this deterred a WHO group including Darby and Krewski from putting out a “handbook" which makes unqualified assertion after assertion as if LNT were an established fact for radon.[201] The carefully parsed statements are gone. The handbook never mentions the Cohen or Worcester or Columbia studies. Ignoring Cohen, Worcester, and the non-imputed Krewski data, we make the usual jump from the double negative “There is no known threshold concentration below which radon exposure represents no risk." to LNT: “The proportion of all lung cancers linked to radon is estimated to be between 3 and 4%.".

There is even a chapter on messaging with helpful spinmeister advice on how to keep the message simple enough so that even the dullest will be appropriately terrified. The communicator is told that “non-verbal communication is just as important as verbal communication when trying to establish credibility". Numbers are to be avoided in favor of “comparative" statements such as “In Europe, many more people die from radon-related lung cancer than from melanoma."

The WHO Handbook on Indoor Radiation is a political document, not a serious scientific survey.

5.6.6 Taipei Cobalt-60 Exposure

Recycled rebar, containing Cobalt-60, was accidentally used in the construction of 180 apartment buildings in Taiwan. Over 20 years, 8000 people received an average of 400 mSv each.[41] ^{60}Co emits two high energy photons and has a half life of 5.3 years. So most of this dose was received in the first ten years. According to Chen et al, the high cohort (about 11%) of the population received a mean cumulative dose of 4000 mSv with a max of 6000. The highest annual dose rate is estimated at 910 mSv.[41]. Hwang et al put the excess dose lower, claiming a mean of 47.8 mSv with a range of 1 to 2,363 mSv.[111] According to Hwang, the cancers expected normally for this population is 115, the cancers actually observed was 95.[111][Table III] ***According to LNT, we should have seen 153 cancers.***

The Hwang paper is interesting because it was designed to shoot down the earlier Chen paper, and re-establish LNT. In their abstract, Hwang et al don't even mention the reduction in all cancers, nor the failure of LNT to predict the results. Instead they say

> The SIR [Standardized Incidence Rate] were significantly higher for all leukemia except chronic lymphatic leukemia in men, and marginally significant for thyroid cancers in women.
>
> Conclusion: The results suggest that prolonged low dose-rate radiation exposure appears to increase risks of developing certain cancers in specific subgroups of this population in Taiwan.

Hwang broke their results down into 24 different cancers and men and women. The male leukemia statement is based on 6 observed cases when the expected was 2; the female thyroid also on 6 observed cases with 2 expected. In other words, we ignore the overall results and pick through a list of 48 sub-samples until we find two that we decide to call attention to. A 95% confidence interval means if you have 48 samples, the probability that at least one of those sample will show a 95% Confidence Interval is 0.92, even if there is no causal relationship at all.

Hwang et al later published a "follow up" paper which found 34% more cancers had been diagnosed in the population.[112] But Doss went to the Taiwan Cancer Registry and did the SIR's (which Hwang did not) and found that the expected increase in cancer for this population over this time period was 36%.[74] Rather than use SIR's in the 2008 paper, Hwang et al assumed LNT to predict the cancer incidence, even though their data shows no increase.

Bottom line: the Taipei apartment data is inconsistent with LNT. Hwang's methodology in attempting to refute this conclusion suggests that we are dealing with defense lawyers, not scientists. On the other hand, I don't think we can make much of the decrease in cancer. This was an upwardly mobile, relatively affluent cohort. Social status likely played a role here.

5.6.7 The radium watch painters

Between 1915 and 1950, numerals on luminous watch dials were hand painted using radium paint for the most part by young women. Prior to 1928, the ladies used their tongues to form the tip of the brush into a point, sipping radium into their bodies. Chemically radium is similar to calcium and accumulates in the bones, where it has a 40 year biological half-life. The total skeletal doses varied by over a factor of 1000. But the maximum cumulative dose was an incredible 444,000 mSv.

Argonne did an extensive study of the results.[223] In spite of the large cumulative doses to all parts of the body only two types of cancers were diagnosed: 64 bone cancers and 32 head carcinomas. Strangely no excess leukemias, breast cancers nor lung cancers. Reliable dose measurements were available for 2,383 women. All the 64 bone cancers occurred in the 264 women with a bone dose of more than 190,000 mSv.[223][page 107] ***No bone cancers were found in the 2,110 women with less than 190,000 mSv dose.***[33] See Figures 5.10 and 5.11

Despite the obvious non-linearity with a jump from flat zero at less than 160,000 mSv to around 25% cancers at 190,000 mSv or more, several experts tried to fit a straight line to the data, claiming with a straight face in peer reviewed journals that LNT could not be rejected. Evans applied a chi-squared test for goodness of fit and found that the probability that a linear process would come up with this data was less than 1 in 200,000,000.[223][page 108]

---

[33] Radium and its daughters are principally (81%) alpha emitters. Argonne reports dose in energy per kg tissue (12,000 mGy). The approximate conversion factor is 16 mSv/mGy.

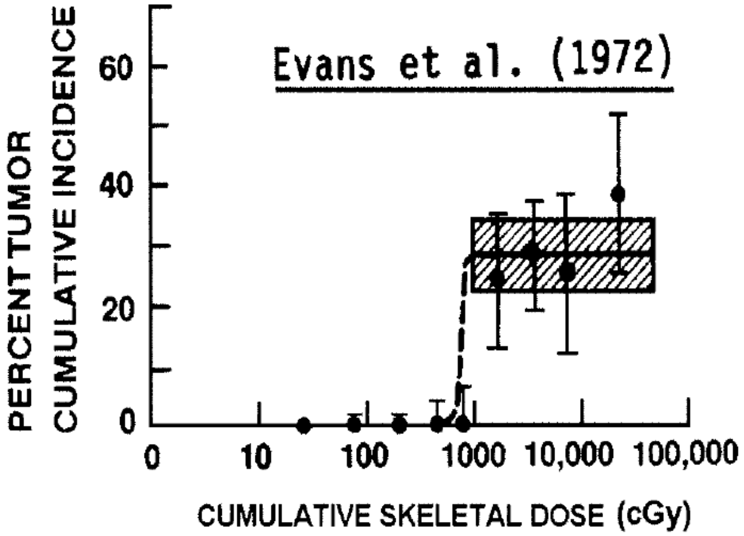


Fig. 11. Cumulative bone sarcoma incidence in people exposed to ^{226}Ra as a function of cumulative dose to the skeleton as reported by Evans et al. (1972).

Figure 5.10: Dial Painters: Frequency versus dose

64 unnecessary cancers is a tragic number. ***But the radium watch painter tragedy not only does not support LNT, it is strong proof that LNT is false.***

How did the EPA react to this is in setting radium protection standards?

> EPA policy is to assess cancer risks from ionizing radiation as a linear response. Therefore, use of the dial-painter data requires deriving a linear risk coefficient from significantly non-linear exposure data or abandoning EPA policy. [3]

Abandoning EPA policy was not an option. The dial painter data was dismissed.

In 1928, the longest the ladies could have been sipping radium is about 15 years. The minimum dose that resulted in cancer is 190,000 mSv. So the dose rate for the cancer victims was at least 35 mSv/day, and that assumes they painted watches every day of the year. The maximum dose that resulted in no cancer is 160,000 mSv. The corresponding lowest possible dose rate is 29 mSv/day. It appears that the dial painters' repair systems could cope with up to 30 mSv/day, but not much more.

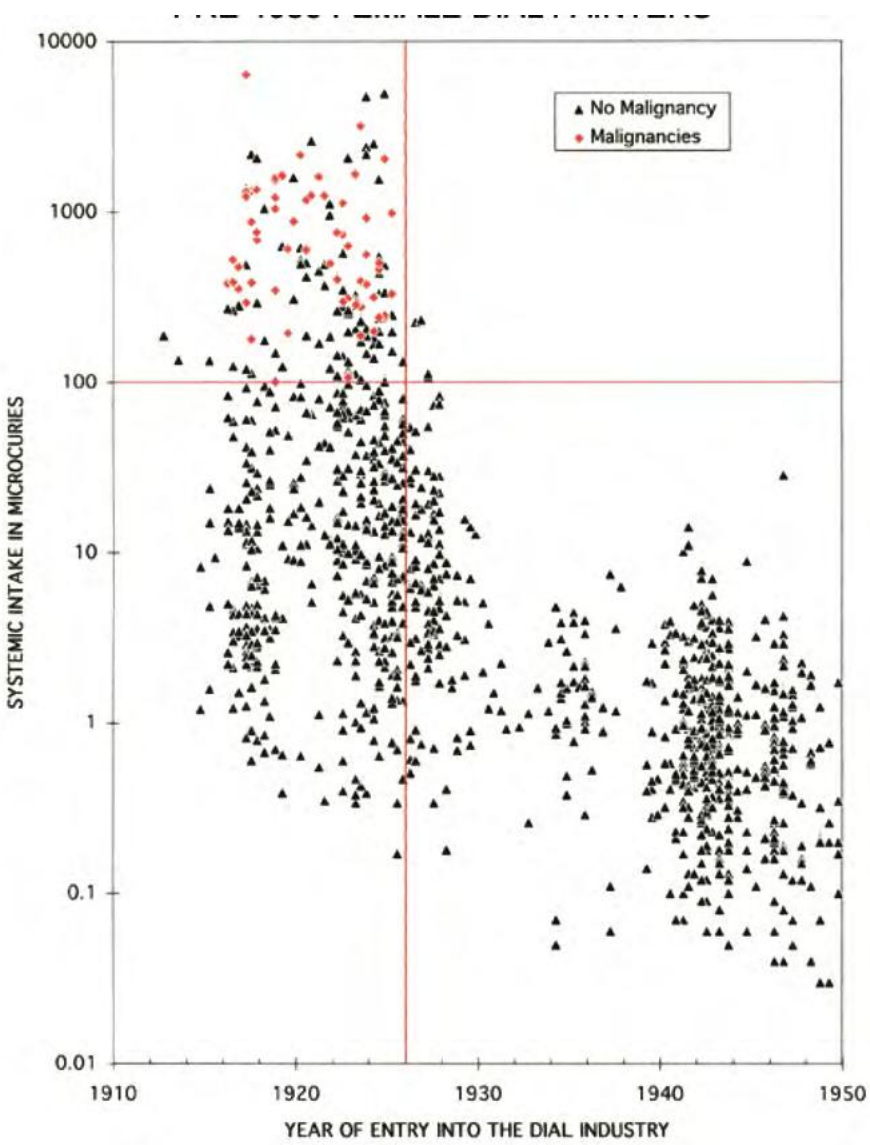


Figure 5.11: Scatter diagram of dial painter malignancies. 100 microCuries is about 12,000 mGy

5.6.8 Eben Byers and Radithor

The strange case of Eben Byers gives us an upper bound on the dose rates our bodies can handle. In the early 20th century, Byers was a wealthy socialite, ladies man, and excellent athlete. He was the 1906 USA Amateur golf champion. Returning from the Yale-Harvard game in 1927, he fell from his Pullman berth, and injured his arm. The arm failed to heal properly. So in January, 1928, his doctor proscribed Radithor, a nostrum containing radium, whose "inventor", William Bailey, claimed would cure just about any medical problem. Byers immediately started feeling better and quickly increased his uptake to more than three bottles per day.

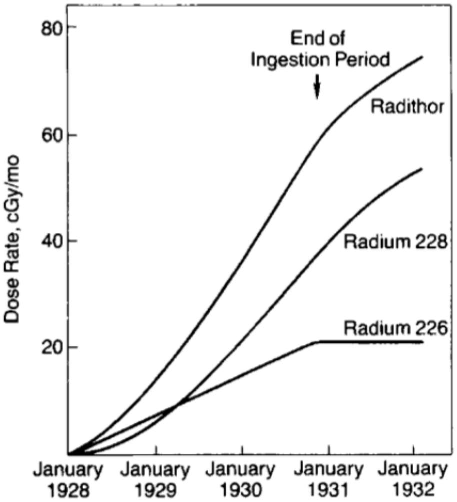


Figure 5.12: Byers' Dose Rate Profile

But in 1930, he started experiencing blinding headaches and terrible toothaches. In December, 1930, he stopped taking Radithor; but by that time he was deteriorating rapidly. His teeth fell out. His jaw just crumbled away. He died a miserable death in 1932.

In 1965, Byers' body was temporarily exhumed and studied. Macklis et al used the results to estimate his dose rate profile, Figure 5.12.[154][p 621] Byer's dose rate quickly built up to 15 mGy per day. Since the dose was almost all alpha, this is close to 300 mSv/day. This dose rate overwhelmed Byers' repair systems.

Macklis et al reckon that, by the time Byers died, he had received a total absorbed skeletal dose of 366,000 mSv. 360 sieverts is 50 times the lethal acute dose. The authors take this in stride, commenting "It is surprising that the patient remained asymptomatic until late in 1930."[34] Actually, if LNT is valid, it is impossible.

Eben Byers was not the only person who took Radithor. Robley Evans estimates that Bailey had more than a 1000 customers for his concoction. Evans was able to track down about 200 cases of very high radium doses and study them intensely, including xraying their bodies.

When he plotted the results against the maximum dose rate they had received, he found no clinical symptoms in the subjects whose energy dose rate had peaked at about 4 mGy/d or below.[80][Fig 14]. However, a few of the less than 4 Gy/d xrays showed abnormalities down to about 1 mGy/d. Since almost all the dose was alphas, these Gy numbers correspond to close to 80 and 20 mSv/d respectively. More evidence that our bodies can handle dose rates up to at least 20 mSv/d.

---

[34] The fraudster Bailey partook of his own product. When his body was exhumed, Rowland found he had consumed roughly one-third as much Radithor as Byers.[223] William Bailey died at 64 of bladder cancer, probably unrelated to the Radithor.

5.6.9 The Nuclear Shipyard Workers Study

In the late 1970's, the Department of Energy became concerned about the effects of low level radiation, especially among workers involved in the overhaul of nuclear submarines. The shipyards presented a nearly ideal population to study. Not only were the doses of the workers qualified for radiation work measured by standardized procedures imposed by the Navy, but a control group of workers in the same yards not so qualified was available. From a database of almost 700,000 shipyard workers including about 107,000 nuclear workers two closely matched groups consisting of 28,000 nuclear workers and 33,500 non-nuclear workers holding the same kind of jobs was selected.[160] The study operated over a 13 year period until 1991. Table 5.15 summarizes the results.[160][page 303] Almost all the dose was Cobalt-60, a strong photon emitter. SMR is short for Standardized Mortality Rate: the age and sex adjusted ratio of deaths observed to that of the general population.

	Sample size	SMR
Non-nuclear workers	32,510	1.00
Less than 5 mSv	10,348	0.81
5 mSv to 10 mSv	5,431	0.72
10 mSv to 50 mSv	13,353	0.79
50 mSv to 100 mSv	4,846	0.76
More than 100 mSv	4,238	0.72

Table 5.15: Shipyard Study Mortality rates from Table 3.1.C, page 303

The mortality rate of the nuclear workers was 16 standard deviations below that of the non-nuclear workers. In this case, the Healthy Worker Effect cannot be invoked since both groups had basically the same jobs. The study was carefully designed to eliminate the Healthy Worker Effect. Of course, any one who has actually been in a shipyard would not be talking about the healthy worker effect. A shipyard is a dirty, dusty, dangerous place. In fact the nuclear workers had a significantly higher incidence of mesothelioma, presumably because they had more exposure to asbestos. In general, the mortality rates for particular diseases was both up and down between the two groups; but the over all effect was strongly positive for the nuclear workers.

But even if we confine our attention in Table 5.15 solely to workers who were qualified for radiation work, there is no evidence for a linear dose-response curve. In fact, there is strong evidence that mortality is independent of dose, at least over the range 0 to 100 mSv.

It is hard not to sound like a conspiracy theorist but this 10 million dollar shipyard study was never published. When Ted Rockwell asked DOE why not, the reply was “It wasn't in the contract". An abstract was eventually published but it carefully avoided saying anything that could be construed to be anti-LNT. The request for money for further follow up of this interesting population was rejected.

Despite the fact that the non-nuclear workers showed no sign of a healthy worker effect — the SMR for the Non-Nuclear Workers in Table 5.15 is 1.00 — when compared with the general population, in September, 1991 DOE issued a press release saying "The results of this study indicate that the risk of death from all causes for radiation-exposed workers was much lower than for US males. These results are consistent with other studies showing that worker populations tend to have lower mortality rates than the general population because workers must be healthy to be hired, and must remain healthy to continue their employment." This carefully worded deception is reprehensible.

One of the weirder aspects of this whole story is DOE attempting to suppress results which do not support LNT. You would think that the agency which was founded to promote nuclear would embrace and trumpet such numbers. But that did not happen. We will find out why in Chapter 11 when we follow the money.

In 1998, the NCRP committee established to evaluate LNT refused to be blinded by the obvious. They dismissed the shipyard study saying "This interpretation [that radiation had anything to do with the lower mortality] ignores the likelihood there were occupational selection factors that led some to qualify for radiation work while others did not. The fact that there was a difference for total mortality, and not just for radiosensitive cancers, supports the interpretation that selection factors were operative".[231][page 22] Not only does this tortured logic ignore the effort to match the study groups, but it also ignores the highly significant reduced SMR's for death from "all malignant neoplasms" shown in Table 3.6B on page 328. Only the insignificant SMR's for leukemia and lymphatic cancers are considered "radiosensitive cancers". In other words, the cancers where there were insignificant differences between the two groups are radiosensitive. The cancers where there were big differences are not.

5.6.10 The US Plutonium Injections

In 1950, the American government carried out a reprehensible set of experiments. Concerned about the health hazard of plutonium, which was being routinely handled by bomb workers, 18 people, ages 4 to 69, were injected with plutonium without their knowledge. All these people had been diagnosed with terminal disease. Eight of the 18 died within 2 years of the injection. All died from their pre-existing illness or cardiac failure. None died from the plutonium itself.

One of the people selected was Albert Stevens, a 58 year old house painter. Stevens had been misdiagnosed. His terminal stomach cancer turned out to be an operable ulcer. Stevens died at the age of 79 of heart failure, never knowing he had been injected. The researchers made every effort to maximize the damage. Stevens was injected directly into the blood stream with highly soluble, plutonium nitrate that had been spiked with ^{238}Pu, the isotope with the highest activity. Normally, almost all plutonium is in the form of insoluble oxides. If ingested, the body is very inefficient at absorbing plutonium. Only about 30 ppm will be taken into the blood from the intestine.[105][page 44] The experimenters had to figure out a way around this.[35]

Over the 21 year period between his injection and his death, Stevens' body received a cumulative dose of 64,000 mSv. According to LNT, he should have been dead 10 times over. And we can be pretty confident that he would have died if he had received one-tenth this dose over a short period.

The conclusion is inescapable. The impacts of acute and chronic doses on mortality are quite different. The LNT assumption that dose rate is irrelevant is not just wrong, it is totally wrong.

5.6.11 Weapons Test Downwinders

Washington county in southwest Utah is 200 miles east (downwind) of the Nevada Test Site. The county capitol is St. George. The largest fallout was from “event Harry" (later “dirty Harry") with an estimated effective dose of 25-29 mSv to the residents.[44] The total dose for the 1951-1958 testing period is estimated to have been about 36 mSv. These numbers are roughly 2 to 3 times the doses experienced after Fukushima. The maximum dose rate at St. George was 3.5 mSv/h on May 19, 1953. At Fukushima the maximum dose rate was 1 - 10 mSv/h at the plant's main gate of March 11, 2011 and 0.045 mSv/h four days later 25 miles downwind.

In 1950, the exposure guide was 39 mSv per test series with evacuation “to be considered" at 250 mSv. While the area was carefully monitored, there was no evacuation, and life went on pretty much undisturbed. Dr. Tony Brooks recalls as a boy observing the flash and then counting the seconds to the rumble to calculate the distance to the test.

Utah has the lowest cancer fatality rate of any state in the USA. Washington county has one the lowest cancer fatality rates in Utah. Many of the residents are Mormon who neither smoke nor drink. All the residents benefit from a healthy rural life style.

A number of studies were undertaken of cancer incidence in this population. There was no statistical evidence of any increase after the tests. Here's Dr. Ray Lloyd of the University of Utah talking about his work on leukemia.[44][p 6]

> After almost 3 years of intensive study, we concluded to our astonishment that the official AEC/DOE exposure estimates were not seriously in error, and the total exposure at St. George was only of the order of 4 R [40 mSv].
>
> ...
>
> When I initiated this analysis, I expected that I would be able to identify an unmistakable excess of leukemia in the population. My anticipation was that I could use this value with the collective dose to estimate a leukemia risk coefficient for low dose radiation exposures, but I was surprised that a clear excess did not emerge from the data.

---

[35] Inhalation is much more efficient; but requires that the plutonium be in the form of very small particles, preferably soluble.

The population of Washington county experienced about the same or worse exposure as the population at Fukushima. There was no disruption, no economic cost, no evacuation induced deaths and no observable increase in cancer.[44]

You think this story is to too good to be true? You're right. In the late 1970's a series of lurid books were published making all sorts of unsupported claims about the fallout. Now people became worried. Ambulance chasers arrived promising large amounts of compensation.

Anecdotes proliferated. In 1979, Gloria Gregerson recalled that when she was 12 years old "the fallout was so thick, it was like snow, [We] liked to play under the trees and shake this fallout onto our heads and our bodies ... then eat the fallout on my hands"[164][p 20] In the contemporary accounts, there is no mention of any such fallout, and others could not recall any such snow. But Gloria's story was widely circulated as fact. Every cancer in the area was blamed on the testing.

Dirty Harry even killed John Wayne, a four pack a day smoker, because Wayne shot the movie Conqueror in the area. The cast of Conqueror arrived in St. George in June of 1954, over one year after shot Harry was detonated. Testing did not resume until February, 1955, six months after the cast had left. But the headline was irresistible.

Quickly all these stories became fact. People in the area became convinced they had been lied to. All the government funded studies were cover ups. It was taken for granted that just about any illness was caused by the testing. Curiously, there were no such stories and no such concerns prior to 1977.

Politicians, always ready to buy votes with other people's money, responded in 1990 by passing the Radiation Exposure Compensation Act by which anyone living is a wide swath of Nevada, Utah and Arizona at the time of the testing who gets a range of cancers is awarded $50,000. So far the program has paid out 2 billion dollars. Each of these recipients surely believes his cancer was caused by the testing. And anyone can point to this program as a clear admission by the government that the downwinder dose rates are deadly.

5.6.12 Techa River Contamination

In 1949, the Mayak Production Association near Ozyorsk started producing plutonium for the Soviet nuclear weapons programs. The methods were crude and produced enormous amount of liquid waste. At first the waste which contained transuranics, fission products and all manner of chemicals was simply dumped into the Techa River. Some say 100 PBq was released into the river between 1949 and 1956, of which 12 PBq was ^{90}Sr and 13 PBq ^{137}Cs. The rest was mostly shorter lived isotopes such as ^{103}Ru and ^{106}Ru. 100 PBq would be roughly the size of Fukushima; but these are guesstimates. There were no measurements. In the 1950's they started building storage tanks; and in 1956 the direct discharges to the river largely stopped.

Several dams were built across the river, to form sedimentation ponds to capture some of the mess. Periodically these reservoirs have discharged water into the Techa, contaminating the flood plain. Some 30,000 people in 41 villages along the river received low dose rate radiation, mainly from consuming water and food contaminated with ^{90}Sr and ^{137}Cs. Some 7500 people were evacuated between 1953 and 1961 from villages less than 78 km from the plant, Figure 5.13.

Figure 5.13: Techa River Villages

In 1967, efforts to measure the harm to the people along the river began with an attempt to define the Techa River Cohort. The cohort has been modified and extended several time since then. The most recent update to this study is Davis et al.[63] Their results are summarized in Figure 5.14. The dose estimates are a mixed bag. The cohort wore no dosimeters. The cumulative doses are reconstructed, from ^{90}Sr teeth and whole body measurements, more recent air dose and well water readings along the river, and dietary consumption patterns. There has been no attempt to estimate the dose rate profiles.

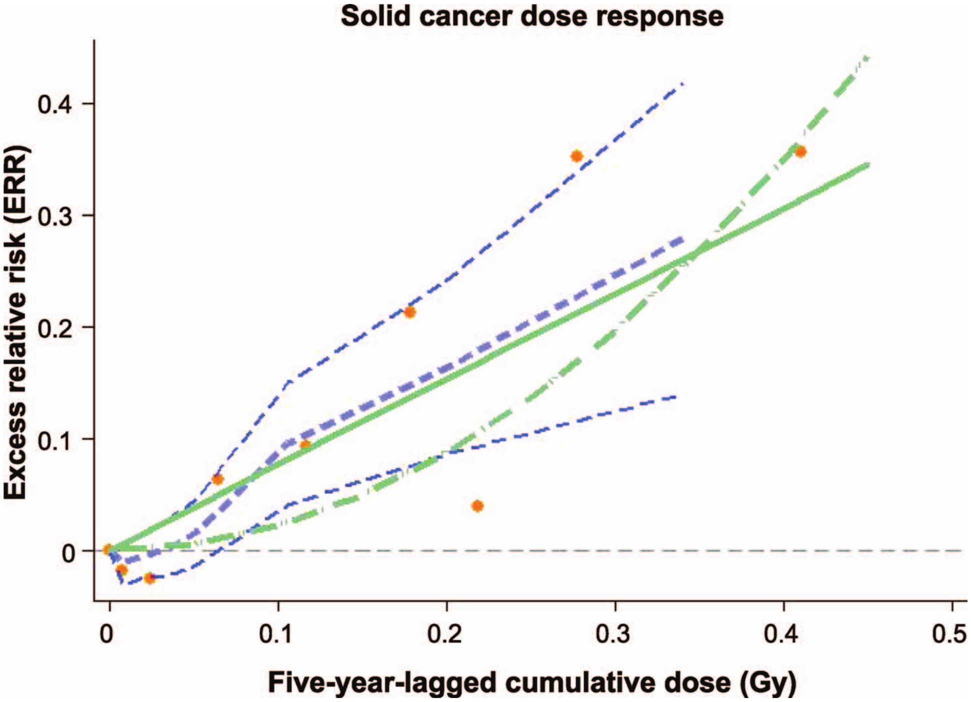


Figure 5.14: Techa River Cancer Incidence. Dose is cumulative over average 27 years.

Davis et al found a pure quadratic fit their data better that a straight line. So even if you believe that cumulative dose is all that counts, this cohort does not support LNT. Nonetheless Davis et al opt for LNT on “grounds of parsimony and simplicity".[63][p 62]

Far more fundamentally, the cumulative doses are small and the dose rates miniscule. The average exposure time for the cohort was 27 years. Over that time, over 90% of the group acquired less than 100 mSv.[36] These are background dose rates in large parts of the planet. Table 5.15 shows the estimated 1998 dose rates in the two river towns closest to the Mayak plant that were not evacuated. The highest dose rate group in the highest dose village is averaging a little more than 1 mSv/y.

At these dose rates, separating the impact of radiation from all the other sources of cancer is simply impossible. To make matter worse, the Techa River waste was a combination of

---

[36] We are not told the number of people in each bin. Nor are we given error bars. Nor, given these dose rates, is there any explanation of how the top end people got the doses they did.

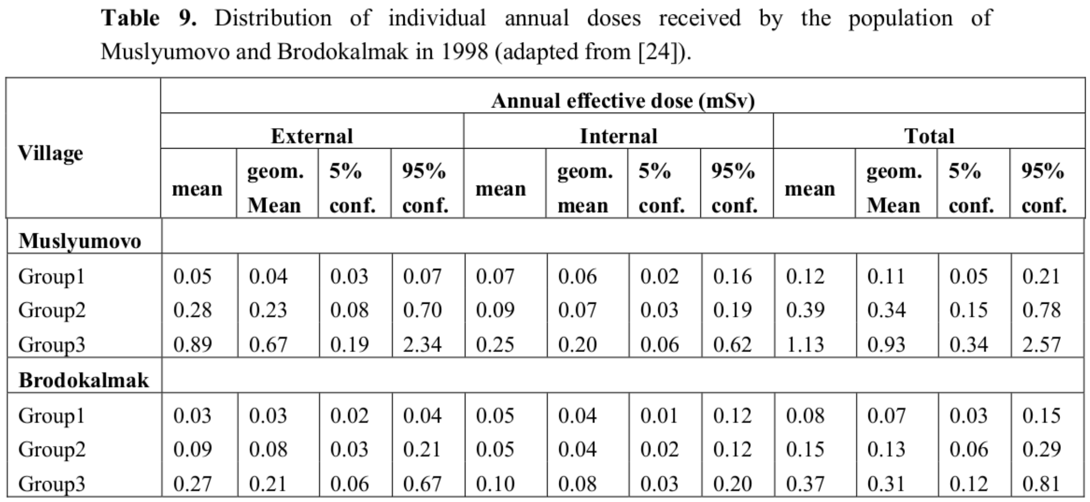


Table 9. Distribution of individual annual doses received by the population of Muslyumovo and Brodokalmak in 1998 (adapted from [24]).

Village	Annual effective dose (mSv)											
	External				Internal				Total			
	mean	geom. Mean	5% conf.	95% conf.	mean	geom. mean	5% conf.	95% conf.	mean	geom. Mean	5% conf.	95% conf.
Muslyumovo												
Group1	0.05	0.04	0.03	0.07	0.07	0.06	0.02	0.16	0.12	0.11	0.05	0.21
Group2	0.28	0.23	0.08	0.70	0.09	0.07	0.03	0.19	0.39	0.34	0.15	0.78
Group3	0.89	0.67	0.19	2.34	0.25	0.20	0.06	0.62	1.13	0.93	0.34	2.57
Brodokalmak												
Group1	0.03	0.03	0.02	0.04	0.05	0.04	0.01	0.12	0.08	0.07	0.03	0.15
Group2	0.09	0.08	0.03	0.21	0.05	0.04	0.02	0.12	0.15	0.13	0.06	0.29
Group3	0.27	0.21	0.06	0.67	0.10	0.08	0.03	0.20	0.37	0.31	0.12	0.81

Figure 5.15: Techa River 1998 Dose Rates, reference [241].

radioisotopes and carcinogenic chemicals. So we have an additional confounding factor.

In the Techa River cohort, most of the radiation harm should be from the ^{90}Sr.[37] Strontium apes calcium. It has high uptake, concentrates in the bone, and stays there for a long time, 18 years on average. So we expect bone cancer. But in the Techa River cohort, there is no evidence of increased bone cancer. Much of what excess cancer there is in the esophagus. Neither cesium nor strontium spend any time in the esophagus. But any chemical you swallow has to go through that organ. The cancer type is a strong hint that, whatever excess cancer there is in the Techa River cohort, it is not due to the radiation.

5.6.13 Kyshtym Explosion

In addition to the Techa River waste, the Mayak facility has experienced a number of episodic releases. The largest of these occurred on September 29, 1957, when a storage tank exploded. The tank contained liquid waste from the reactors used to produce plutonium. The decay heat from the fission products meant that the tank had to be cooled. The cooling system for this tank had failed but was not repaired. Evaporation solidified the waste, which included ammonium nitrate, the explosive that leveled a portion of Texas City in 1947 and Beirut in 2020, and flammable acetates. The tank heated up to 350C, the mixture's ignition temperature, and at 4:22 PM exploded with the force of 70 tons of TNT.

The 1 meter thick concrete slab on top of the tank was tossed aside and 800,000 TBq of

---

[37] This is not the case in a nuclear power plant release. Strontium is not volatile, and any strontium that is released will fall out close to the plant.

radioactivity was released, second only to Chernobyl. However, this was not a nuclear power plant release. The short lived fission products such as ^{131}I had decayed away. The release consisted mainly of strontium-90 and cesium-137. Both have half-lives of about 30 years. ^{90}Sr, an electron emitter, has to be ingested or inhaled to cause harm.

Most of the release settled close to Mayak; but about 80,000 TBq rose high in the air and moved to the northeast in a narrow plume, Figure 5.16. This became known as the East Urals Radiation Trace (EURT).

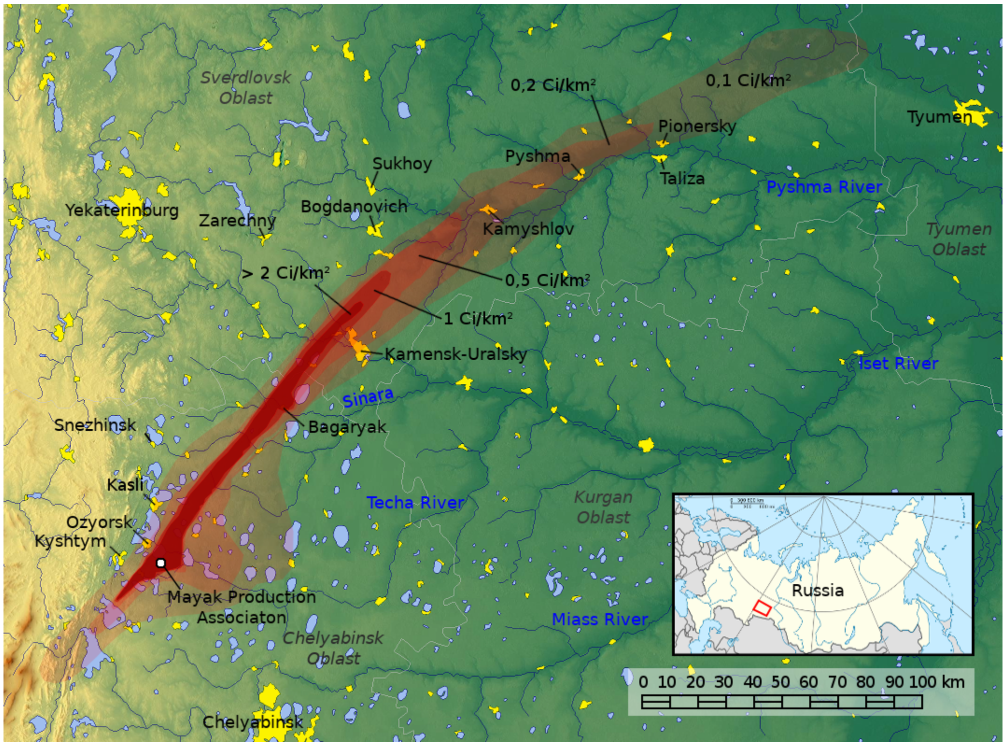


Figure 5.16: Kyshtym Plume, aka East Urals Radiation Trace

About 10,000 people from 22 villages ended up being evacuated. But the first evacuations started a week after the explosion, and most did not take place until 250 to 670 days later. Kostyuchenko et al divided the evacuees into three groups, Table 5.16: High (average cumulative dose, 496 mSv), Medium (average 120), and Low average 40 mSv.[135] These doses are reconstructed, not measured, and highly uncertain. The High group was evacuated in 14 days or less. These people may have incurred a dose rate of 35 mSv/day or more, prior to evacuation. The other groups had far lower dose rates. For all three groups, the observed standardized cancer mortality rate was well below that of the region as a whole and of the USSR.

Despite the apparent lack of harm, the EURT was depopulated. The houses were burned

Table 5.16: Kyshtym Evacuees: Dose, Dose Rate SMR

Group	Persons	Average Cum Dose mSv	Period Days	Dose Rate mSv/day	Stnd Cancer Mortality per 100,000
I	1505	496	<14?	35???	110
II	2803	120	<250	0.5??	94
III	3382	40	330-670	0.06-0.12??	112
Control					
Region					154
USSR					152

down to prevent looters from hauling away contaminated material. The area is now called the East Ural Nature Preserve.

But the Mayak facility, where most of the debris landed, never stopped operating. It is still storing and reprocessing spent fuel.

5.6.14 Chernobyl liquidators

Background

On the night of April 25, 1986, Unit 4 of the Chernobyl nuclear power station exploded. Chernobyl is located in northeast Ukraine, very close to both Russia and Belarus. The reactor was a water cooled, graphite moderated design originally designed for weapons plutonium production. It was a massive, klunky, low efficiency design which needed to produce 3200 MW of thermal energy to create 1000 MW of electricity. The core was 12 meters in diameter and 7 meters high, made up of 1700 tons on graphite drilled with 2488 holes containing a tube of uranium, surrounded by an annulus of high pressure (70 bar) flowing water. There was no radiation containment structure.

Worse, the design was inherently unstable. It is not difficult to build inherently stable reactors, reactors in which any increase in temperature automatically decreases power output. This decrease does not depend on operator or control system action. It is part of the reactor physics. All commercial reactors built in the west and all commercial reactors currently being built anywhere have this property. But with the Chernobyl design, it was possible to put the reactor in a state where an increase in temperature, increased power, further increasing temperature, creating a run away power excursion. The Chernobyl explosion was a nuclear power disaster in the same way the Hindenburg was an air transportation disaster. It showed us how not to do it.

The actual explosion was the result of this inexcusable design fault, combined with a series of human screw ups during an improvised stress test that should have taken place prior to commissioning; but had been put off to meet an arbitrary start up date. To do this test, the staff had to bypass parts of the safety system. The reactor went into a run away chain reaction creating a steam explosion, which blew the reactor apart. The 2000 ton core lid was blown into the air, and the flimsy structure above it was obliterated, Fig 5.17.

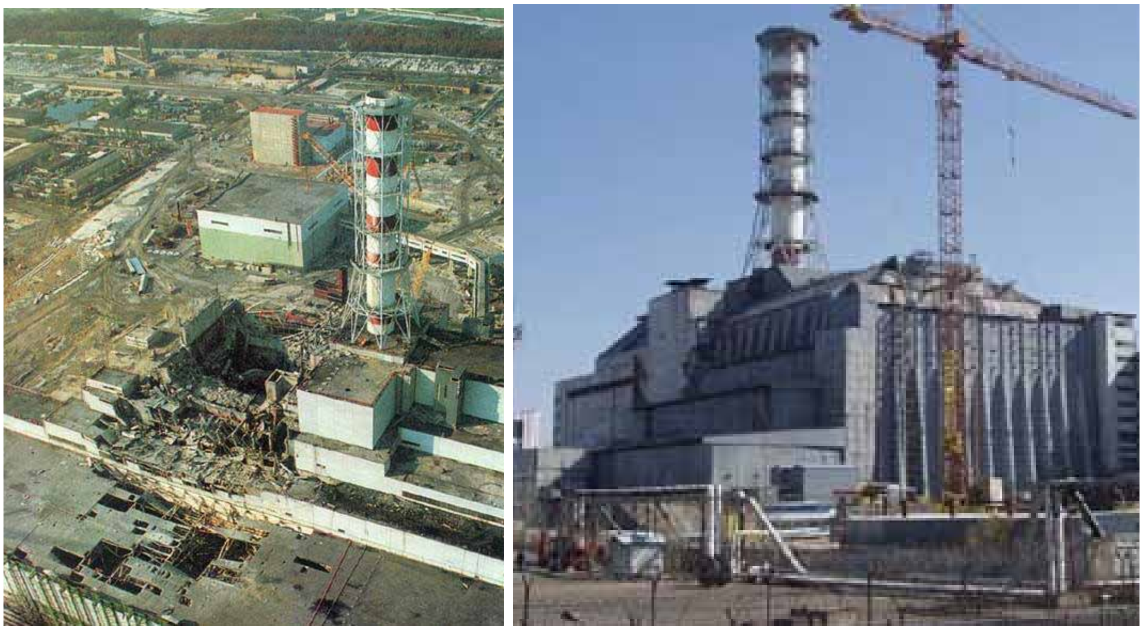


Figure 5.17: Left: Chernobyl Unit 4. Unit 3 is on the right. Right: Sarcophagus in place.

The reactor core was exposed to the atmosphere. Big chunks of core graphite were thrown everywhere including onto the roof of the neighboring Unit 3. A radioactive plume rose 1500 meters into the air and began moving northwest.

As a reactor operates, it builds up an inventory of radioactive fission products. Even after the reactor is shut down (or blown apart) and the chain reaction has stopped, the decay of these fission products continues to produce heat. This *decay heat* starts out at about 6% of the normal power, drops rapidly to less than 1% a day after shutdown, and then starts falling much more slowly. 1% of 3200 MW is still a great deal of heat. The decay heat in the Unit 4 rubble and burning graphite kept the mess glowing hot, producing a thermal plume that continued to pull radioactive particles out of the pit for at least 10 days.. Overall 50% of the iodine and 30% of the cesium in the reactor were ejected into the air.[6][Table 1] Hard to imagine a worse casualty.

After the disaster, the USSR conscripted some 200,000 men to try to clean up the mess, and cover the reactor with an improvised concrete and steel sarcophagus. They became known as *liquidators*. The liquidator tour of duty was one to two months. However, there was an individual limit of 250 mSv in 1986 which was dropped to 100 mSv in 1987. In the first year, you were supposed to be rotated out when you reached 250 mSv, but that did not always happen. Most of the men did not have dosimeters. One dosimeter was issued to a member of each group, which he reported as the group's dose rate at the end of each day. Big possible biases both up and down.

To clear the debris and build the sarcophagus, the men had to work very close to the exposed reactor. The dose rates were off scale, as high as 100,000 mSv/h.[107][p 279] One of the worst jobs was clearing chunks of core graphite and fuel tubes off the roof of neighboring Unit 3. The men had to shovel this stuff off the roof of 3 and toss it into the gaping hole that was Unit 4. It only took them a minute or two to use up their 250 mSv allotment. 3828 men were used in this operation.

Figure 5.18: Liquidators on Unit 3 Roof

On October 1, 1986, the sarcophagus was complete. The same day Unit 1 was restarted. Unit 2 was restarted in November. Unit 3 which abutted Unit 4 was restarted in December, 1987. Unit 1 operated until 1991; Unit 2 until 1996. Unit 3 was shut down in 1999 under pressure from the European Union. Up to 4000 people worked at the plant between 1987 and 2000.

In the towns around the plant, ground level dose rates started out in the 0.400 to 4 mSv/h range.[28][p 31,42-43] 10,000 or more times lower than the Unit 3 roof. After Unit 4 was entombed, dose rates depended on local ground contamination, and fell into the micro-Sievert per hour range. In the Red Forest, the hardest hit area just west of the plant, the dose rates leveled off in the 50 to 100 μSv/h range,then continued to fall slowly as the amount of Cesium-137 reduces by half every 30 years. In 2018, Stone et al measured 30 to 40 μSv/h in the Red Forest. Elsewhere by 1995 the rates varied from normal background (0.1 to 0.2 μSv/h) to a few hot spots with up to 20 μSv/h.[174][p 14] In 2018, Stone et al measured 3.7 μSv/h next to the sarcophagus, Figure 5.19.

If dose rate is important, we need to divide the liquidators into pre-sarcophagus and post-sarcophagus. Many of the men who worked on building the sarcophagus received their 250 mSv in an acute fashion, much like the atom bomb survivors. After the sarcophagus was in place, you might still get 250 mSv (or later 100 mSv) before your tour was up; but, if so, it was almost always over a period of weeks.

Figure 5.19: Dose rate in μSv/h next to the sarcophagus, 2018. Credit: Robert Stone

Cancer Incidence

There have been attempts to reconstruct the cumulative doses.[124] Kashcheev et al focused on 67,568 Russian liquidators who worked in the exclusion zone in the first year after the explosion. According to their reconstruction, the mean/median dose for this group was 132/102 mGy.[38] Unfortunately, there was no attempt to stratify by dose rate.

The cumulative dose range was very large. The lowest dose was 0.1 mGy and the largest 1240 mGy. 572 people received doses of 300 mSv or more. Figure 6.16 shows the distribution that these authors came up with. There are two peaks: one in the 200 to 250 mSv range and another in the 50 to 100 mSv, reflecting the pre-1987 and post-1987 dose limits.

By 2009, this group had suffered 4002 cases of solid cancers. The Standardized Incidence Rate (SIR) was 18% higher than the SIR for Russian men as a whole. The authors accept LNT as gospel. When the authors fitted a straight line to a scatter diagram of relative risk versus dose, they came up a significant positive correlation with a maximum likelihood slope of 0.47/Gy. This is the same number that the RERF group came up with for the bomb survivors. With this linear fit, they attributed 5.8% or 233 of the 4002 cancers to radiation, Table 5.17.

---

[38] Here we are concerned with external photon radiation for which grays and sieverts are numerical equal.

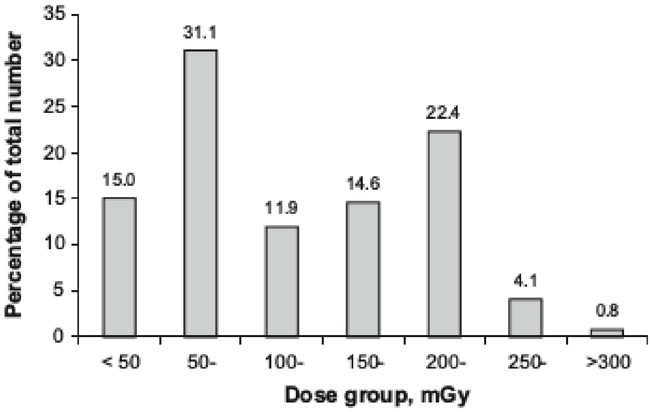


Figure 5.20: Kashcheev liquidator dose distribution

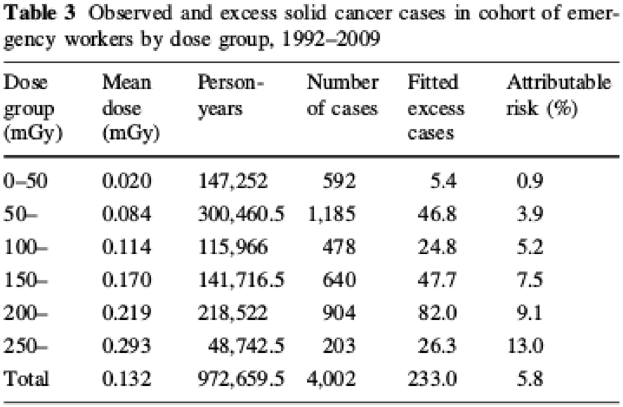


Table 3 Observed and excess solid cancer cases in cohort of emergency workers by dose group, 1992–2009

Dose group (mGy)	Mean dose (mGy)	Person-years	Number of cases	Fitted excess cases	Attributable risk (%)
0–50	0.020	147,252	592	5.4	0.9
50–	0.084	300,460.5	1,185	46.8	3.9
100–	0.114	115,966	478	24.8	5.2
150–	0.170	141,716.5	640	47.7	7.5
200–	0.219	218,522	904	82.0	9.1
250–	0.293	48,742.5	203	26.3	13.0
Total	0.132	972,659.5	4,002	233.0	5.8

Table 5.17: LNT fit to liquidator cancer incidence, 2nd column is Gy, not mGy

The difference between 18% and 6% was attributed to “screening effect" since the liquidators received much more regular and thorough medical examinations than an average Russian. Then the authors did something interesting, a non-parametric analysis treating the 0-5 mGy dose group as the control.[39] Figure 5.21 shows the results. There is no discernible increase up to about 100 mGy. There is no statistically significant increase up to about 200 mGy. Figure 5.21 looks much like the Bomb Survivor data, Figure 5.2.

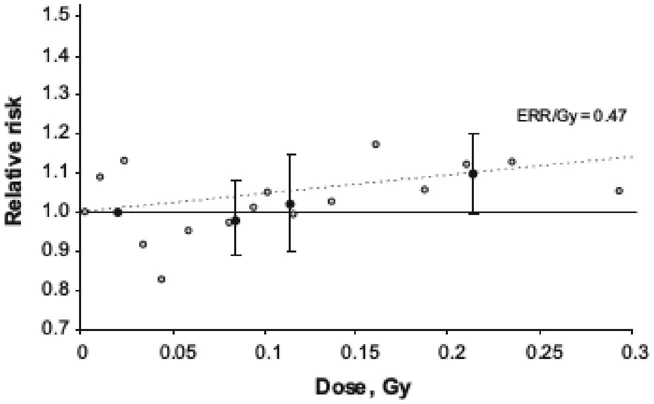


Fig. 4 Relative risk (RR) of all solid cancers by dose groups (*black point* estimates, *vertical lines*—95 % CIs) calculated from Eq. (5); *gray points* represent RR for all 16 dose groups (0–5 mGy is control group); *dashed line* represents the value RR(d) = 1 + ERR(d), where the ERR value was calculated from Eq. (3)

Figure 5.21: Kashcheev et al Liquidator Relative Cancer Incidence vs Cumulative Dose

---

[39] The authors divided the liquidators into 16 different dose bins, but frustratingly they did their calculations on six 50 mGy wide bins, once again obscuring what’s happening at the low end.

Cancer Mortality

Despite the higher apparent cancer Standardized Incidence Rate, Kashcheev's cohort had a significantly ***lower*** Standardized Mortality Rate (SMR).

> it was found that average solid cancer mortality rate in the studied cohort of emergency workers over the entire follow up period from 1992 to 2009 is 5% lower than that for men in Russia. (SMR = 0.95 95%CI 0.92:0.99)[124][page 19]

Earlier detection and better care more than made up for the apparent increase in incidence. The plot of cancer mortality versus dose, Figure 5.22 shows an area extending out to 150 mGy in which there is no increase in mortality relative to the under 5 mGy group. Despite this, Kashcheev et al fit a straight line to the data and come up with a slope of 0.58 per gray. From this they deduce that 7.1% of the 2442 or 172 deaths were due to radiation.

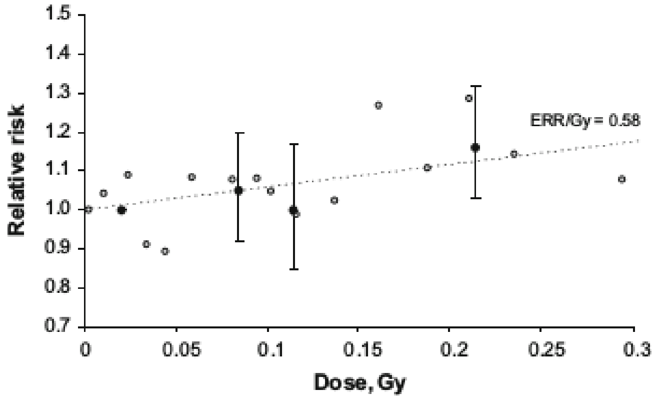


Fig. 6 Relative risk (RR) of all solid cancer deaths by dose groups (*black point* estimates, *vertical lines*—95 % CIs) calculated from Eq. (5); *gray points* represent RR for all 16 dose groups (0–5 mGy is control group); *dashed line* represents the value RR(d) = 1 + ERR(d), where the ERR value was calculated from Eq. (3)

Figure 5.22: Kashcheev et al Liquidator Cancer Death vs Cumulative Dose

Summary

Russians represented 30% of the first year liquidators.[102][Table 2.] If we accept the Kashcheev analysis at face value and assume the other first year liquidators have the same dose distribution, through 2009 there were about 600 early solid cancer deaths caused by radiation among the first year liquidators. But from the point of view of life expectancy you are better off being an average liquidator than a non-liquidator. For most of the liquidators it was a clear win. Nil increase in cancer from the job and you got the perks.

One thing is for sure. There is no support for LNT in the Kashcheev liquidator solid cancer data. In fact, the data supports the position that 100 mSv received over a relatively short period results in no measurable increase in solid cancer.

5.7 Animal Experiments

5.7.1 Fruit flies

Remember Muller's fruit flies that started us down the LNT path. Well, since Caspari, researchers have noted all kinds of non-linear responses in these bugs. For example, Antosh et al found that, in order to shorten fruit fly life at all, they needed a dose of 23,000 mSv, Figure 5.23.[12]

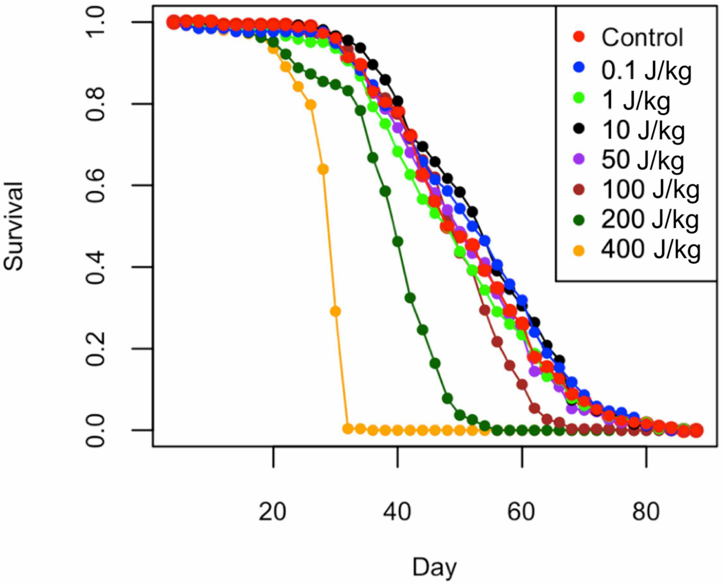


Figure 5.23: Fruit fly survivorship curves. The different curves are for incident photons. The authors estimate that 46% of the radiation was actually absorbed by the flies. Below 50 J/kg incident (23,000 mSv dose), there was no statistically significant difference in life span.

5.7.2 The Russell Mice Fiasco

Shortly after the war, the AEC started studying the effects of radiation on mice at the Oak Ridge National Lab (ORNL). This grew into a massive project, capable of handling 250,000 mice at a time. Over 20 years, they went through three million mice. The project was led by William Russell and his wife Liane.

The program studied changes in fur color and ear size, not cancer. The Russells found that mice were 15 times more sensitive to radiation than fruit flies. The results showed strong dose rate dependence. For females, there appeared to be a threshold. For males, the low dose rate mutations were down 70%. But Russell, who was on the BEAR1 committee, downplayed his results for a long time. It was not until 1970, that Russell clearly broke with the establishment, stating that LNT does not apply to mice. He said his results could only be explained by repair. In 1972, the BEIR-1 report came out. The report admitted that dose rate effects were real; but decided to stay with LNT, in part because the male mice results did not show a threshold.

In 1995, the Russells asked a younger colleague, Paul Selby, to computerize all their data. One issue was "mutation clusters" in which a male transmits a mutation to a large number of offspring. Selby sees the cluster issue goes back to 1951. He finds that the Russells excluded the cluster data from controls but not from the irradiated group.[229] When Selby brings this up with the Russells, they are strangely unresponsive.

This results in a showdown, in which ORNL tried to paper over the problem. Selby claims that by "sanitizing" the data in this manner, making mice 15 times more sensitive than fruit flies, the Russells were able to argue for taxpayer money and build their program. Whatever the motivation, when you correct the data for the cluster "mistake", the female mice show a hormetic (beneficial) effect and the males a threshold at the lower dose rates. With or without the cluster correction, the voluminous Russell mice data contradicts LNT.

5.7.3 Beagles

In the 1950's and 1960's, the AEC and DOE funded research on radiation lavishly. As a result, we know a great deal more about radiation than we do about many health risks. One area was in animal studies. Two hundred million dollars were spent on beagles. The beagle was chosen as a compromise on size, ease of housing, and life span. Some 7000 dogs were sacrificed in a wide range of experiments. Non-linear responses abounded. Here's two.

Figure 5.24 shows the incidence of lung cancer associated with breathing PuO2. There is a sharp dip around 250 mGy above which tumor incidence increases in a roughly linear pattern.

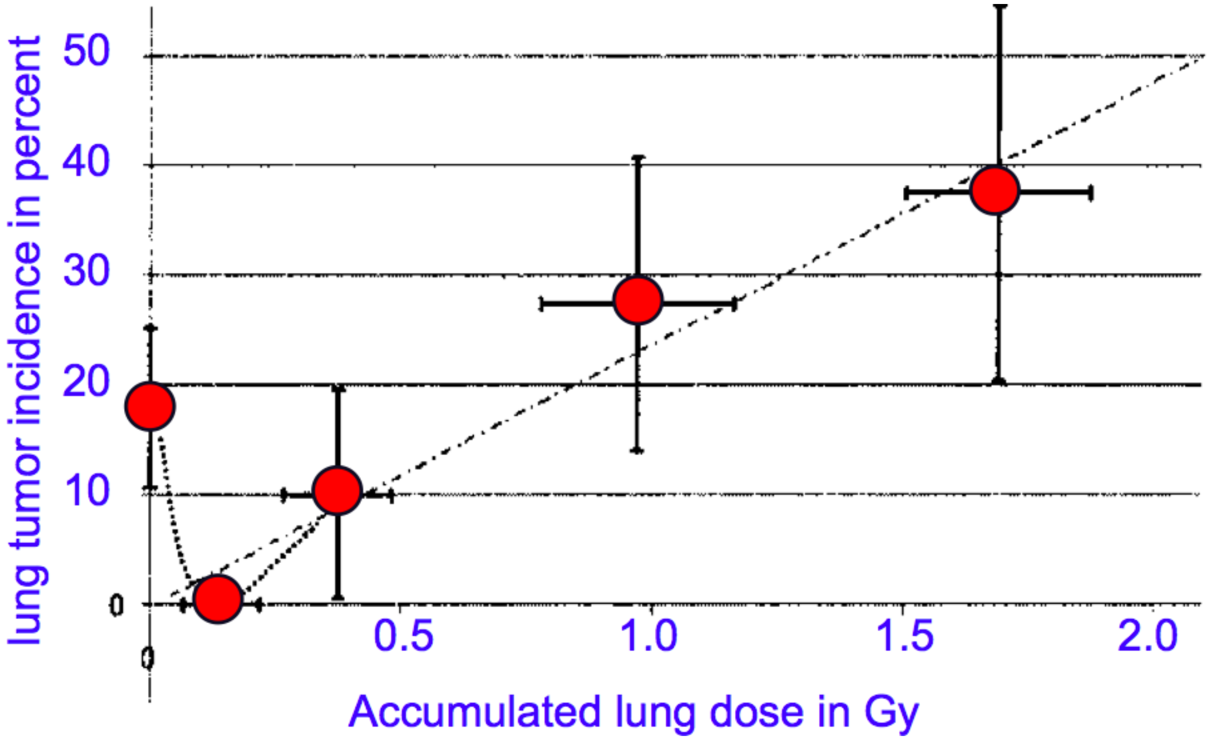


Figure 5.24: Effect of breathing plutonium oxide on beagle lung tumors, reference [82][Fig 4]

Figure 5.25 shows the effect on beagle longevity from external photon radiation. There was not much response up to 1 mSv/d. The curve is flat in this region, a sharp drop off above this, and then the curve flattens out again. The dogs were able to cope with 1 mSv/day but 50 mSv/d killed them rapidly. Overall, we have a highly non-linear S-shaped curve.

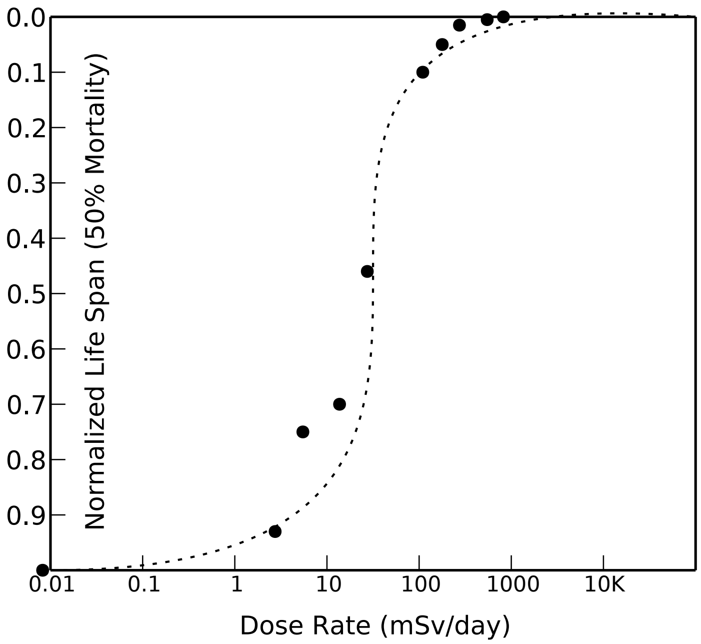


Figure 5.25: Highly non-linear response of beagle longevity to dose rate, reference [60][Fig 2]

Figure 5.26 shows a more informative way of looking at the beagle mortality data. In this set of experiments, the dogs were exposed to steady whole body photon radiation until they died, at dose rates varying from 540 mSv/day to background for the control group. The key point to take away from this figure is the overwhelming importance of dose rate. Since the radiation stopped when the dogs died, the cumulative doses increase as you move to the right in the figure, until you get down to a dose rate of 7.5 mSv/day. The dogs who received the larger cumulative doses lived longer, because they were getting that dose at a lower dose rate. Dose rate was much more important than cumulative dose. Notice there is very little difference between the dogs that were continuously exposed to 3 mSv/day and the control group.

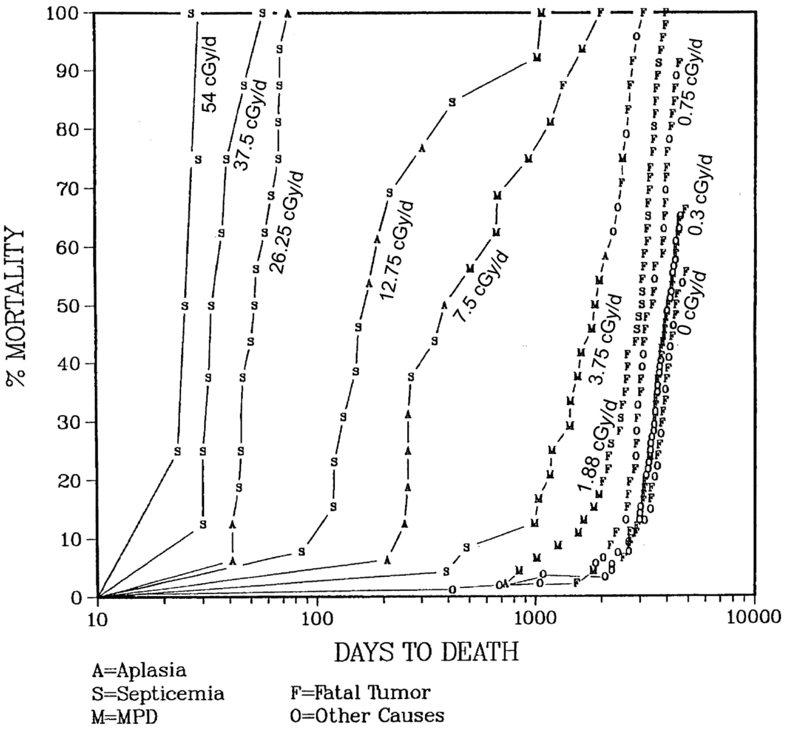


Figure 5.26: Effect of dose rate (1 cGy = 10 mSv) on beagle longevity.[84]

5.7.4 MIT Mice

This 2012 study focused on dose rate.[198] 24 mice were given an acute dose of 105 mSv in 1.4 minutes. 60 mice were administered the same dose spread evenly over 5 weeks. This is a dose rate of 2.9 mSv/day. According to LNT, the difference in dose rate should have no effect.

The latest techniques were then used to look for DNA and other cell damage. The authors say

> Consistent with previous studies exposure to 105 mSv delivered acutely resulted in a significant increase in micronuclei.[40] In contrast, no significant increase in micronuclei was observed in continuously irradiated mice.

The repair processes were able to keep up with a dose rate of 3 mSv/day, but not 70 mSv/minute.

---

[40] Micronuclei are the detritus left over when a chromosome or fragment of a chromosome is not incorporated into the cell nuclei.

5.7.5 Yamamoto Mice

In these experiments, 550 mice were fed tritium laced water for their whole lives until they died.[161] The mice who received 3.6 mGy/day or less had essentially the same cancer incidence and life span as the control group, Figure 5.27. Above that dose rate, the experimenters started to see increases in cancer and decreases in life span. The 3.6 mGy/day mice received water that had so much tritium in it, the activity was 14,000,000 Bq/L. That's 1400 times higher than the WHO drinking water limit.

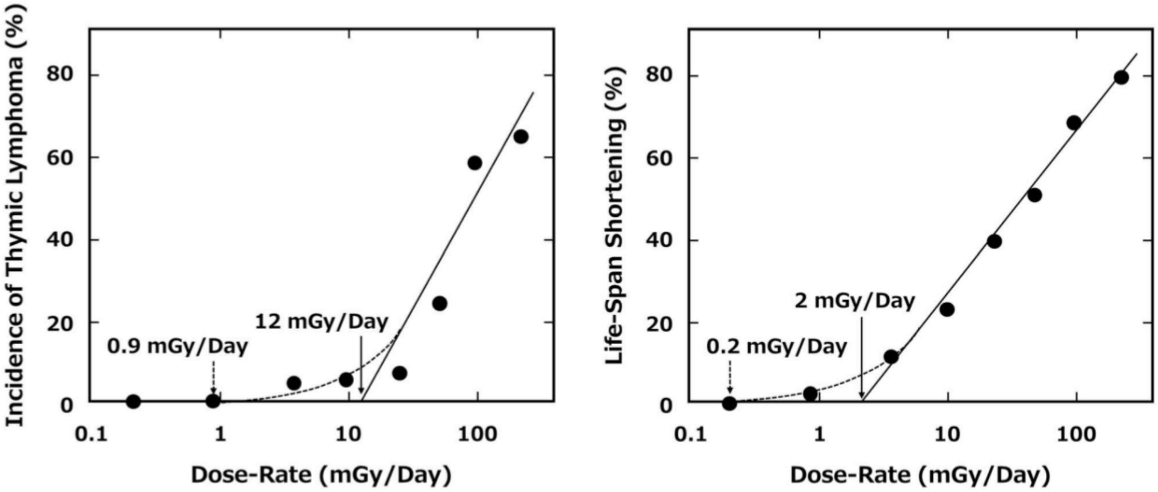


Fig. 6. Incidence of thymic lymphoma and lifespan shortening in mice ingested at different dose-rate of HTO [19].

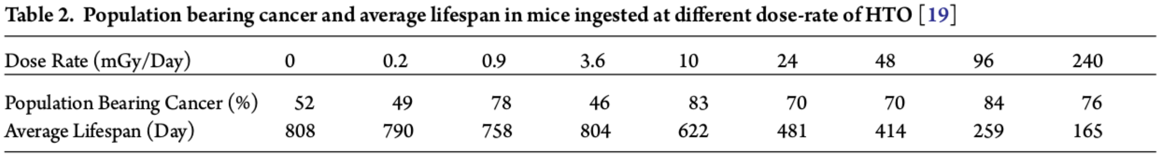


Table 2. Population bearing cancer and average lifespan in mice ingested at different dose-rate of HTO [19]

Dose Rate (mGy/Day)	0	0.2	0.9	3.6	10	24	48	96	240
Population Bearing Cancer (%)	52	49	78	46	83	70	70	84	76
Average Lifespan (Day)	808	790	758	804	622	481	414	259	165

Figure 5.27: Effect of dose rate on mice cancer and lifespan.[161]

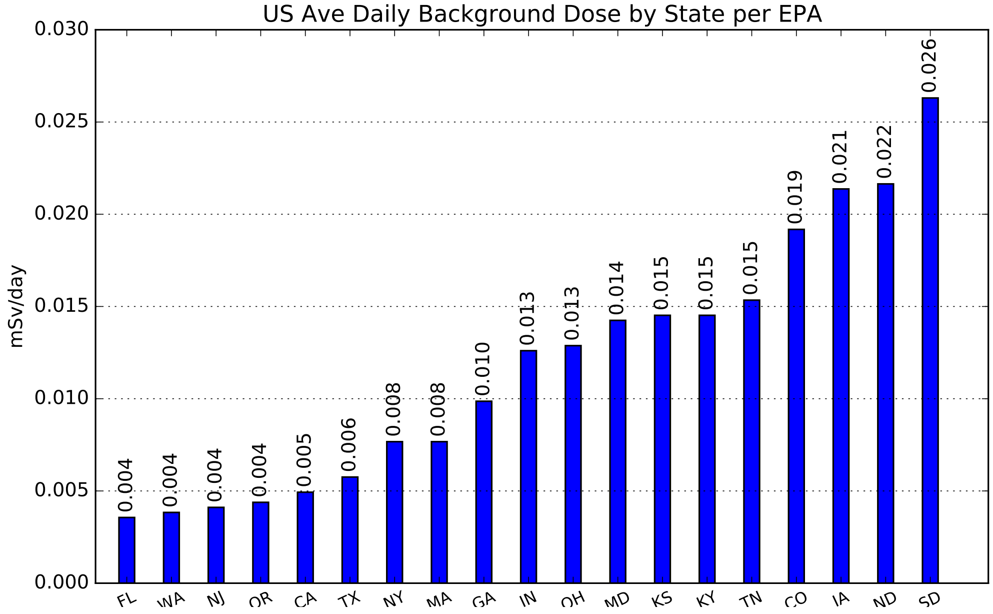


Figure 5.28: USA average dose rate by State.[162]

5.8 High Background Radiation

The world average daily dose from all sources is about 0.007 mSv. But there is a large range. In Europe the average daily dose in the UK is less than 0.005 mSv; but it is about 0.016 in Sweden, 0.022 in Finland, and over 0.027 in parts of Norway, southeast Finland and northwest Spain.. In the US, the average background dose rate in Florida is about 0.004 mSv/d but 0.026 in South Dakota, Figure 5.28.[41]

Increasing background radiation by a factor of two or more does not take much. The average for Italy is about 0.008 mSv/d but the dose rate in St Peter's Square is about 0.019 mSv/d due to all the travertine stone. For the same reason, dose rates in Grand Central Station and the US Capitol are elevated by about 0.011 mSv/d.[42] The really hot spots are:

Ramsar, Iran This Iranian town on the Caspian Sea has background dose rates as high as 0.7 mSv per day.from radon.[92] However, the hot spots are quite localized. Ramsar is divided into eight health districts. In a study of lung cancer rates, the highest mortality rate was is a district called Galesh Mahaleeh where the radon levels are normal. The lowest lung cancer rates were in a district called Ramak where the radon level are highest.[172] The radon levels in Ramak are up to 3700 Bq/m3, 19 times higher than the EPA limit for

---

[41] Americans, more or less voluntarily, tack on another 0.008 mSv/d in medical exams and treatment. This is about five times the world average.

[42] If the Capitol were a US nuclear power plant, it would be shut down.

Figure 5.29: Dose Rate, μSv/h, Black Beach, Guarapari, Brazil. Credit: Robert Stone

remedial action. The sample size in this study was very small; but the data we do have does not support LNT. The locals are unconcerned about living with dose rates that are 10 to 100 times more than the dose rates that resulted in a panicked evacuation at Fukushima.

Guarapari, Brazil Guarapari is a coastal town whose popular beaches have peer reviewed dose rates up to 0.5 mSv/d. Figure 5.29 shows 30.3 microsieverts per hour in the sand, about the same as Chernobyl's Red Forest in 2018. This corresponds to 0.7 mSv/day. Many beachgoers bury themselves in the sand. They believe it eases their health problems. However, the high levels are confined to the beaches. Even Brazilians don't spend all their time on the beach. The residents' average daily dose is about 0.014 mSv but with a max of 0.077 mSv.[59] As far as I know, there has been no quantitative study of the cancer incidence in the area, but the locals are unconcerned.

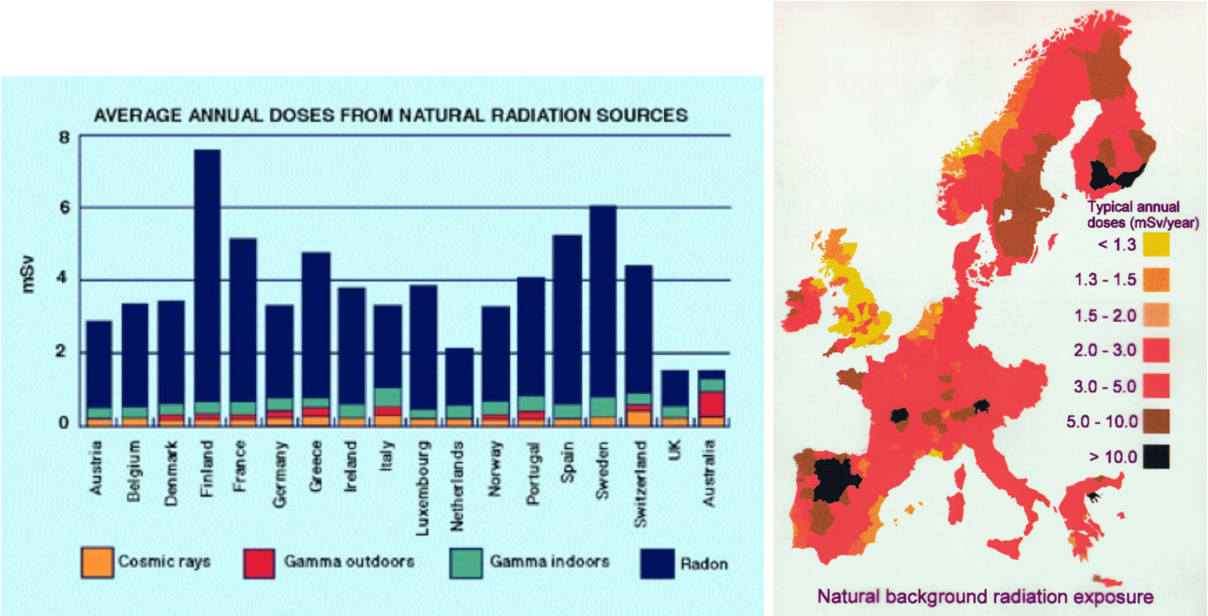


Figure 5.30: Variation in European Dose Rates

Finland The background dose rates in Finland are much higher than most of Europe, Figure 5.30. The residents of the town of Pispala average 0.096 mSv/d.[204] The Finns rank in the bottom third with respect to cancer incidence in first world countries.

Other hot spots in Europe include northwest Spain and the health spas in Austria. Under Austrian law, a health spa owner must maintain his radon levels 30 times higher than the EPA action level. If he fails to do so, his customers can no longer use their government health insurance to pay for the treatment. Austria is stridently anti-nuclear power.

Yangjiang, China Yangjiang is an area in which the sand is high in thorium. Thorium is very weakly radioactive. The sand is used for the bricks with which the locals build their homes. Two groups were studied. One had an average dose rate of 0.017 mGy per day and control group from a neighboring city with an average dose rate of 0.007 mGy per day. The study involved more than a 100,000 people and 1.7 million people years. Let's let the authors speak for themselves:

> During the period 1987-1995, we observed 926,226 person-years by following up 106,517 subjects and accumulated 5,161 deaths, among which 557 were from cancers. We did not observe an increase in cancer in the HBRA [high background radiation area] (RR=0.96, 96%CI, 0.80,1.15). The combined data for the period 1979-1995 included 125,079 subjects and accumulated 1,698,316 person

> years, observed 10,416 total deaths and 1,003 cancer deaths. The relative risk of all cancers from the whole HBRA area as compared with the control area was estimated to be 0.99 (95% CI, 0.87 to 1.14). ... We did not find any increased cancer risk associated with the high levels of natural radiation in HBRA. On the contrary the mortality of all cancers in HBRA was generally lower than that in the control area, but not statistically significant.[244]

Kerala, India The coastal belt of Kerala has a sand that is very high in thorium. Some locations on the shore have dose rates as high as 0.21 mSv/d.[177] UNSCEAR measured mean dose rates of 0.08 mSv/d inside buildings in the village of Kadipattam.[257][Annex B, page 55] The max was 0.11 mSv/d. 173,000 residents of this area were studied for 15 years; but the average time an individual was in the study was 10.5 years due to start up delays, migration and death. Table 5.18 summarizes the results for the residents of an area with the lovely name of Karunagappally. The average cumulative dose over the study period from terrestrial photon radiation was 161 mSv or about 0.04 mSv/d.[43]

Table 5.18: Risk of all solid cancers, [178][Table 4]

	Cumulative Dose (mSv) over 10.5 years on average				
	0 - 49	50 - 99	100 -199	200- 499	500+
Mean dose	35	74	141	283	628
std dev	6	9	17	49	118
person-yrs	211,968	228,091	206,3377	83,836	6,355
Relative Risk	1.00	0.97	1.02	0.93	0.95
95% Conf.Int	Reference	0.83-1,14	0.87-1.19	0.77-1.13	0.60-1.49

If you are silly enough to try and fit a straight line through this data, you get a negative slope of -0.13/Sv. But the important take away is ***there is no observable difference between the cancer incidence of Karunagappallians with a cumulative dose of 35 mSv and those with a cumulative dose of 628 mSv.*** 0.16 mSv/d for 10.5 years had no noticeable effect. According to LNT, the 500+ group should have a 6% higher cancer rate.

---

[43] The reported doses appear to be on the low side:

1. The researchers decided not to estimate the dose from inhalation and ingestion. In a separate study, which sampled 200 dwellings in the area, Chougaonkar et al found that about 30% of the total dose was from inhalation.[43]
2. The researchers attempted to calibrate the dose rates measured in air 1 m above ground in a sample of houses and outdoor locations, with actual dose rates as measured by 150 people fitted with dosimeters. Only after throwing out 25 "outliers" that had doses three standard deviations higher than the mean did they get a reasonable agreement between the body dosimeters and the air dosimeters.

LNTers often argue that the reason we can't see the elevated cancer rates at low doses that LNT calls for, is the sample size is not large enough. Brenner, a strong supporter of LNT, argues that to be statistically confident of the impact of a 5 mSv difference in dose we would need to study a population of ten million people for their entire life.[25][Figure 1] But he is done in by LNT's cumulative assumption. Brenner using the same argument calculates that to see the impact of 500 mSv difference we would need 1000 people. The Kerala study easily meets his requirement.

The leader of the study was Dr. Ragu Ram K. Nair. Here's his own summary of the work.

> The coastal belt of Karunagappally, Kerala is known for its high background radiation (HBR) from thorium containing monanzite sand. In coastal panchayats, median outdoor radiation levels are more than 4 mSv/y and, in certain locations on the coast, it is as high as 70 mSv/year. Although HBR has been repeatedly shown to increase the frequency of chromosome aberrations in the circulating lymphocytes of exposed persons, its carcinogenic effect is still unproven. A cohort of 385,103 residents in Karunagappally was established in the 1990's to evaluate health effects of HBR. Based on radiation level measurements, a radiation subcohort aged 30-84 was analyzed. Cumulative radiation dose for each individual was estimated based on outdoor and indoor dosimetry of each household, taking into account sex and age specific house occupancy factors. Following 69,958 residents for 10.5 years on the average, 736,586 person-years of observation were accumulated and 1,379 cancer cases including 30 cases of leukemia were identified by the end of 2005. Poisson regression analysis of cohort data, stratified by sex, attained age, follow-up interval, socio-demographic factors and bidi smoking, showed no excess cancer risk from exposure to terrestrial gamma [photon] radiation. The excess relative risk of cancer excluding leukemia was estimated to be -0.13 per 1000 mSv (95% CI: -0.58, 0.46). In site specific analysis, no cancer site was significantly related to cumulative radiation dose. Leukemia was not significantly related to HBR either. ... our cancer incidence study, together with previously reported cancer mortality studies in the HBR area of Yangjiang, China, suggest it is unlikely that estimates of risks are substantially greater than currently believed.[178].

The last sentence is revealing. Our study is not inconsistent with LNT. It just shows that LNT is not under-stating the risk. Dr. Nair, a respected member of the radiation protection establishment, cannot bring himself to say the obvious.

The problem for LNT is that in none of the high background radiation areas or populations do we find evidence of increased cancer due to radiation despite some very determined searching.

5.9 The Importance of Dose Rate

Table 5.19 summarizes the main studies that have been done on people who have received far larger than normal radiation doses.[44]

Table 5.19: Groups exposed to large doses of radiation
Single acute dose above top horizontal line; repeated doses below. Belarus/Ukraine kids: thyroid dose

Group	Size	Period	Cumulative dose mSv	Dose rate mSv/day	Result
Bomb survivors	33,459	seconds	5 to 150	5 to 150	Insignificant decrease in leukemia
Bomb survivors	5,463	seconds	150 to 300	150 - 300	Insignificant increase in leukemia.
Bomb survivors	6,793	seconds	300-5000+	300-5000+	Significant increase in leukemia.
5-20	14,555	seconds	5 to 20	5 to 20	Insignificant decrease in solid cancers.
20-40	6,411	seconds	20 to 40	20 to 40	Solid cancers same as control
40-125	10,970	seconds	40 to 125	40 to 125	Insignificant increase in solid cancers.
125+	16,166	seconds	125+	125+	Significant increase in solid cancers.
Louis Slotin	1	seconds	21000	21000	Died in 9 days
H. Daghlian	1	seconds	5900	5900	Died in 25 days
Norway tech	1	< hour	38500	38500	Died in 13 days
Tokaimura	3	seconds	3000-17000	3000-17000	>10,000 mSv died
Goiania	≈46	hrs or less	1000-6000	1000-6000	50% mortality abv 4000 mSv
Thai scrap	≈10	hrs or less	1000-6000	1000-6000	100% mortality abv 6000 mSv
Chern 1st responders	134	<2 hrs	1000-16000	1000-16000	Sigmoid mortality, 50% mortality at 6000 mSv.
Chernobyl liquidators	220,000	2 min to 90 days	1-1500	nil to 1500 most < 2	Low/high dose rate mushed together. 6% increase in cancer. Decrease in mortality.
Litvenko	1	3 weeks	96,000	4,000	Died in 23 days
Belarus kids	13,127	2-3 weeks	ave 780 max 48k	39-2400	45 thyroid cancer, eventual 50? deaths
Ukraine kids	11,611	2-3 weeks	ave 560 max 33k	28-1600	87 thyroid cancer, eventual 50? deaths
Eben Byers	1	2 years	366,000	300	Horrible bone cancer. Died in 3 years.
Evans radium hi	127	10 years	>80000	80+	Cancers. Hi mortality >200 mSv/d
Dial painters hi	273	up to 15 yrs	190000-440000	35 to 80+	96 bone cancers
Evans radium mid	17	10 years	20000-80000	20 to 80	Abnormalities. Nil clinical symptoms.
Dial painters lo	2,110	up to 15 yrs	200 - 160000	up to 30	Zero bone cancers.
Evans radium lo	59	10 years	up to 20000	max 20	Nil abnormalities.
Albert Stevens	1	20 years	61,000	8	Died at age 79 of heart failure.
UPPU Club	26	≈10y	up to 7200	0.03-2	Lower mortality than coworkers.
Taipei Apt hi	1,100	18 years	up to 4000	up to 3	Decrease in cancer, maybe non-rad.
Taipei Apt mid	900	18 years	ave 420	up to .160	Decrease in cancer, maybe non-rad.
Taipei Apt low	8,000	18 years	ave 120	up to .050	Decrease in cancer, maybe non-rad.
Keralans	69,956	10-15 yrs	50-650	.016 to .160	Insignificant decrease in cancer
NRX Clean Up	≈1000	90s jumps	up to 200	up to 150	Insignificant decrease in cancer

---

[44] In Table 5.19, the acute dose groups are above the top line; the chronic dose groups are below the bottom line. Some (at least 4000 men) of the Chernobyl liquidators received their dose in a matter of minutes. For others the dose was spread over 60 to 90 days. Unfortunately, the individual dose profiles are not readily available.

The atom bomb survivors absorbed their dose *acutely*, in this case, in matter of seconds. The dose rates for the high dose cohorts were in the 1000 mSv/s range and higher. In the bomb survivors, a dose in excess of about 200 mSv clearly increased cancer, and the incidence of cancer increased with further increasing dose. Below 100 mSv acute, we see no or insignificant effect.

But in a nuclear power plant release, the dose is almost always spread over weeks and months and years, at least for the public. The public dose rates are almost never more than 1 mSv/d and for almost everybody much lower.[45] In the jargon, these are called *chronic* doses. When we look at the groups that have received their dose chronically, we find that it almost does not matter how large the cumulative dose is as long as the dose rate is less than a few millisieverts per day. To see detectable harm — get out of the green — requires dose rates of 20 mSv/d or more.

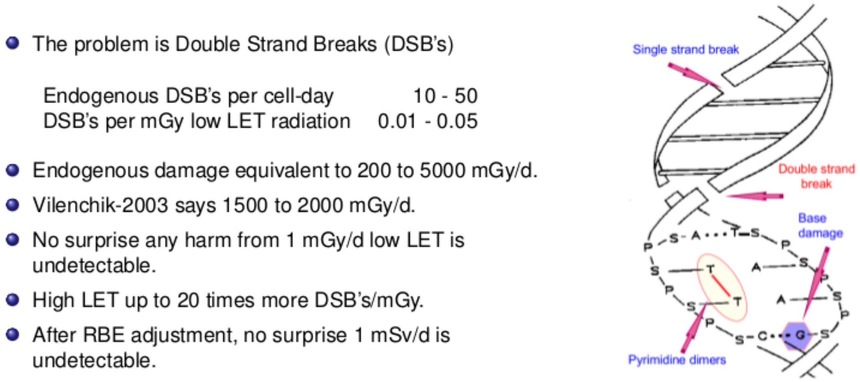
For example, among the radium dial painters, only the women whose dose rate exceeded 30 mSv/day developed bone cancer. ***Dose rate is far more important than cumulative dose.*** This is consistent with what we know about cellular repair. What counts is keeping the damage rate below the repair rate. It's also consistent with radiation regulation prior to 1950. Up to that point, the NCRP and ICRP limit was 1 mSv/day. Table 5.19 says that looks about right, better than a factor of twenty margin on detectable harm.

5.10 DNA Damage and Repair

But why is 1 mSv per day a good rule? To answer that, we must bring in some basic biology. The DNA in our bodies is constantly being assaulted by Reactive Oxygen Species(ROS). These chemical active molecules such as OH^- are the by product of oxygen based metabolism. About one-billion ROS micro-bombs per day per cell leak from our cell's mitochrondia into the rest of the cell. Roughly 1 in 20 thousand of these molecules chemically damage our DNA. This is the price we pay for an oxygen based metabolism.

---

[45] There is one important but unnecessary exception, kids drinking ^{131}I contaminated milk, which we will discuss in Chapter 7.



- The problem is Double Strand Breaks (DSB's)

Endogenous DSB's per cell-day	10 - 50
DSB's per mGy low LET radiation	0.01 - 0.05

- Endogenous damage equivalent to 200 to 5000 mGy/d.
- Vilenchik-2003 says 1500 to 2000 mGy/d.
- No surprise any harm from 1 mGy/d low LET is undetectable.
- High LET up to 20 times more DSB's/mGy.
- After RBE adjustment, no surprise 1 mSv/d is undetectable.

Figure 5.31: Endogneous versus Radiation DNA damage

This damage can take the form of Single Strand Breaks(SSB) and Double Strand Breaks(DSB).[46] Table 5.20 shows some estimates of the number of SSB's and DSB's each of our cells endure per day from normal metabolism.

Table 5.20: Estimates of Endogenous SSB's and DSB's per cell-day

Source	SSB/cell-day	DSB/cell-day
Vilenchik-2003[266]	20,000	10 - 50
Bouwman-2016[24]	20,000	10 - 50
Lieber-2010[148]		about 10
Lees-Miller	60,000	10
Costes-2021[206]		10 - 50
Henriksen-2013[106]	50,000	8

In response to this onslaught, Nature has equipped us with a remarkably accurate DNA repair system. Without this system, we would not be here. SSB's are repaired almost automatically by the clever design of the double helix. The repair uses the intact strand as a template and is essentially error-less. SSB repair takes about 25 minutes.

DSB repair is far more difficult. In portions of the cell cycle, a backup template is available, and can be used to make a practically error-free repair. In the rest of the cell cycle, the attempts at repair, cannot always be successful. Clearly, Double Strand Breaks should be our focus.

---

[46] Some of the damage involves chemical changes other than a break in the strand; but, as long as one side is intact, we call it a Single Strand Break.

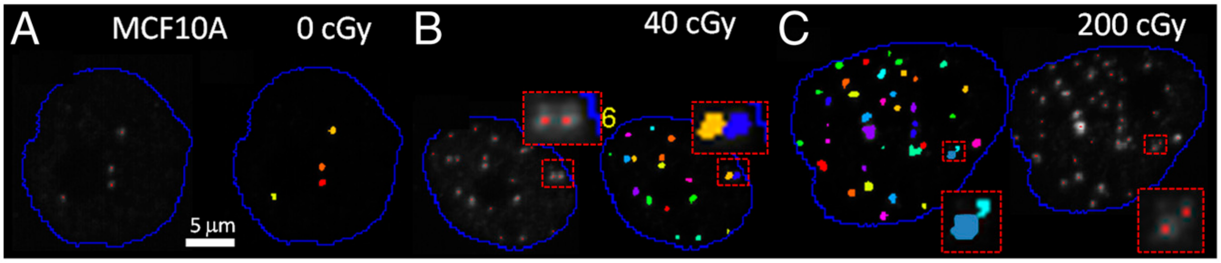


Figure 5.32: UCB pictures of cell repair. The bright spots in the three screenshots are clusters of damage sensing and repair proteins, dubbed Radiation Induced Foci (RIF). Berkeley found that the number of RIF's increases less than linearly with dose. At 0.1 Gy, they observed 73 RIF's/Gy. At 1.0 Gy, they saw 28 RIF's/Gy. If an RIF is faced with a single DSB, the repair is almost always correct. If an RIF is faced with more than one DSB, the error rate skyrockets. We expect 25 to 40 DSB's per gray. Do the math. 40 DSB's and 73 RIF's, no problem. 40 DSB's and 28 RIF's, trouble.

By tagging the ends of the break, Berkeley actually has pictures of the DBS repair process, Figure 5.32, which is largely complete in about 2 hours for acute doses below 100 mSv and 10 hours for doses around 1000 mSv. These experiments show that double strand breaks result in RIF's, clusters of damage sensing and repair proteins. But the number of RIF's does not increase linearly with the dose rate. As long as the number of RIF's is more than the number of DSB's, there is very little unrepaired damage. But if the number of DSB's is larger than the number of RIF's, the amount of unrepaired cells goes up drastically.[47]

A few of these unrepaired cells will escape our immune system; and a few of those will result in a viable mutation that will eventually cause cancer. ***The key feature of this process is it is non-linear.*** And it is critically dose rate dependent. If the damage rate is less than the repair rate, we are in good shape. If the damage rate is greater than the repair rate, we have a problem.

---

[47] The Berkeley work was part of the DOE funded Low Dose Radiation Research Program. Despite the progress at Berkeley and other labs and bipartisan congressional support, DOE shut the program down in 2015. When the DOE administrator of the program, Dr. Noelle Metting, attempted to defend her program, she was fired and denied access to her office. The program records were not properly archived as required by DOE procedures.

Table 5.21 shows estimates of the DSB's per millisievert of radiation.

Table 5.21: Estimates of DSB's per millisievert

Source	DSB/mSv
Vilenchik-2003[266]	0.03
White-2016[280]	0.01 - 0.05
Neumaier-2011[183]	0.025- 0.04

If we conservatively assume 10 endogenous DSB's per cell-day, and 0.04 DSB's per millisievert then it would take 250 mSv per day to equal the number of DSB's produced endogenously. If normal endogenous harm is equivalent to 250 mSv/d, then any harm associated with 1 mSv/d would almost certainly not be detectable. At the same time, it is not surprising that we start to see detectable harm at 20 to 50 mSv/d. At that point, the cell is forced to deal with a substantially higher than normal number of DSB's.

The Table 5.20 and 5.21 numbers are consistent with Table 5.19 the pre-1950 tolerance dose rate, and its implied repair period of a day.

I think it is entirely plausible that our DNA repair system evolved originally to handle radiation damage. Cyanobacteria were around for about two billion years before oxygen breathing organisms developed. These algae can convert sunlight directly to life-sustaining chemical energy. In the process, they produced the free oxygen which allowed O2 breathers to develop. Floating on the surface of oceans and lakes, they were exposed to many times current radiation rates. At the time, there was no ozone in the atmosphere to shield them from high intensity UV-C photons.

Badri et al studied an edible algae called Arthospira, and found that it could survive 6400 grays delivered at a dose rate of 527 Gy/h.[14] Arthospira is high in protein, and shows up in some health foods, under the name spirulina. NASA wants to grow it on space ships.

Like us cyanobacteria are mostly water. The main mechanism for DNA damage was:

1. photon energy ionized cell water,
2. the resulting ROS chemically reacted with and modified DNA.

Cyanobacteria had well developed ROS repair systems long before any oxygen metabolizers were around. Our eukaryotic ancestors incorporated bits of cyanobacteria into their more complicated cells, and co-opted those systems. They then improved on them to handle the even larger ROS production rates associated with oxygen metabolism.

In short, the reason we are so good at handling radiation is we need to be good at repairing DNA damage from O2 metabolism; and the reason we have O2 metabolism is Archean algae had to be very good at repairing DNA damage from radiation. We stole and built on that system.

5.11 Selling LNT

With all this evidence, how has LNT, which claims that dose rate is irrelevant, survived and indeed flourished? The answer is by specious, if sometimes well-intentioned, salesmanship. Birthed by fear of nuclear weapons and geneticist greed, LNT became a dogma to be defended rather than a hypothesis to be examined. Often this bias is embarrassingly transparent. It takes several closely related, over-lapping forms:

Flipping the burden of proof. In honest science, a proponent for a theory must assume as a null hypothesis that his theory is not true, and show that that is not the case. ***One solid counter-example invalidates the theory.*** For the pro-LNTer, the null hypothesis is the response is non-linear and non-cumulative. It's his job to prove the response is linear and cumulative. Unless the data conclusively shows that, then the null hypothesis cannot be rejected. But the LNT community assumes the null hypothesis is LNT.

This leads to totally different standards applied to statements supporting LNT versus those that don't. For the former "statistically consistent" or even "not inconsistent" is good enough. The pro-LNT literature is the land of the double negative.

Data inconsistent with LNT is subject to hostile scrutiny, uncertainties emphasized, and often thrown out for no more reason than it is judged "not representative of the overall body of data". After a group of studies showed that people working in jobs which resulted in higher doses has lower cancer mortality than workers in jobs not involving extra radiation exposure, the National Academy of Science issued the following edict

> Because of the uncertainty in occupational risk estimates, ... the committee has concluded that occupation studies are currently not suitable for the projection of population based risks.[251][p 206]

Basically their position is:

- Our data does not conclusively show that LNT is wrong. Therefore, LNT is valid. Here's how the NCRP itself puts it.

  > However, few experimental studies, and essentially no human data, can be said to prove or even to provide direct support for the concept of collective dose with its implicit uncertainties of nonthreshold, linearity, and dose-rate independence with respect to risk. The best that can be said is that most studies do not provide quantitative data that, with statistical significance, contradicts the concept of collective dose. ...
  >
  > It is conceptually possible, but with a vanishingly small probability, that any of these effects [leading to cancer] could result from the passage of a single charged particle. ... It is the result of this type of reasoning that a linear nonthreshold dose-response relationship cannot be excluded. [125][page 45]

Cannot be excluded is all we need.

- It's true we can't see any increase in cancer in high background populations, but there are so many confounding factors that it might be there, so LNT is valid.
  Think I'm exaggerating? Here's Dr. Werner Roehm, Chairman of the ICRP Committee on Radiation Effects:

> Maybe it's not possible. But I feel we must communicate this to the public. Say maybe there is something at low doses. Maybe there is nothing. We don't know. We have to admit that. It's a matter of honesty and transparency. But we can say for sure that it cannot be much. If it was large, we should see it. That is for sure.[Werner Roehm, Oct 2018, ANS Meeting]

The NCRP and the ICRP are the official defenders of LNT.

Creation of a false dichotomy. The assumption is there are only two possibilities: (a) a positive threshold below which there is absolutely no risk, or (b) LNT.

Then all one has to do is show that the proponents of a threshold are unable to pin point exactly where that threshold is. This is easy to do. Therefore, LNT is valid.

This fallacy often takes the form of: can you prove that even the smallest dose carries zero risk of cancer? Since this is impossible, LNT must be valid. In fact, there are an infinity of non-linear response curves in which any non-zero dose carries some risk. However, as we shall see, at very low doses that non-linear risk can be orders of magnitude less than that predicted by a linear model.

Censorship by policy. In drawing conclusions, ignoring their own data when it does not support linearity or worse indicates that radiation can be beneficial. This is not my conjecture. It is official, explicit EPA policy.

> Moreover, as the purpose of a risk assessment is to identify risk (harm, adverse effect, etc), effects that appear to be adaptive, non-adverse, or beneficial may not be mentioned.[195][page 53]

This document, Risk Assessment Principles and Practice, the official guide to EPA risk assessment, starts off by saying

> *EPA conducts risk assessment to provide the best possible scientific characterization of risks based on a rigorous analysis of available information and knowledge*[195][page 3]

Emphasis theirs. So the best possible scientific characterization involves arbitrarily censoring results. Orwell had everything right except the date.

The LNT hypothesis cannot stand on its own two feet. It must be defended by rhetorical tricks, tortured statistics, cherry picking, and fiat. Lauriston Taylor, founding chairman of the NCRP, called these machinations "a deeply immoral use of our scientific heritage".[48] But that's a monumental understatement. By defending LNT speciously, the promoters of LNT are playing a key role in not only generating tragic responses to a release of radioactivity; but much worse preventing mankind from solving the Gordian knot of electricity poverty and global warming. They are guilty of imposing privation on billions. They could be complicit in dooming the species. Why are they doing this? I have no idea. I don't want to think about it.

The whole concept of a threshold below which there is absolutely no damage seems to have been introduced by Muller in 1948 as a straw man. I have not found the word used any earlier in this context. Prior to World War II, the NRCP and others were careful to talk about a *tolerance dose* which was defined as "the dose of ionizing radiation that, in the light of present knowledge, is not expected to cause appreciable bodily injury to a person at any time during his lifetime. As used here, 'appreciable bodily injury' means any bodily injury that the average person would regard as being objectionable and/or competent medical authorities would regard as being deleterious to the health and well being of an individual".[245][page 26] Taylor puts it more succinctly:

> The adoption of tolerance or permissible doses did not depend upon the assumed existence of a threshold. The setting of the tolerance level was on the basis of whether or not effects could be observed, and this has been the common approach to similar problems for all other toxicological agents.[245][page 13]

---

[48] Here's the entire quote.

> Collectively, there exists a vast array of facts and general knowledge about ionizing radiation effects on animal and man. It cannot be disputed that the depth and extent of this knowledge is unmatched by that for most of the myriads of other toxic agents know to man. No one has been identifiably injured by radiation while working within the first numerical standards first set by the NCRP and then the ICRP in 1934. [1 mSv/day] The LNT is a deeply immoral use of our scientific heritage. [Lauriston Taylor, founder and past president of the National Council on Radiation Protection and Measurements, 1980]

Taylor estimated his personal life time dose at 10,000 mSv, most of which was received in 1929 due to a screwed up x-ray machine at the National Bureau of Standards.[246] According to LNT, his probability of cancer was 1.00. Taylor died in 2004 at the age of 102.

5.12 The Nuclear Establishment's Embrace of LNT

The LNTers have been abetted by a nuclear regulatory-industrial complex which nonchalantly accepted LNT without any argument in 1959. The nuclear establishment made the collective decision to embrace LNT and has stuck with this decision ever since. When Ted Rockwell was asked why he was preaching to the choir about LNT, Rockwell replied "because the choir isn't singing". Rockwell was wrong. The choir was singing LNT.

Why would an organization supposedly promoting nuclear power accept such a momentous change with little or no discussion, and then sing it praises. The AEC funded the Caspari study. They knew Muller had lied. The AEC funded the Neel study. They knew that LNT had crashed and burned genetically. The AEC funded the bomb survivor leukemia study. They must have known the data showed a highly non-linear response. They knew Lewis had lied. At the time, there was no solid tumor cancer data.

I have found no documentation on this crucial decision, so I will have to speculate. I think it was a combination of political expediency and technical hubris. The Rockefeller Foundation's carefully orchestrated campaign had put the AEC in a bind. Under the Foundation's prodding, the NRCP had recommended replacing the tolerance dose with LNT. The NRCP was the AEC's sole independent advisor on radiation safety. If the AEC rejected that recommendation, they would pay a heavy PR price. Nuclear power's opponents in Congress, backed by King Coal, would go ballistic.

Moreover, the AEC's main line of business was nuclear weapons. The idea that a radioactive release was tolerable was anathema to both people who opposed the atom bomb and people that supported the atom bomb program on the grounds that mutually assured destruction — scaring the hell out of everybody — would prevent World War III. Almost nobody was prepared to go to the public and make the case that a large release was tolerable. It was far easier to claim there would be no such release. But to do this, the nuclear power establishment had to convince themselves they could prevent such a release. In a fit of collective hubris, they managed that.

Earlier I quoted Mike Derivan, the reactor operator at Davis-Besse who, faced with the same failure as Three Mile Island, figured out what was happening and the proper response despite the fact that all his training told him it was the wrong response. Derivan is a thinker. Here's another Derivan quote.

> The simple fact is that before TMI the Institutional Arrogance of the whole Nuclear Industry did not believe a core damage event was even possible. Events were postulated and consequences were analyzed because it was the licensing methodology that was used; but it was the belief that core damage was never going to happen ... period.[65]

Institutional Arrogance may be too polite a term. In 1969, the Atomic Industrial Forum told the AEC that research on core meltdown was unnecessary since "a major meltdown would not be permitted to occur"[279][p 37]. This hubris is the reason that today nuclear power is crippled by LNT. Since we are never going to have a release, what difference does it make what radiation harm model we use?

But now nuclear power was in a new bind. 1f a release could be as catastrophic as LNT claims, proponents of nuclear power had to argue that a major casualty was astronomically unlikely. They had to come up with meltdown probabilities that are easily shown to to be bogus, Section 4.1. Worse they had to come up with a regulatory process, which would achieve these totally unrealistic numbers. This attempt was doomed to failure, and in the process make nuclear electricity prohibitively expensive.

This is all very depressing. Let's go on to the next question. If LNT is invalid, with what should we replace it?

Chapter 6

The Sigmoid No Threshold Radiation Harm Model

> A number of important questions about the effects of low level radiation evaded sure answers and stirred debate among scientists. One was whether a threshold existed for somatic radiation injury. If so, it indicated that there was a level at which exposure was safe. If not, it implied that a person would develop cancer, proportional to the dose received.[271][p 302]

The above quote is from the official history of the NRC. One of the most pervasive fallacies in the radiation business is that the no-perfectly-safe-dose hypothesis, — the assumption that even the smallest dose could result in cancer — implies a linear dose response curve. This false dichotomy, either there is a threshold or the dose response curve is a straight line, crops up time and time again.[1] It is accepted not only by LNT promoters, but by many who argue for a threshold. This is willful nonsense. There are a myriad of non-linear dose response functions which accept the no-perfectly-safe-dose hypothesis. This chapter studies one obvious example, the logistic family of curves. These S-shaped curves are the standard dose response model outside of radiation protection.

In this chapter, we focus on non-thyroid cancers. The discussion of thyroid cancer will be deferred until Chapter 7.

---

[1] Okrent reports that at a 1959-04-16 ACRS meeting, the committee was told that at a recent symposium members of the AEC Division of Biology and Medicine indicated that no threshold existed for biological damage from radiation.[197] Okrent indicates the committee was surprised by this revelation. This is the earliest report I have found of the AEC moving away from the position that there is a tolerance dose below which there is no detectable harm. LNT was the accepted doctrine almost immediately thereafter. But I have found no documentation of this momentous policy change. There appears to have been no formal decision making. But it seems the AEC thought its choice was

1. a threshold, or
2. LNT.

The opening quote is interesting not only for the false dichotomy, but also for its definition of "safe". Only zero risk is safe. This is not an anti-nuke talking. This is a historian hired by the NRC.

6.1 Introduction

In order to reconcile the statistically significant increase in cancer that is observed for ***acute*** radiation doses of much more than 100 or 200 mSv, with the fact that large populations living in high background radiation areas for 70 years or more during which time they receive a dose of 600 mSv or more show no discernible increase in cancer, as well as artificial situations in which people have received thousands of mSv over 10 years or more with no significant increase in cancer, the cancer radiation dose response curve must be non-linear.

A reasonable set of rules for a dose response curve are:

1. Harm increases with increasing dose. There is considerable evidence, that in certain situations, a modest amount of radiation, can stimulate repair responses that result in a decrease in cancer. This is particularly apparent when a small *priming* dose is administered prior to a much larger *challenge* dose. However, much of the data is based on lab experiments with simple organisms. The applicability of this behavior to humans in a nuclear power plant release is far from clear. To be conservative, we adopt a monotonically increasing curve.
2. The slope of the response curve goes to zero at zero dose. We know that radiation can damage our DNA. We also know that evolution has equipped us with an exceedingly effective damage repair system. The repair system can be overwhelmed if the dose rate is high enough. It seems reasonable to assume that the repair system is perfectly accurate at zero dose and the accuracy drops off in non-jumpy fashion as the dose increases. Under these assumptions, the slope of the dose response curve at zero dose must be zero.[2]
3. Similarly, it makes sense to assume that the slope of the response curve also goes to zero at the high, always fatal end. As we approach, the always fatal dose, there's nobody left to kill.

Under these rules, we need a sigmoid (S-shaped) response function. The five parameter logistic function is a family of such functions that allows us to model a wide range of dose responses meeting these basic rules.

This is neither radical nor original.[72, 237] Even the ICRP found that cataract opacity followed a sigmoid response to radiation dose.[137] It embodies the establishment position: no

---

[2] In a system with repair, harm, for example cancer mortality, $C(d)$, is given by $C(d) = D(d)p_{nr}(d)$ where d is the dose, $D(d)$ is the damage at dose d and $p_{nr}(d)$ is the probability that the repair fails. If the damage and probability that the repair fails goes to zero at zero dose, then the slope of the response curve must go to zero at zero dose. This can be seen by taking the derivative of the above product.

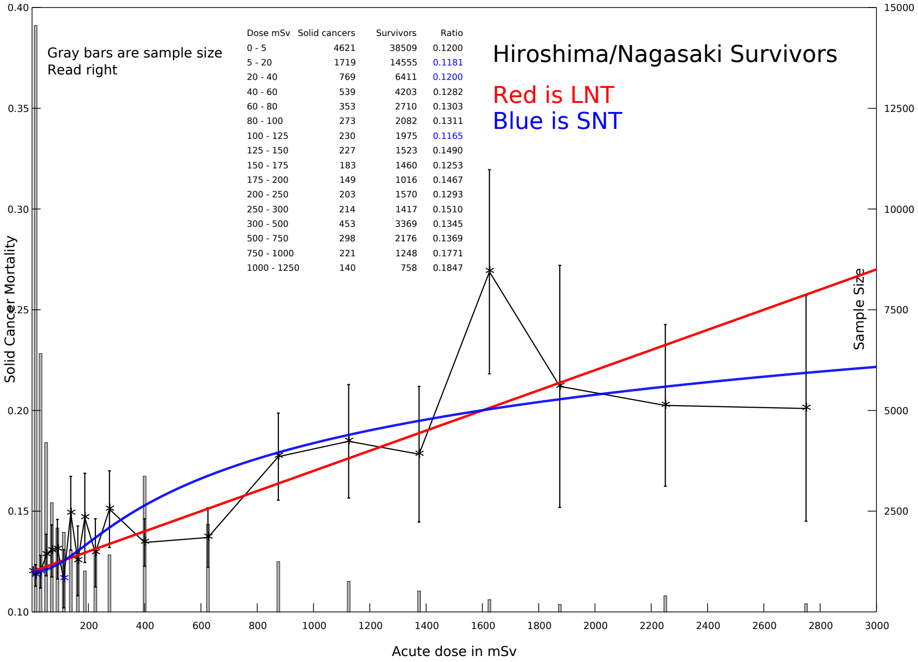
Assuming damage is linear in dose, and the probability of repair drops off linearly as the dose increases, leads to a quadratic response at the low end. A quadratic response is qualitatively different from the linear-quadratic model which LNTers sometimes resort to to explain obvious non-linearity. The slope of a quadratic curve goes to zero as the dose approaches zero. The slope of a linear-quadratic model goes to the linear coefficient as the dose goes to zero. Qualitatively different behavior at the low dose end. Both the quadratic and linear-quadratic models are nonsense at the high end, as is LNT.

In a model that recognizes repair, the repair probability can depend on the type of radiation, avoiding the alpha paradox.

threshold, risk increases with dose. In fact, logistic dose response is standard practice throughout medicine except in radiation. There are a half dozen software packages on the market to help you fit logistic curves to dose response data.

6.2 Fitting the Logistic Function to the RERF data

As a poor example, let's fit a logistic curve to the RERF Life Span Study solid cancer data for the Hiroshima and Nagasaki survivors. This sloppy fit is based on the grouped figures shown in Figure 5.3. This is just the raw cancer mortality data binned. It has not been stratified by sex, age, or anything else. Moreover, there are all sorts of problems with the RERF data and I will compound those by blithely converting grays to sieverts on a 1 to 1 basis. This exercise is aimed at highlighting the qualitative differences between Linear No Threshold and Sigmoid No Threshold from a policy point of view. It is not an attempt at a quantitatively accurate fit to a particular data set. Figure 6.1 compares a least squares linear fit with the best logistic fit I was able to come up with.

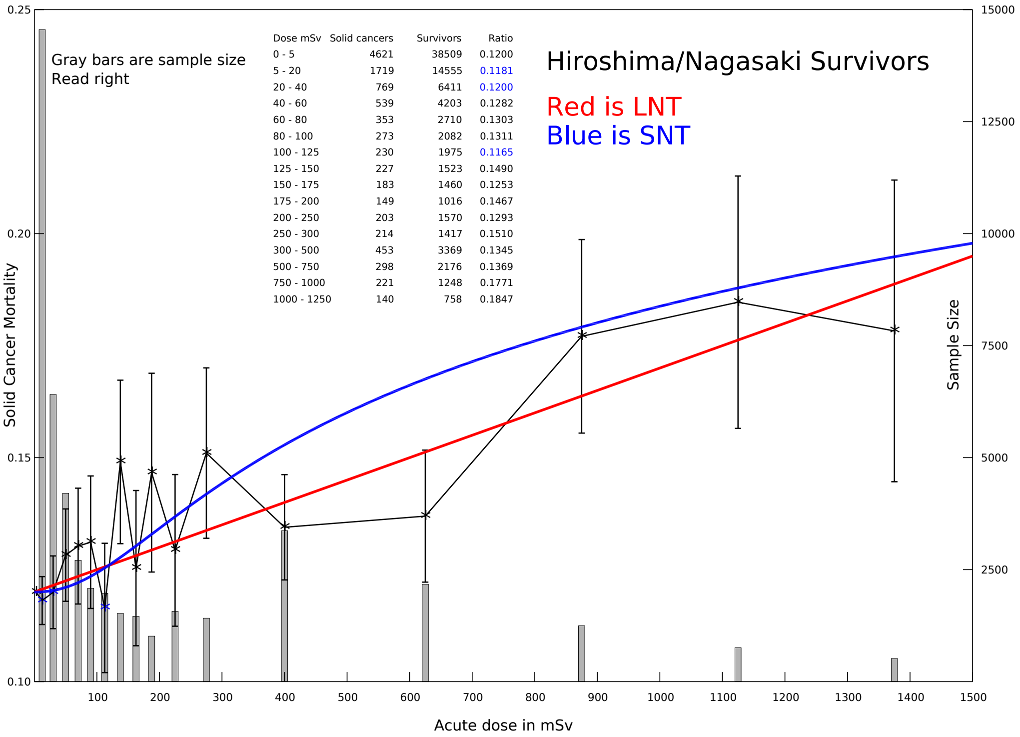


Dose mSv	Solid cancers	Survivors	Ratio
0 - 5	4621	38509	0.1200
5 - 20	1719	14555	0.1181
20 - 40	769	6411	0.1200
40 - 60	539	4203	0.1282
60 - 80	353	2710	0.1303
80 - 100	273	2082	0.1311
100 - 125	230	1975	0.1165
125 - 150	227	1523	0.1490
150 - 175	183	1460	0.1253
175 - 200	149	1016	0.1467
200 - 250	203	1570	0.1293
250 - 300	214	1417	0.1510
300 - 500	453	3369	0.1345
500 - 750	298	2176	0.1369
750 - 1000	221	1248	0.1771
1000 - 1250	140	758	0.1847

Figure 6.1: Linear versus Sigmoid NT for RERF Solid Cancers: 0 to 3,000 mSv Acute Dose

Figure 6.1 is the kind of big picture that the RERF likes to show us. From this broad perspective, there's not that much difference between the two approaches. From this distance, just about any family of curves can be made to look like a fit.[3] At the top end, the two curves diverge as the logistic fit slowly heads for the assumed top end of 1.0 while the LNT line shoots up to where it will kill the same people over and over. But aside from having a model that does not do anything nonsensical, we are not really that interested in the high end. What counts is the low end.

Figure 6.2 takes a closer look at the portion of the curves below 1500 mSv. Now we begin to see some interesting differences between the two fits.



Dose mSv	Solid cancers	Survivors	Ratio
0 - 5	4621	38509	0.1200
5 - 20	1719	14555	0.1181
20 - 40	769	6411	0.1200
40 - 60	539	4203	0.1282
60 - 80	353	2710	0.1303
80 - 100	273	2082	0.1311
100 - 125	230	1975	0.1165
125 - 150	227	1523	0.1490
150 - 175	183	1460	0.1253
175 - 200	149	1016	0.1467
200 - 250	203	1570	0.1293
250 - 300	214	1417	0.1510
300 - 500	453	3369	0.1345
500 - 750	298	2176	0.1369
750 - 1000	221	1248	0.1771
1000 - 1250	140	758	0.1847

Figure 6.2: Linear versus Sigmoid NT for RERF Solid Cancers: 0 to 1500 mSv Acute Dose

The zero slope at zero dose requirement forces the logistics curve lower in the very low dose end and pushes it to a steeper slope in the intermediate dose range. Radiotherapists have been

---

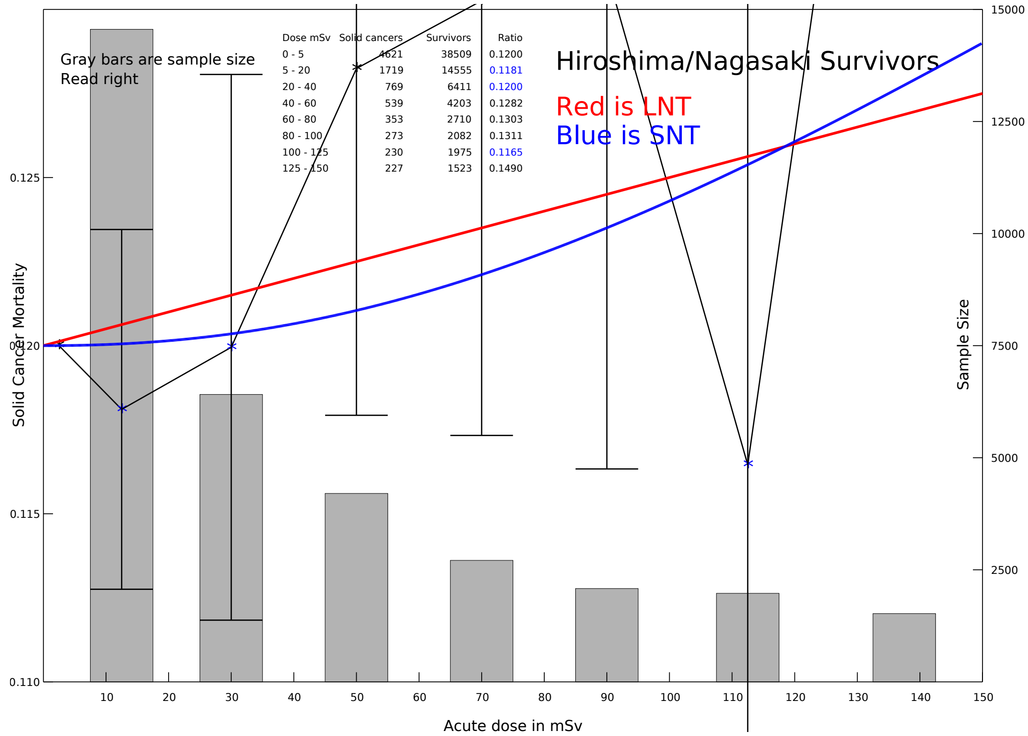
[3] Socol and Dobrzynski performed an insightful exercise.[237, page 11] They did a Monte Carlo in which the "data" was generated by their RERF sigmoid fit with its large sample variance. They showed you could fit a straight line to this scatter diagram and pass the weak statistical tests that LNTer's use.

making good use of the latter phenomenon for nearly a century. If the doctor can locate his dose so that the edge of the tumor is in the steep part of the curve, he can do a lot more damage to the tumor than to the surrounding healthy tissue. Here's a quote from the Royal College of Radiologists,[194].

> Dose-response relationships for tumour control are steep and a 4-5% dose increase might lead to a 10% increase in probability of tumour control.

It is often claimed that LNT is conservative. But that is only true at the low end. In the mid dose range, the logistic fit is higher. For this data, the cross over is slightly above 200 mSv. The best 5 parameter logistic fit is highly asymmetric. The high end portion of the "S" is far larger than the low end. In fact, the low end hook is barely visible in Figure 6.1. There is no reason to expect a symmetric curve. But the fact that the low end hook is small when viewed from the scale of Figure 6.1 is one of the reasons that has allowed Linear No Threshold to survive.

When we zoom in on the 0 to 150 mSv range, Figure 6.3, which is what we are really interested in, we start to see how large the ***relative*** differences are.



Dose mSv	Solid cancers	Survivors	Ratio
0 - 5	4621	38509	0.1200
5 - 20	1719	14555	0.1181
20 - 40	769	6411	0.1200
40 - 60	539	4203	0.1282
60 - 80	353	2710	0.1303
80 - 100	273	2082	0.1311
100 - 125	230	1975	0.1165
125 - 150	227	1523	0.1490

Figure 6.3: Linear versus Sigmoid NT for RERF Solid Cancers: 0 to 150 mSv Acute Dose

But to really appreciate how large this relative difference is, we need to look at the numbers, Table 6.1. The last column is just the Linear NT fit excess cancer mortality ratioed to the Sigmoid NT fit excess cancer mortality. At 100 mSv, the difference is a factor of two. As you move down in dose, this difference increases rapidly. At 25 mSv, the difference is a factor of 9. At 5 mSv, it is a factor of 60. Both fits ignore the reduced solid cancer mortality in the 20,000 person 5-20 mSv, and 20-40 mSv groups. But the logistic curve clearly does a less bad job of fitting the data in this range than the straight line.

Cancer LLE years=12.00 2023-09-22T23:37:59Z

Acute Dose mSv	SNT Fit	LNT Fit	LNT LLE days	SNT LLE days	LNT excess risk over SNT excess risk
0.02	0.120000000	0.120001	0.0042	0.00000018	22514.38
0.10	0.120000001	0.120005	0.0208	0.00000617	3370.35
0.50	0.120000047	0.120024	0.1040	0.00020618	504.53
1.00	0.120000213	0.120048	0.2081	0.00093431	222.68
2.50	0.120001572	0.120119	0.5201	0.00688624	75.53
5.00	0.120007123	0.120237	1.0403	0.03120022	33.34
10.00	0.120032256	0.120475	2.0805	0.14128196	14.73
15.00	0.120077968	0.120713	3.1208	0.34149949	9.14
20.00	0.120145690	0.120950	4.1610	0.63812132	6.52
25.00	0.120236347	0.121187	5.2012	1.03519920	5.02
30.00	0.120350529	0.121425	6.2415	1.53531576	4.07
40.00	0.120650571	0.121900	8.3220	2.84949908	2.92
50.00	0.121046014	0.122375	10.4025	4.58154318	2.27
80.00	0.122769476	0.123800	16.6440	12.13030655	1.37
100.00	0.124301918	0.124750	20.8050	18.84240291	1.10
200.00	0.134220286	0.129500	41.6100	62.28485239	0.67
300.00	0.144256410	0.134250	62.4150	106.24307699	0.59
500.00	0.160060512	0.143750	104.0250	175.46504373	0.59
1000.00	0.183778013	0.167500	208.0500	279.34769700	0.74

Table 6.1: Linear NT excess cancer mortality vs Sigmoid NT excess cancer mortality

To really see the difference between the two models at the low end, we need a log-log plot, Figure 6.4. In this graph I've switched to plotting excess cancer mortality. At 0.1 mSv, the SNT curve is 6000 times lower than the LNT curve and the models are diverging very rapidly.[4]

According to the logistic fit and a conservative mortality calculation, a 20 mSv acute dose is equivalent to a Lost Life Expectancy (LLE) of 0.3 days.[5] This is far less than the risks we accept without any thought in the normal course of living. According to Cohen, being a pedestrian has an LLE of 36 days.[51] Bernie estimates automobile use costs us 207 days, Figure 6.5. He puts

---

[4] At low doses, SNT approaches a power law.[96][Table 3] In this case, the exponent is 2.18 versus LNT's 1.00.

[5] The LLE's are based on a lost life expectancy given that a person gets cancer of 12 years.[238] This is a USA number which is on the high side world wide.

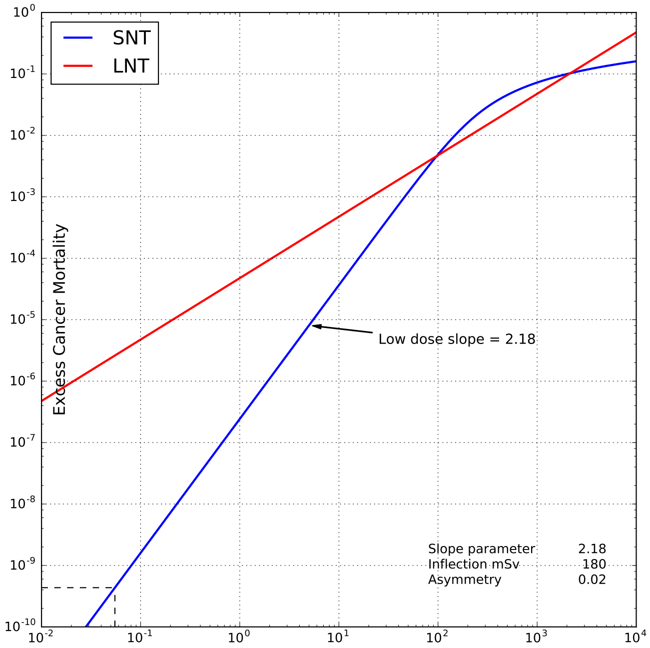


Figure 6.4: Loglog plot of Linear versus Sigmoid NT Excess Cancer Mortality

the LLE associated with abandoning the 55 mph speed limit at 2.0 days. Relaxing the speed limit had overwhelming political support. The body politic judged that the benefits of relaxing the speed limit far outweighed the costs. Airline travel is perceived to be extremely safe. Bernie puts the LLE of airline travel for the average American at 0.4 days. In the case of nuclear power, we should make the same kind of comparison. Dockery and Pope estimate that living in a mildly polluted city has an LLE of 292 days and living in a badly polluted city has an LLE of 1,150 days.[73] These are the sort of numbers we should compare with Table 6.1. My standard is coffee drinking. According to Cohen, this vice is costing me 6 days. That tells me I don't worry about activities with an LLE of 6 days or less. And I'm definitely not in favor of a 55 mph speed limit.

Another way to look at this is in terms of dollars. Value of life figures vary widely; but an upper bound is the US dialysis standard of $129,000 per year or $350 per day. In these terms, a 20 mSv acute dose has an LLE cost of $115. But our focus should be on chronic doses.

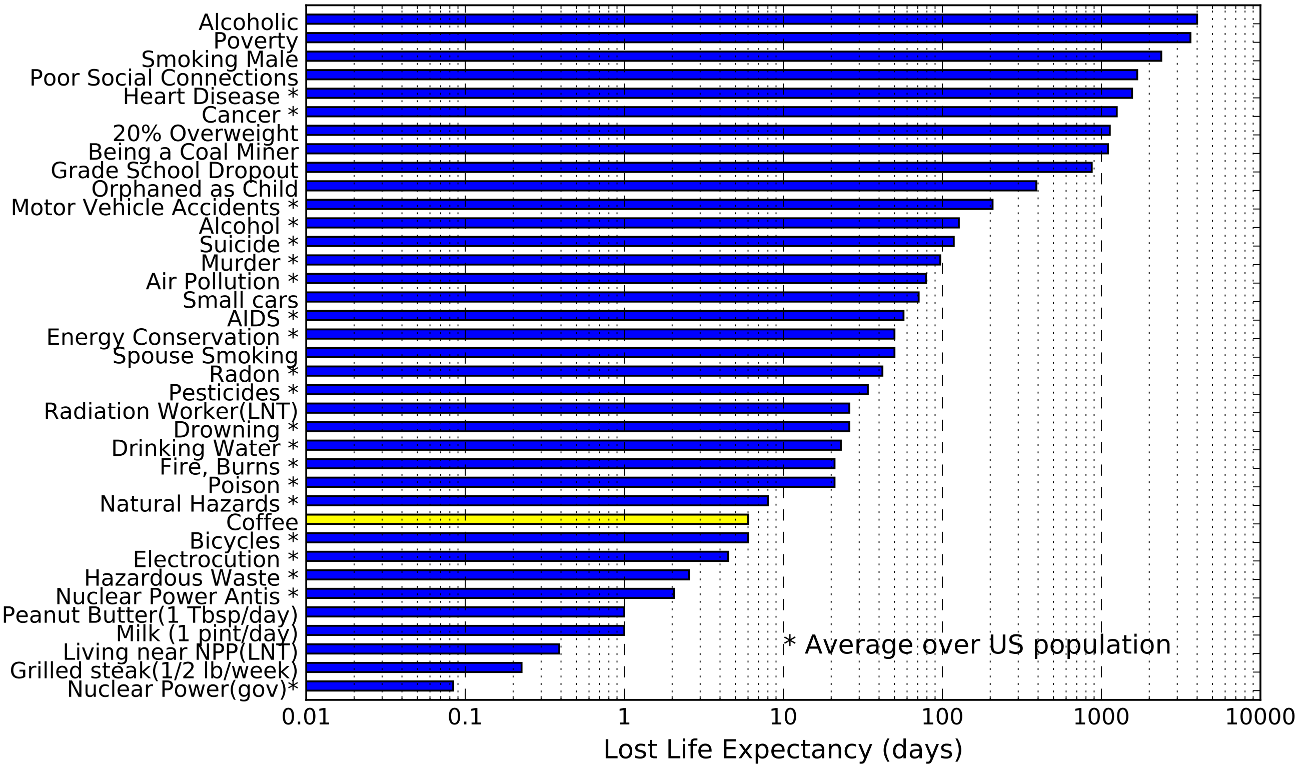


Figure 6.5: Days of Lost Life Expectancy from every day behavior, reference [51].

6.3 Handling Chronic Dose

In the great majority of real world radiation releases, the dose is received over an extended period. LNT for which dose rate is irrelevant claims this make no difference. The only thing that counts is the cumulative dose. Table 5.19 says that's nonsense. What counts is keeping the damage rate below the repair rate. The dose in the repair period is what's important. How can we represent the importance of dose rate starting from acute dose data?

Here's one possibility:[6]

1. Choose a repair period. We know most of the intra-cellular mechanisms operate on time scales of several hours or less. Berkeley found that cell repair was essentially complete in about 10 hours, Section **??**, even for awfully high doses. If we assume a repair period of a day, we are on the conservative side.
2. Treat each repair period as an independent event. Either that day's damage is fully repaired on not. Repair in this context includes successful elimination of any damaged but unrepaired cells. Either we get cancer from that day or we don't. This means we can add the daily probabilities to obtain the total probability of contracting cancer; but in so doing we have to weight each day's probability with the probability of not getting cancer up to that point. Otherwise, we could end up with a probability over 1. Put another way, we are computing the probability of at least 1 cancer.
3. Apply our logisitic curve to each repair period separately, assuming incorrectly that all the radiation received in that period is received as an acute dose at the start of the period. This conservative fabrication allows us to use our acute dose logistic figures to (over-)estimate chronic dose risk.[7]

The resulting Sigmoid No Threshold model has several important implications:

1. There is a cumulative effect. The daily probabilities add. And since the LLE is just the probability of cancer times the average reduction in life due to cancer, the LLE's also add.[8] However, we are adding LLE's, not doses. If the dose in day 1 is 25 mSv, and in day 2 is 10 mSv, and in day 3 is 5 mSv, then we can add the LLE's of each of those days to end up with $0.031 + 0.141 + 1.035 = 1.208$ days.[9] This is quite different from the LLE associated with an acute dose of $25 + 10 + 5 = 40$ mSv or 2.849 days.

   Suppose a person lives in a area which has a high background dose rate of 7.3 mSy/y. Then his daily dose is 0.02 mSv which according to Table 6.1 has an LLE of 0.00000018 days. If he lives in this area for 80 years (29,200 days), the model claims his LLE will be

---

[6] Allison has suggested a similar procedure.[8]

[7] If harm is linear in dose, it does not matter what the repair period is. However, you chop up the dose, when you combine the individual periods, you will end up with the same harm. Linear and cumulative are not two separate assumptions. Each implies the other.

[8] Our ethical judgement that all life-years are equal allows us to do this.

[9] I'm neglecting the probability of already having cancer adjustment which in this case will be very close to 1.00.

$29,200 \cdot 0.00000018 = 0.005$ days.

The Sigmoid No Threshold model is consistent both with the fact that we can't see any increase in cancer incidence in high background dose areas, and the fact that an ***acute*** dose of much more than 100 mSv will generate observable increases in cancer.[10] According to LNT, this dose rate should have increased our septuagenarian's chance of becoming a cancer patient by 4%.[251, Table ES-1] This is an easily observable number.

But what about the radium dial painters? I was afraid you would ask that. Table 6.2 shows the SNT and LNT numbers for a range of daily doses with an exposure period of 20 years. Since we are dealing with very high dose rates over an extended period, we adjusted the LLE in each repair period by the probability of reaching that period without fatal damage.

Repair period(days) = 1 2023-09-23T17:24:46Z
Cancer LLE years=12.00 Exposure period years = 20

Dose mSv /day	SNT Excess Risk	LNT Excess Risk	LNT LLE days	SNT LLE days	LNT excess risk over SNT excess risk
0.50	0.000	0.173	759.9	1.5	504.62
1.00	0.002	0.347	1519.8	6.8	222.85
2.00	0.007	0.694	3039.6	30.8	98.63
3.00	0.017	1.041	4559.4	74.2	61.43
4.00	0.031	1.388	6079.2	137.9	44.08
5.00	0.051	1.735	7599.0	222.1	34.22
6.00	0.075	2.082	9118.8	326.3	27.94
7.00	0.103	2.429	10638.6	449.7	23.66
8.00	0.135	2.776	12158.4	590.9	20.58
9.00	0.171	3.123	13678.2	748.2	18.28
10.00	0.210	3.470	15198.1	919.5	16.53

Table 6.2: SNT/LNT Lost Life Expectancy, constant daily dose for 20 years, 1 day repair period

According to LNT, a daily dose of 8 mSv over 20 years will kill you with probability 0.94. In fact, Albert Stevens survived a daily dose of 8 mSv for 20 years with little apparent harm. SNT claims he had a 13% increased chance of dying of cancer. No real conflict there.

According to Table 5.19, there were no bone cancers in the radium dial painters, unless the dose rates were in excess of 10 mSv/day. But LNT claims 10 mSv per day over 20 years will almost certainly kill you. Almost all these ladies should have gotten cancer. SNT with a 1 day repair says each lady at 10 mSv/day had a 21% chance of dying of bone cancer, but none did. We would need the individual dial painter dose profiles to make a stronger statement; but for now all we can say is both models over-predict the dial painter harm: LNT outrageously so, SNT with a 1 day repair period somewhat less outrageously so.

---

[10] In the Kerala study, a group of people received 0.164 mSv per day for 10.5 years (3833 days). The SNT excess cancer risk is 0.0002%, which over-predicts the actual data. The LNT excess cancer risk for this group is 6%.

2. This brings us to an interesting question. How does SNT jibe with the pre-1950 NCRP/ICRP tolerance dose of 1 mSv/day? The SNT lifetime cancer mortaltiy risk for a constant daily dose of 1 mSv is 0.6%, Table 6.3, with an LLE of 27 days. This would be difficult to detect, which is the tolerance dose criteria. But SNT with a 1 day repair period is definitely more conservative than the 1 mSv/day dose rate.

Repair period(days) = 1 2023-09-23T16:56:55Z
Cancer LLE years=12.00 Exposure period years = 80

Dose mSv /day	SNT Excess Risk	LNT Excess Risk	LNT LLE days	SNT LLE days	LNT excess risk over SNT excess risk
0.50	0.001	0.500	2191.8	6.0	364.06
1.00	0.006	0.750	3286.7	27.2	120.77
2.00	0.028	0.938	4106.8	122.0	33.67
5.00	0.188	0.999	4374.7	823.0	5.32

Table 6.3: SNT/LNT Lost Life Expectancy, constant daily dose, 80 years, 1 day repair period

3. Unlike Linear No Threshold, dilution is an effective countermeasure even if it increases the exposed population proportionally.[11] If we are able to dilute from a single person dose of 50 mSv's down to a dose of 1 mSv, even at the cost of increasing the exposed population by a factor of 50, the collective LLE goes from 2.48 days to $50 \cdot 0.0005 = 0.025$ days.
4. Under SNT, we shall see in the next section, in a release of radiation, we can count everybody's dose. There is no need for an arbitrary cut off. There is no need for the preposterous inconsistency of accepting the Linear No Threshold hypothesis, but then claiming we can ignore its implications at low dose. UNSCEAR for one appears to hold this indefensible position.[260, page 64]

6.4 SNT and your choice of residence

If you are an LNTer, background radiation levels might well affect the choice of where you live. Table 6.4 shows the LNT and SNT LLE's for a range of background levels.

Using the EPA numbers, Figure 6.28 living in a high background state will cost each of your family members something like 100 days of life on average, compared to living in a low background state. 100 days is roughly the LLE associated with car crashes. From time to time, we all worry about losing a loved one to a car crash. Just about all of us know someone who died in a car crash. If you are not similarly worried about getting cancer from living in a high radiation state, then you are not an LNTer.

---

[11] After Chernobyl, Swedish dairy farmers discovered that some of their milk was contaminated with Cesium-137 above the legal limit of 300 Bq per liter. They proposed that their milk be diluted with uncontaminated milk on a 10 to 1 ratio, reducing the contamination to 30 Bq per liter. The proposal was rejected on the grounds that the collective risk would be the same.[120] LNT in action.

Life years = 80 2023-09-22T22:57:23Z
Repair period days= 1 Cancer LLE years=12.00

Dose mSv /yr	SNT Excess Risk	LNT Excess Risk	LNT LLE days	SNT LLE days	LNT excess risk over SNT excess risk
1.00	0.00000002	0.00380	16.6	0.0001	235092
2.00	0.00000007	0.00760	33.3	0.0003	103746
4.00	0.00000033	0.01520	66.6	0.0015	45788
6.00	0.00000080	0.02280	99.9	0.0035	28377
8.00	0.00000150	0.03040	133.2	0.0066	20209
10.00	0.00000245	0.03800	166.4	0.0107	15530

Table 6.4: SNT/LNT Lost Life Expectancy, constant daily dose for 80 years, 1 day repair period

6.5 SNT and Government Regulatory Limits

Bureaucrats love to proscribe limits. All the nuclear regulatory agencies have promulgated their ideas of what is an acceptable risk. Based on these pronouncements and LNT, they have derived maximum acceptable dose rates. What are the implications for these regulatory dose rates if the regulators switched from LNT to SNT?

The NRC has something they call a Quantitative Health Objective (QHO). For cancer, the QHO is the annual risk of cancer fatality to an individual living within 10 miles of a nuclear plant should not exceed 2 in one million. If we assume an 80 year life, to first order this translates to 160 in one million (0.00016).

The EPA has a somewhat similar standard called Maximum Individual Risk (MIR). The EPA's lifetime MIR for contacting cancer is 100 in one million. Since roughly half of cancers eventually prove mortal, the EPA's MIR is 50 in one million (0.00005) fatalities, about one-third the NRC's QHO.

The UK Health and Safety Executive (HSE) has three mortality levels:

1. 1 in 10,000 per year is the "tolerability" limit.
2. 1 in 100,000 per year is their target for nuclear power plants,
3. 1 in 1,000,000 is so “broadly acceptable" that there are no ALARA requirements. (The Brits term for ALARA is As Low as Reasonably Practical (ALARP).)

All these limits strike me as arbitrary and ad hoc. There's no explicit attempt to balance risk versus benefit. The EPA appears to recognize this. They allow themselves the ability to adjust the MIR, presumably because the cost of abiding by the 100 in one million number is judged too high. The EPA has accepted 200 in one million in several cases. The NRC QHO is is not even operational. It is not at all clear how you would determine compliance. But let's assume like the EPA they really mean the most exposed person, and translate the limits into dose rate profiles.

Table 6.5 shows the allowable lifetime constant dose rate for a range of MIR's using LNT and SNT to convert dose rate profile into cancer incidence.

Table 6.5: LNT and SNT constant lifetime dose rates for a given cancer mortality rate

	Lifetime Risk of fatal cancer	LNT mSv/d	SNT mSv/d	LNT mSv/y	SNT mSv/y	SNT dose rate to LNT	Lost Life Days
HSE max tol	0.00800	5.767e-03	1.058e+00	2.10	386.03	183	35.04
HSE NPP	0.00080	5.765e-04	3.679e-01	0.21	134.28	638	3.50
NRC QHO	0.00016	1.153e-04	1.758e-01	0.04	64.18	1526	0.70
EPA MIR max	0.00010	7.206e-05	1.417e-01	0.03	51.74	1967	0.44
HSE no alara	0.00008	5.763e-05	1.279e-01	0.02	46.69	2220	0.35
EPA MIR	0.00005	3.603e-05	1.031e-01	0.01	37.64	2862	0.22

The bureaucratic consensus seems to be that somewhere around 100 in one million (0.0001) is an acceptable life time risk. For cancer, this translates to an LLE of less than a half-day, which is according to Cohen is the LLE of relaxing the 55 mph speed limit, which enjoyed overwhelming support.[51] This tells me that the EPA's definition of acceptable risk is almost certainly well below a democratically determined level. But for now let us assume this is society's definition of acceptable risk.

For LNT, this translates to a constant dose rate of 0.03 mSv per ***year***. For SNT, the corresponding dose rate is 0.14 mSv per ***day***. If you are an LNTer as EPA and NRC most stubbornly are, then the NRC's 1 mSv/y public dose is too lax. Even EPA's CERCLA superfund limit of 0.15 mSv/y is high. Interestingly, the UK tolerability limit combined with SNT comes up with a max "tolerability" dose rate which is almost the same as the NRCP/IRCP tolerable dose rate prior to 1950.

For now, the main point is that, if you assume that the EPA's view of acceptable risk is correct, the difference between the LNT max acceptable dose rate and the SNT max acceptable dose rate is a factor of roughly 3000. This leads to completely different policies. Under SNT, as we shall see, even a very large nuclear power plant release is no more harmful to the public than a major industrial casualty.

6.6 Sigmoid No Threshold and Chernobyl

6.6.1 Preamble

This section applies the Sigmoid No Threshold harm model to the release of radioactive material at Chernobyl. The goal is to estimate the public Lost Life Expectancy associated with the casualty. The analysis is meant to be illustrative only; but with luck we may be able to obtain some important insights.

6.6.2 UCS LNT Statistical Deaths

Even in a release as large as Chernobyl, dose rates above those in high background areas were confined to a few hundred thousand people.[36] However, the number of people exposed to a slightly elevated dose rates was in the hundreds of millions. LNT claims more cancers among the slightly elevated group than among those who have received unnaturally high dose rates. The usual work around is to gin up an arbitrary cut off, and ignore doses below that cut off. Such an inconsistent procedure persuades no one, nor should it. If we must have a simple model, let's have a simple model we can actually use.

The Union of Concerned Scientists does LNT right.[98] Table 6.6 compares their analysis of cancers due to Chernobyl with an SNT based analysis using the same numbers.[12] UCS's estimate is 26,400 statistical deaths excluding thyroid cancer. Nearly 80% of these “deaths" resulted from dose rates that are well below background in large parts of the planet.

Table 6.6: UCS estimate of Chernobyl cancer statistical deaths excluding thyroid.

Group	Population	Average Dose mSv	Exposure Days	Statistical Deaths LNT	SNT
liquidators	530,000	145.00	14	4380	258
Actual was about 220,000 at these dose rates					
evacuees	115,000	43.00	1	282	87
SCZ residents	270,000	59.00	365	908	0.40
Other contaminated	6,400,000	9.00	365	3283	0.16
Other USSR	92,000,000	0.90	365	4720	0.015
Other Europe	500,000,000	0.33	365	9405	0.0090
Other N. Hemis.	3,000,000,000	0.02	365	3420	0.0002
				26398	346

In contrast, SNT claims the focus should be completely on the people who lived in the vicinity of the plant and the liquidators.[13] This is the only point to take away from Table 6.6. Our job now is to try and do the SNT column correctly.

---

[12] The UCS liquidator numbers are clearly inflated. The numbers from the All Union Distribution Register are 1986: 138,390, 1987: 85,556, 1988: 26,134, 1989: 43,020. The 1986 liquidators accounted for almost all the high dose rate doses.

[13] And in doing so, we must somehow estimate the individual dose rates through time. We cannot use group averages as I have done in Table 6.6.

6.6.3 The Golikov Model

Radioactive release analysis must start out with an estimate of the dispersion and contamination by major isotope through time. This is usually measured by the air dose rate 1 m above ground in μGy/h.[14] Then we need a method for converting the outside air dose rate to individual effective doses by day for all the members of the population. To be realistic such a model must:

1. Model not just the radioactive decay; but also the *weathering* and shielding by type of location, or *locale*. Weathering refers to the migration of the isotope deeper into the soil, or its being washed away, or any process other than radioactive decay that reduces the air dose rate at a location. Weathering is particularly important for cesium.
2. Model the fraction of the time various population groups spend in each locale.
3. Convert the air dose in grays to absorbed dose in sieverts.
4. Account for the variation in absorbed dose within each population group. SNTers cannot use average doses.

Golikov attempted such a model for Chernobyl.[95] He divided everything into Rural and Urban. He then divided the Rural/Urban Locales and Populations, as shown in Tables 6.7 and 6.8.

Table 6.7: Golikov Locales

Rural	Wood Home	Brick Home	High Rise Apartment	Work Shop	Office	Outside	Work Yard	Ploughed Field	Virgin land
Urban	Wood Home	Brick Home	High Rise Apartment	Office	Dirt	Paved	Park	Garden	Virgin land

Table 6.8: Golikov Population Groups

Rural:	Indoor Workers	Outdoor Workers	Pensioners	School Kids	Pre-school kids
Urban:	Indoor Workers	Outdoor Workers	Pensioners	School Kids	Pre-school kids

He then developed weathering factors for undisturbed land by measuring the migration of the main isotopes into the soil.[15] He then estimated *locale factors*, which is the air dose in each locale relative to outdoors in undisturbed land, by a sample of actual measurements. Some of the locale factors are time dependent, since weathering is not really exponential. He produced a 2x5x9 table of *occupancy factors* by surveying a sample of the Russian population in the district nearest Chernobyl. He used 0.7/0.8/0.9 for his Gy to Sv conversion factors for adults/school kids/pre-school children.

Finally, he used dosimeters to measure the actual dose received for a sample of Russians in the district nearest Chernobyl, and then fitted a lognormal dose distribution for each group. It

---

[14] Most dosimeters and many authors call this μSv/h; but μGy/h would be a better name, and I will use it when I'm referring to the air dose rate.

[15] He picked a 'average' soil for this purpose. A better model would account for type of soil.

turned out the highest 5 percentile absorbed about twice the dose as the median in each group. The Golikov model could be improved in any number of ways; but, for our illustrative purposes, it is a useful starting point.

If we accept SNT as our model of radiation harm, we can then convert these daily dose profiles by group to Lost Life Expectancies (LLE). In doing so, we must be careful to compute the dose received by each sub-group, each 5 percentile in the group's lognormal dose distribution, and calculate that sub-group's LLE, before combining sub-group LLE's. SNT gives far more weight to the top 5 percentile, than to the average. SNT focuses strongly on the people who absorb the highest dose.

6.6.4 Chernobyl Release Amounts

In all the nuclear power plant releases to date, almost all the radiation harm to the public was due to the four isotopes shown in Table 6.9.

Table 6.9: Four Most Harmful Isotopes at Chernobyl

Isotope	Half-life	Release PBq	Photon fraction
131I	8.021d	1760.0	0.587
134Cs	2.061y	54.0	0.069
137Cs	30.188y	85.0	0.052
132Te	3.230d	1150.0	0.293

^{132}Te decays to ^{132}I which decays in 2.3 hours. Most of the radioiodine is gone in a matter of weeks. The fact that, as a practical matter, we only need to worry about iodine and cesium, simplifies things a lot.[16] Iodine goes to the thyroid; but the only real pathway is through ingestion which can pretty easily be controlled since the half-life is short. At Fukushima, the Japanese did a good job controlling local food, until the radioactive iodine had decayed away. Ingested cesium distributes itself pretty evenly in soft tissue. Even if cesium is ingested, the biological half-life in humans is about 70 days, or in the case of ^{137}Cs, about 0.6% it's radioactive decay half-life. As long as you control contaminated food, the cesium dose is largely external.[17]

But attempts to control contaminated food after Chernobyl were not very effective. Reference [23] claims roughly half the dose was internal from cesium ingestion. For now, we will accept this claim and simply double the external dose in our Chernobyl calculations. This is a conservative assumption, at least for the high external dose rate groups.

---

[16] Radiation protection people divide radiation into low LET (spread out) and high LET (highly localized). There is some evidence that there are qualitative differences in the body's response to high LET as opposed to low LET.[27] Low LET damage is very similar to the damage generated by normal metabolism. Iodine and cesium radiation is all low LET.

[17] This does not necessarily mean destroying contaminated animals. For example, the biological half-life of cesium in sheep is 2 to 3 weeks.[105][p 39] The sheep need only be fed uncontaminated food for a few months, and most of the radiocesium will be cleared.

6.6.5 The Evacuations

The release effectively ended on May 6, Figure 6.6.

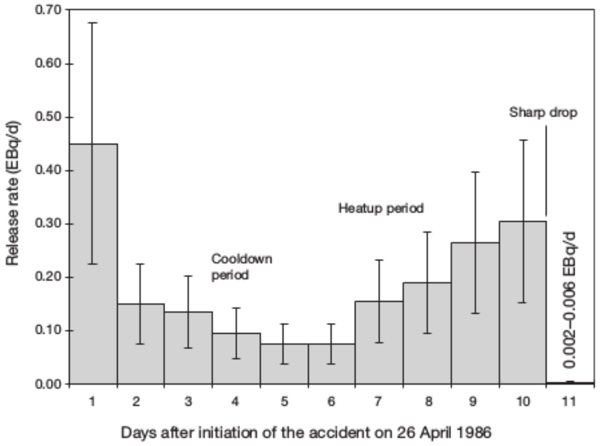


FIG. 3.1. Daily release rate to the atmosphere of radioactive material, excluding noble gases, during the Chernobyl accident. The values are decay corrected to 6 May 1986 and are uncertain by ±50% [3.1].

Figure 6.6: Chernobyl release rates 27 April to May 6

The evacuations took place in stages:

1. The town of Pripyat (49,360 people) and the neighboring village of Yanov (254 people) were evacuated on 27 April. Both are about 3 kilometers from the plant. The air dose rate in Pripyat at the time was 10 to 100 μGy/h, but this was early in the release.
2. Between 30 April and 3 May, 10,090 Ukrainians living within 10 km of the plant were evacuated.
3. Between 2 May and 7 May, 11,358 Belarussians living within 30 km of the plant were evacuated.
4. Between 3 May and 7 May, 28,133 Ukrainians living in the 10 to 30 km were evacuated. This included 14,000 residents of the town of Chernobyl.
5. Between 3 June and 10 June 6,017 Belarussians living outside 30 km were evacuated.
6. Between 14 May and 16 August, 2585 Ukrainians outside the 30 km zone were evacuated. Reference [259][page 473] says the 10 May air dose rate for these areas was 42 to 166 μGy/h.
7. In August and September, another 29 Belarussian villages totaling 7350 peoples outside 30 km were evacuated. The outside 30 km evacuees appears to be based on limiting the 1st year dose to 100 mSv. By autumn of 1986, 116,000 people had been evacuated.
8. ***Four years later***, in 1990, after mapping the ground contamination, another 220,000 people were evacuated from areas in which the contamination was greater than 555 Bq/m2.

Evacuation of Pripyat The city of Pripyat, 2.5 km from the plant, and the village of Yanov were evacuated about 36 hours after the first release. This involved nearly 49,500 people, 49,000 from Pripyat itself.[18] Figure 6.7 shows the initial dose rates near the reactor.[19]

Portions of Pripyat started out at about 1000 μGy/h.

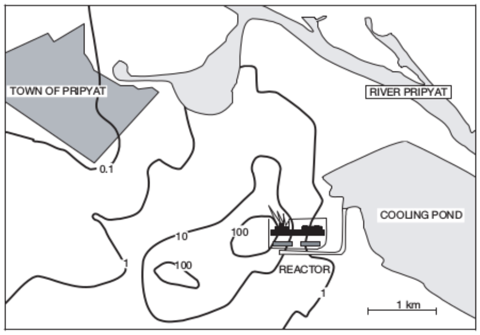


FIG. 6.3. Measured exposure rates in air on 26 April 1986 in the local area of the Chernobyl reactor. Units of isolines are R/h (1 R/h is approximately 0.2 Gy/d) [6.12].

Figure 6.7: Air dose rates next to reactor.[259][Fig XII] Multiply R/h by 8770 to get μGy/h.

Figure 6.8 shows the fall off in air dose rate in undisturbed locales (untilled fields, forests), for a location with an initial dose rate of 1000 μG/h. At Chernobyl, about 88% of the initial air dose rate was due to ^{131}I and ^{132}I. The radioiodine was effectively gone in two months. After that, the daily dose falls off far less rapidly. The long term behavior is determined by ^{137}Cs and its weathering. Cesium binds to just about everything and most cesium compounds are highly soluble in water. Cesium will wash off buildings and pavement. In urban environments, ecological half-lives as low as a year or two have been observed. On the other hand, organisms such as mushrooms have the ability to concentrate cesium creating very localized hotspots.

According to our decay model, the current undisturbed land dose rate in Pripyat should be 6 μGy/h. This corresponds to about 0.9 μGy/h in paved areas and 3 μGy/h in urban parks. In fact, almost everywhere in the town the air dose rates are in the 0.2 to 1.0 μGy/h range, although you can find a few, very localized hotspots higher.[20] The decay model appears to be conservative; but not outrageously so.

---

[18] Actually 44,460 were evacuated on the 27th. About 5000 stayed behind, mostly plant workers. Later the plant workers commuted from more distant towns.[209]

[19] The great bulk of the non-volatile material including the fuel and the transuranics fell to the ground within 2 km of the reactor. This was consistent with earlier experiments in the US.[145]

[20] In 2009, one anti-nuke group was able to get a reading of 22 μGy/h, by touching the dosimeter to a mushroom in the cemetery, clearly not a 1 m above ground reading. Cemeteries are unusual in that the soil is rarely disturbed.

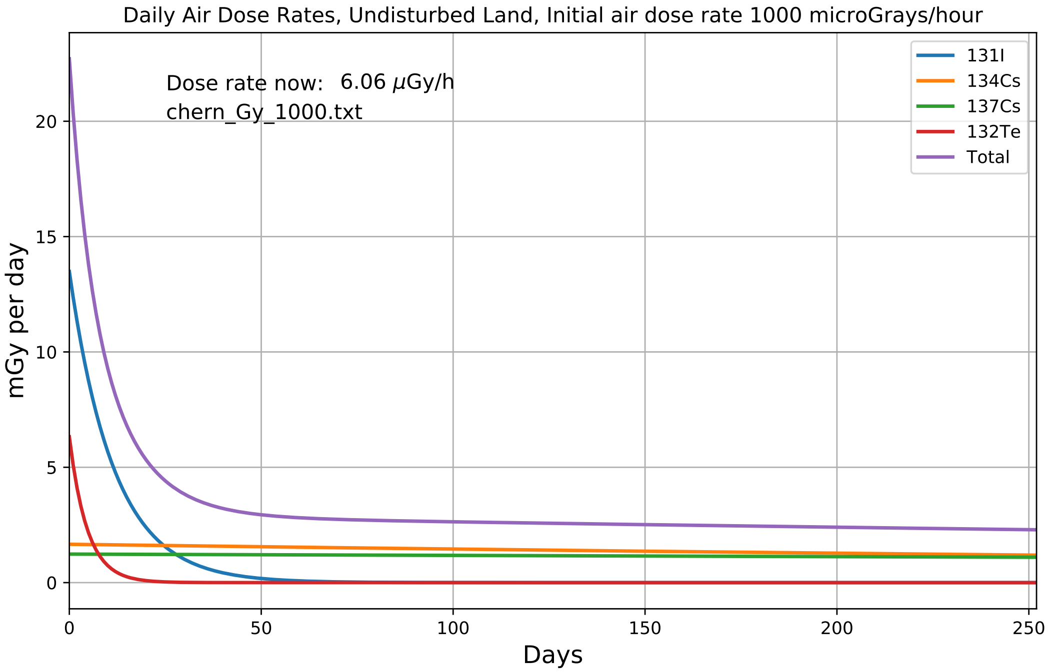
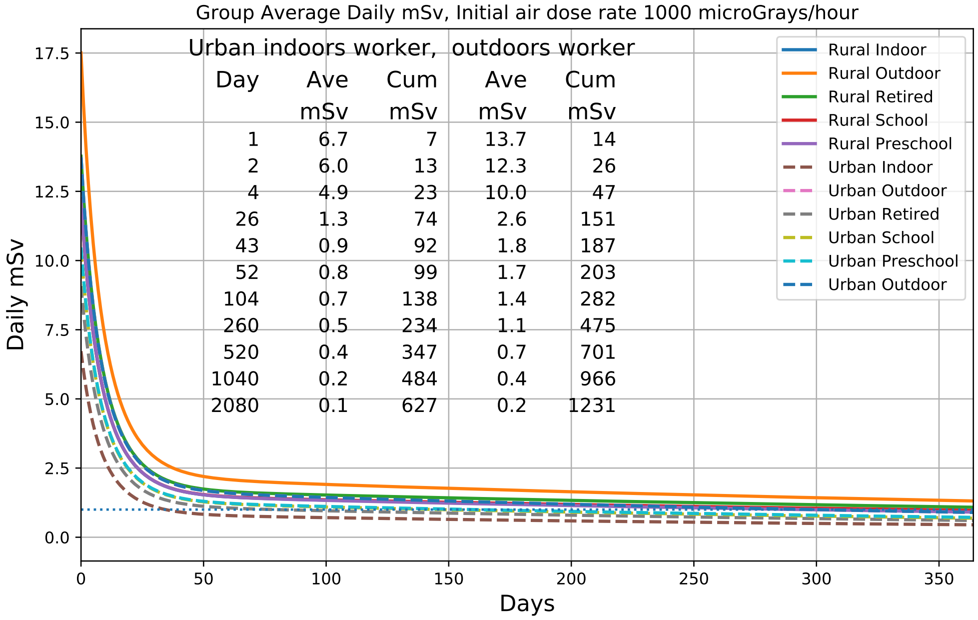


Figure 6.8: Daily air doses: open field locale, initial dose rate of 1000 μGy/h.

Figure 6.9 converts the air dose rate in grays per hour to effective daily dose in sieverts for each of the ten population groups, assuming no evacuation and no behavioral changes.

1. The urban indoors worker group average starts out at 7 mSv per day. By day 40, the dose rate is down to the pre-1950 tolerance rate of 1 mSv/day. However, the urban outdoors worker group starts out at 14 mSv/d and is not down to the old tolerance dose until about day 300.
2. The difference between the max dose group and the min dose group is close to a factor of three. Modest changes in behavior can reduce dose significantly.
3. The Top 5 percentile will absorb about double these doses. These are the people for which behavioral changes will make the most difference.
4. All these doses could be nearly halved by reasonable control of contaminated food.
5. Over time the cumulative dose builds up. But as we as we've seen, what counts is keeping the damage rate below the repair rate.



	Urban indoors worker,		outdoors worker	
Day	Ave mSv	Cum mSv	Ave mSv	Cum mSv
1	6.7	7	13.7	14
2	6.0	13	12.3	26
4	4.9	23	10.0	47
26	1.3	74	2.6	151
43	0.9	92	1.8	187
52	0.8	99	1.7	203
104	0.7	138	1.4	282
260	0.5	234	1.1	475
520	0.4	347	0.7	701
1040	0.2	484	0.4	966
2080	0.1	627	0.2	1231

Figure 6.9: Average Group Daily doses for a location that starts out at 1000 μGy/h.

If we adopt the SNT model of radiation harm, we can convert these daily dose rates into Lost Life Expectancies by group, Figures 6.10 and 6.11. The striking features of these two graphs is the differences between groups and within groups. A model that does not account for these differences is not much of a model at all.

The difference between the average urban, indoor worker, and someone who spends a lot of time outdoors in a rural environment is on average a factor of 7. The difference between the average urban, indoor worker, and the top 5 percentile rural outdoors sub-group is a factor of 30. For most Pripyans, the LLE is under 9 days. The worst case sub-group LLE is about 90 days; but this could be cut by a factor of 20 or more, by a combination of behavior changes and controlling contaminated food,

The other option is evacuation. Figures 6.10 and 6.11 indicate the LLE's can be reduced by at least a factor of 3 or more by a 3 month evacuation. This might make sense for high dose groups for whom the behavior changes are difficult. The value of extending the evacuation falls off quickly after that. As long as people have the option of spending more time indoors, it is hard to make a strong case for involuntary evacuation of everybody from these numbers. The decision to prevent relocation back to Pripyat for 40 years has no sound basis. In fact, Chernobyl Units 1 and 2, a few 100 meters from the stricken plant were restarted 5 and 6 months after the explosion.

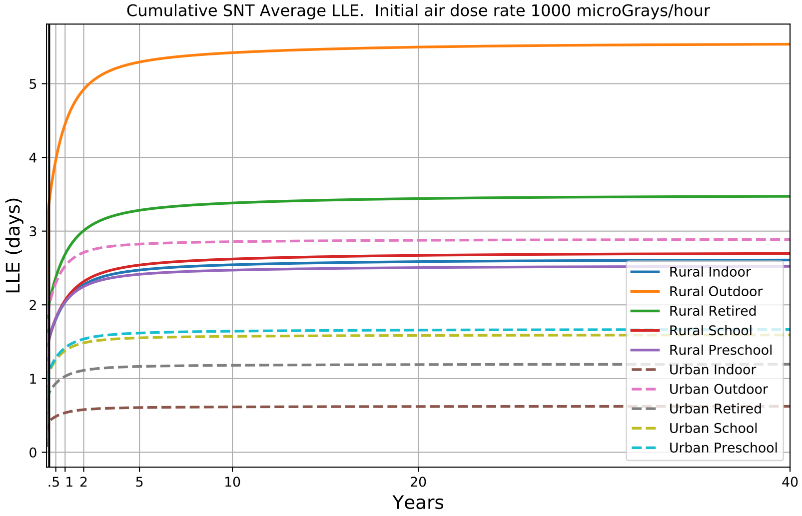


Figure 6.10: Chernobyl average group LLE's, 1000 μGy/h initial air dose rate.

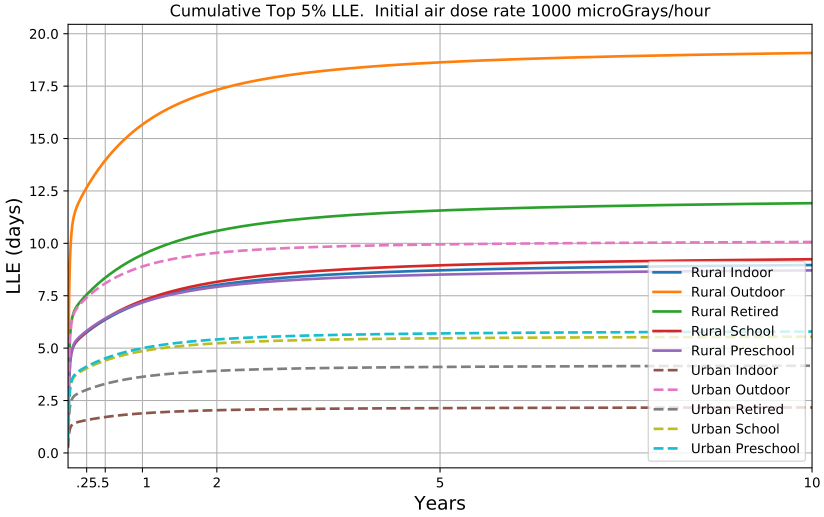


Figure 6.11: Chernobyl Top 5% sub-group LLE's, 1000 μGy/h initial air dose rate.

People whose life has been disrupted and possibly shortened should be compensated. Table 6.10 imagines we have a compensation schedule, based on a Value of Life-day.[21] The figure used, \$350 per day, is the US dialysis standard which is \$129,000 per year. The dialysis standard is very much on the high side worldwide.

Since it will be infeasible to identify who are the high and low dose individuals in each group, the compensation should probably be based on the highest dose sub-group. Under these assumptions, the average compensation for the urban population would be about \$2000 per person and \$5000 for the rural groups.

Table 6.10: Chernobyl Group LLE's for Pripyat.

Area = Pripyat			Initial air dose rate μGy/h = 1000.0		
Internal f = 2		USD/LLE-day = 350		2023-09-25T18:02:02Z	
Pop.=1000			Rural		
	Inside work	Outside work	Retired	School kids	Pre-school
Average LLE	2.61	5.54	3.47	2.70	2.52
Maximum LLE	9.19	19.49	12.23	9.50	8.89
Average EER	0.00060	0.00126	0.00079	0.00062	0.00058
Average mSv	2587	3463	2994	2718	2398
Group pop.	200	380	200	140	80
Group LLE	522	2103	694	377	202
Group USD ave	182,564	736,198	243,043	132,124	70,632
Ave \$/head	913	1937	1215	944	883
Max \$/head	3217	6820	4282	3326	3112
Group USD max	643,424	2,591,755	856,359	465,664	248,920
Pop.=49000			Urban		
	Inside work	Outside work	Retired	School kids	Pre-school
Average LLE	0.62	2.89	1.19	1.59	1.67
Maximum LLE	2.20	10.17	4.21	5.61	5.87
Average EER	0.00014	0.00066	0.00027	0.00036	0.00038
Average mSv	1097	2080	1457	1641	1758
Group pop.	13720	13230	9800	6370	5880
Group LLE	8553	38181	11706	10135	9793
Group USD ave	2,993,449	13,363,313	4,097,195	3,547,389	3,427,612
Ave \$/head	218	1010	418	557	583
Max \$/head	769	3558	1474	1963	2055
Group USD max	10,556,226	47,075,895	14,444,873	12,504,229	12,082,083

An interesting compensation question is how to handle evacuation. One possible approach is to ignore it; by which I mean each individual gets the same compensation whether or not he evacuates, but that's it. A young three person Pripyat family might choose to take their \$6,000 and start a new life elsewhere. An elderly couple might decide that a probably phony 2 days LLE is not worth the disruption and stay. All sorts of intermediate choices are possible, but the decision would be made by the individuals involved.

---

[21] The compensation should be based on the difference in the release LLE's and background LLE's. For SNT, this will be a tiny correction in all but the highest background areas; so we will ignore it. Another error on the side of conservatism.

6.6.6 Evacuation of the 3 to 10 km zone

Approximately 10,000 people were evacuated from the area outside 3 km but inside 10 km in the first week of May. A possible guess at an “average" initial dose rate in this area is 600 μGy/h. Since these were all small villages, the population is practically all rural. Under this assumption, the current air dose rate should be 3.6 μGy/h. Figure 6.12 indicates this is in the ballpark as an average for the 3 to 10 km zone. However, the distribution is very patchy, with a range of 10 or more. Actual releases take the form of radial plumes. In this case, the two main plumes were to the west southwest and to the north northeast. Using distance from the plant as a proxy for dose is highly inaccurate. Once again, an actual analysis would use the real, measured numbers by location.

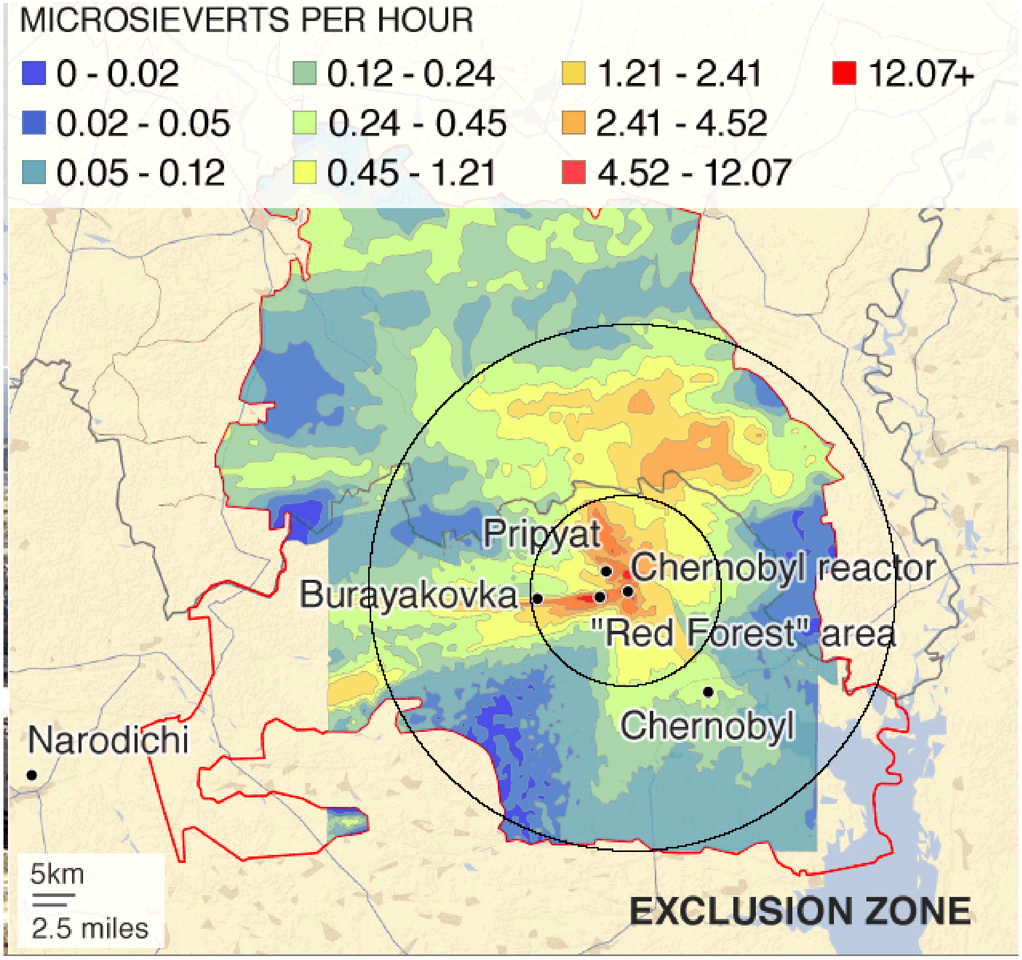


Figure 6.12: 2019 air dose rates (Gy’s called Sv) Chernobyl Exclusion Zone. Inner/outer circle 10/30 km radius. Source: BBC.

Table 6.11 shows the LLE's for this population assuming an initial 600 μGy/h. The LLE's fall off sharply with decreasing initial air dose rate. The worst case sub-group LLE's for 600 μGy/h are in the 4 to 7 day range. The average LLE's are around a day. Spending more time indoors, controlling contaminated food, compensation, and voluntary evacuation would seem to be indicated. The compensation and evacuation decision should be based on the actual initial dose rate for each village.

Table 6.11: Chernobyl Group LLE's for initial air dose rate of 600 μGy/h.

Area = 3-10 km			Initial air dose rate μGy/h = 600.0		
Internal f = 2		USD/LLE-day = 350		2023-09-25T18:02:02Z	
Pop.=10000			Rural		
	Inside work	Outside work	Retired	School kids	Pre-school
Average LLE	0.86	1.82	1.14	0.89	0.83
Maximum LLE	3.02	6.42	4.02	3.12	2.92
Average EER	0.00020	0.00042	0.00026	0.00020	0.00019
Average mSv	1552	2078	1797	1631	1439
Group pop.	2000	3800	2000	1400	800
Group LLE	1714	6916	2282	1240	663
Group USD ave	599,829	2,420,576	798,669	434,098	232,076
Ave $/head	300	637	399	310	290
Max $/head	1058	2245	1408	1093	1023
Group USD max	2,115,241	8,532,778	2,816,193	1,530,817	818,379
Pop.=0			Urban		
	Inside work	Outside work	Retired	School kids	Pre-school
Average LLE	0.20	0.95	0.39	0.52	0.55
Maximum LLE	0.72	3.34	1.38	1.84	1.93
Average EER	0.00005	0.00022	0.00009	0.00012	0.00012
Average mSv	658	1248	874	985	1055
Group pop.	0	0	0	0	0
Group LLE	0	0	0	0	0
Group USD ave	0	0	0	0	0
Ave $/head	72	332	137	183	192
Max $/head	253	1170	484	645	675
Group USD max	0	0	0	0	0

6.6.7 Evacuation of the 10 to 30 km zone

40,000 people were evacuated from the 10 to 30 km including 14,000 from the historic town of Chernobyl.[22] Outside of 10 km, the current air dose rates, Figure 6.12, are almost all in the 2 μGy/h range or less. Assuming an initial air dose rate of 300 μGy/h, leads to a current undisturbed dose rate of 1.8. Table 6.12 shows the corresponding LLE's. We are now dealing with worst case, no evacuation LLE's of less than 2, and average LLE's of less than a half a day. In areas with an initial air dose rate of 300 μGy/h, evacuation should be voluntary.

Table 6.12: Chernobyl Group LLE's for initial air dose rate of 300 μGy/h.

Area = 10-30 km			Initial air dose rate μGy/h = 300.0		
Internal f = 2		USD/LLE-day = 350		2023-09-25T18:02:02Z	
Pop.=26000			Rural		
	Inside work	Outside work	Retired	School kids	Pre-school
Average LLE	0.19	0.40	0.25	0.20	0.18
Maximum LLE	0.67	1.42	0.89	0.69	0.65
Average EER	0.00004	0.00009	0.00006	0.00004	0.00004
Average mSv	776	1039	898	815	720
Group pop.	5200	9880	5200	3640	2080
Group LLE	984	3970	1310	712	381
Group USD ave	344,229	1,389,503	458,368	249,119	133,185
Ave $/head	66	141	88	68	64
Max $/head	233	496	311	241	226
Group USD max	1,214,161	4,900,629	1,616,719	878,689	469,768
Pop.=14000			Urban		
	Inside work	Outside work	Retired	School kids	Pre-school
Average LLE	0.05	0.21	0.09	0.12	0.12
Maximum LLE	0.16	0.74	0.31	0.41	0.43
Average EER	0.00001	0.00005	0.00002	0.00003	0.00003
Average mSv	329	624	437	492	527
Group pop.	3920	3780	2800	1820	1680
Group LLE	177	791	242	210	203
Group USD ave	61,991	277,000	84,868	73,491	71,010
Ave $/head	16	73	30	40	42
Max $/head	56	258	107	142	149
Group USD max	218,665	976,999	299,354	259,222	250,468

---

[22] The town of Chernobyl is about 13 km from the plant to which it gave its name.

6.6.8 Outside 30 km

About 16,000 people were evacuated from outside 30 kilometers. Outside of 30 km, the current air dose rates, Figure 6.12, are almost all below 1 μGy/h range or less. Assuming an initial air dose rate of 150 μGy/h, leads to a current undisturbed dose rate of 0.9. Table 6.13 shows the corresponding LLE's. The worst case LLE is about 8 hours. The average group LLE's are in the 1 to 2 hour range. There was no need for anybody in areas that started out with less than 150 μGy/h to evacuate. The involuntary evacuation of the town of Chernobyl, where the air dose rates are now in the 0.1 to 0.2 μGy/h range, was tragically misguided.

Table 6.13: Chernobyl Group LLE's for initial air dose rate of 150 μGy/h.

Area = 30+ km			Initial air dose rate μGy/h = 150.0		
Internal f = 2		USD/LLE-day = 350		2023-09-25T18:02:02Z	
Pop.=16000			Rural		
	Inside work	Outside work	Retired	School kids	Pre-school
Average LLE	0.04	0.09	0.06	0.04	0.04
Maximum LLE	0.15	0.31	0.20	0.15	0.14
Average EER	0.00001	0.00002	0.00001	0.00001	0.00001
Average mSv	388	519	449	408	360
Group pop.	3200	6080	3200	2240	1280
Group LLE	134	539	178	97	52
Group USD ave	46,748	188,715	62,250	33,832	18,087
Ave $/head	15	31	19	15	14
Max $/head	52	109	69	53	50
Group USD max	164,899	665,654	219,578	119,337	63,801
Pop.=0			Urban		
	Inside work	Outside work	Retired	School kids	Pre-school
Average LLE	0.01	0.05	0.02	0.03	0.03
Maximum LLE	0.04	0.16	0.07	0.09	0.09
Average EER	0.00000	0.00001	0.00000	0.00001	0.00001
Average mSv	165	312	219	246	264
Group pop.	0	0	0	0	0
Group LLE	0	0	0	0	0
Group USD ave	0	0	0	0	0
Ave $/head	3	16	7	9	9
Max $/head	12	57	24	31	33
Group USD max	0	0	0	0	0

6.6.9 The 1990 Evacuation

Table 6.14 shows the SNT Lost Life Expectancy as a function of the 1990 ground contamination, assuming no evacuation. By this point, four years after the release, the dose was almost all ^{137}Cs. This table was constructed using daily doses computed by the method of reference [269][page 23] This method converts Bq/m2 to dose rates, attempting to account for both ingested material and weathering. The areas with a 1990 contamination of more than 555 kBq/m2 were evacuated. The additional Lost Life Expectancy in most of these areas, assuming they had not been forced to evacuate, is measured in minutes. Worst case is less than 4 minutes. For this, 220,000 people were uprooted from their homes.

Table 6.14: SNT Lost Life Expectancy as a Function of Initial (1990) Ground Contamination. Areas below line were evacuated.

1990 ^{137}Cs kBq/m2	SNT LLE days	Cum. mSv over 70 yrs
185	0.00002	41
370	0.00005	68
555	0.00009	95
740	0.00016	123
925	0.00025	150
1100	0.00035	176
1295	0.00049	205
1480	0.00064	232
2220	0.00149	341
2960	0.00272	450

This strange, belated evacuation was tragically nonsensical. We are dealing with annual doses of 1 to 7 mSv, dose rates which are routinely experienced by many millions of humans without any discernible harm. This tragedy was largely engendered by LNT's monomaniacal focus on cumulative dose. It appears to have been based on limiting the additional lifetime dose to 100 mSv. It should never have happened.

6.6.10 Total Residents LLE and Compensation, excluding thyroid cancer

Table 6.15 accumulates these LLE's over all groups in an area, and then over all areas. Under SNT, the total non-thyroid cancer, residential public LLE is about 300 life-years, assuming no behavior changes, no effective control of contaminated food, and no evacuation. This is roughly equivalent to an airplane crash that kills 8 people with an average life expectancy of 40 years. At $350 per day, a top end number, the total compensation would be about 130 million dollars. Once again the total LLE could be cut by a factor of 5 or more by behavior changes and controlling contaminated food.[23]

Table 6.15: Chernobyl SNT Compensation at $127,000 per LLE year, excluding thyroid cancer, 40 year cutoff.

chern				Internal factor = 2
Cancer LLE yrs: 12.00				$/life-day = 350
Area	Initial μSv/h	Population	LLE(days)	Compensation
Pripyat	1000	50000	82267	101,469,432
3-10 km	600	10000	12815	15,813,411
10-30 km	300	40000	8979	11,084,677
30+ km	150	16000	999	1,233,271
Total		116000	105061	129,600,793

Table 6.15 is illustrative only. In a real release analysis, we would use far more accurate numbers, based on the actual doses received. But I don't think the overall numbers are misleading, at least not on the low side. In 2019, a team from Harvard Medical School queried the Ukrainian National Cancer Registry.[143] They could find no systematic differences in the solid cancer incidence rates in the districts close to Chernobyl compared to the country as a whole, Figure 6.13, no pattern that pointed to increased incidence in the high dose districts.[24]

Breast cancer is one of the more radiosensitive diseases. Zupunski et al studied breast cancer incidence in the rayons (roughly counties) closed to the plant.[288] The rayon averaged dose rates varied by more than a factor of ten, Figure 6.14. There was no statistically significant difference in the breast cancer rate. If anything, the higher dose rayons tracked below the lower, Figure 6.15.

---

[23] Under SNT, the LLE goes at better than the dose squared. If we had not doubled the external dose to represent ingested dose, the LLE's would drop by close to a factor of five.

[24] According to LNT, there has been a 3% increase in solid cancers in the surrounding districts.[36] In a population of 270,000, this should be statistically detectable. The reference [36] calculation is the source of the “official" estimate of an eventual 4000 to 8000 “deaths" from Chernobyl.

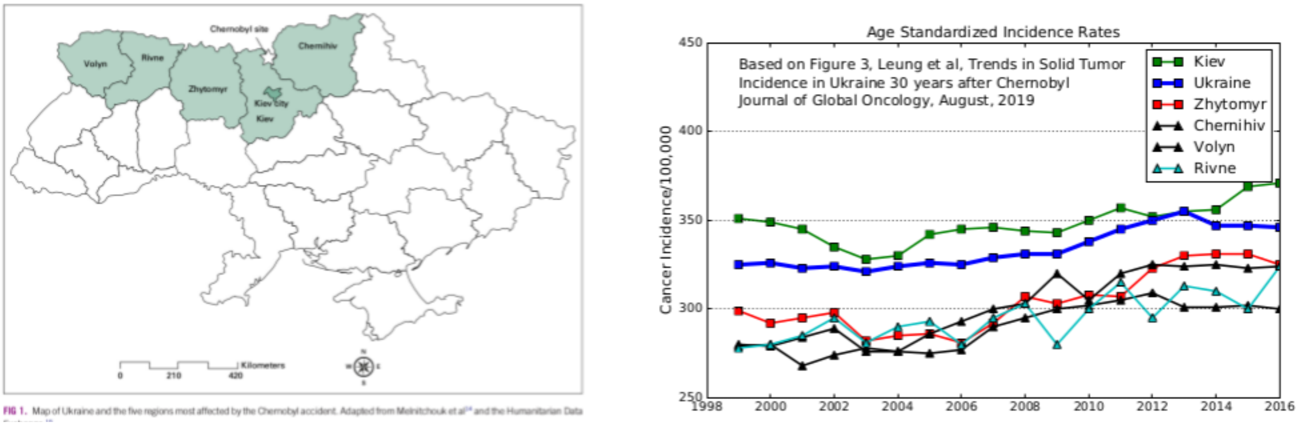


FIG 1. Map of Ukraine and the five regions most affected by the Chernobyl accident. Adapted from Melnitchouk et al[14] and the Humanitarian Data

Figure 6.13: Ukraine cancer incidence, blue line is all of Ukraine

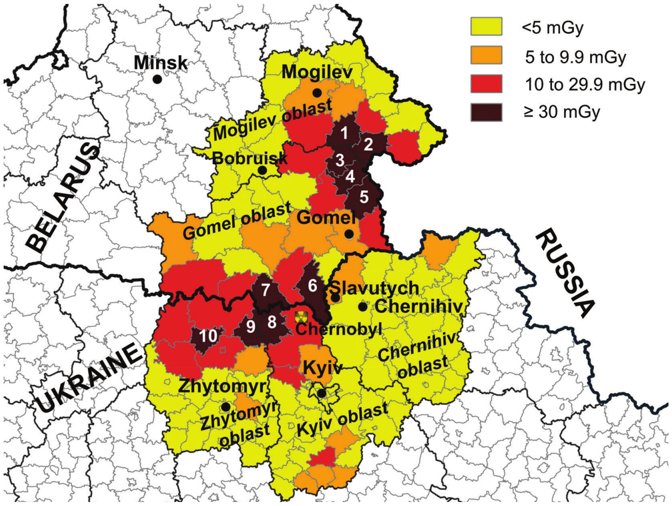


Figure 6.14: Breast Cancer Doses in the Rayons most affected by the release

Our model is based on conservative assumption after conservative assumption. From the point of the people living in the region, Chernobyl, properly handled, was at worst a bad airplane crash spread over 100,000 people. But this depends on a dose-response model that recognizes our ability to repair radiation damage, and the acceptance of this model by all concerned. Otherwise, the response will turn a bad casualty for the people living in the vicinity of the plant into something far worse, which is precisely what happened.

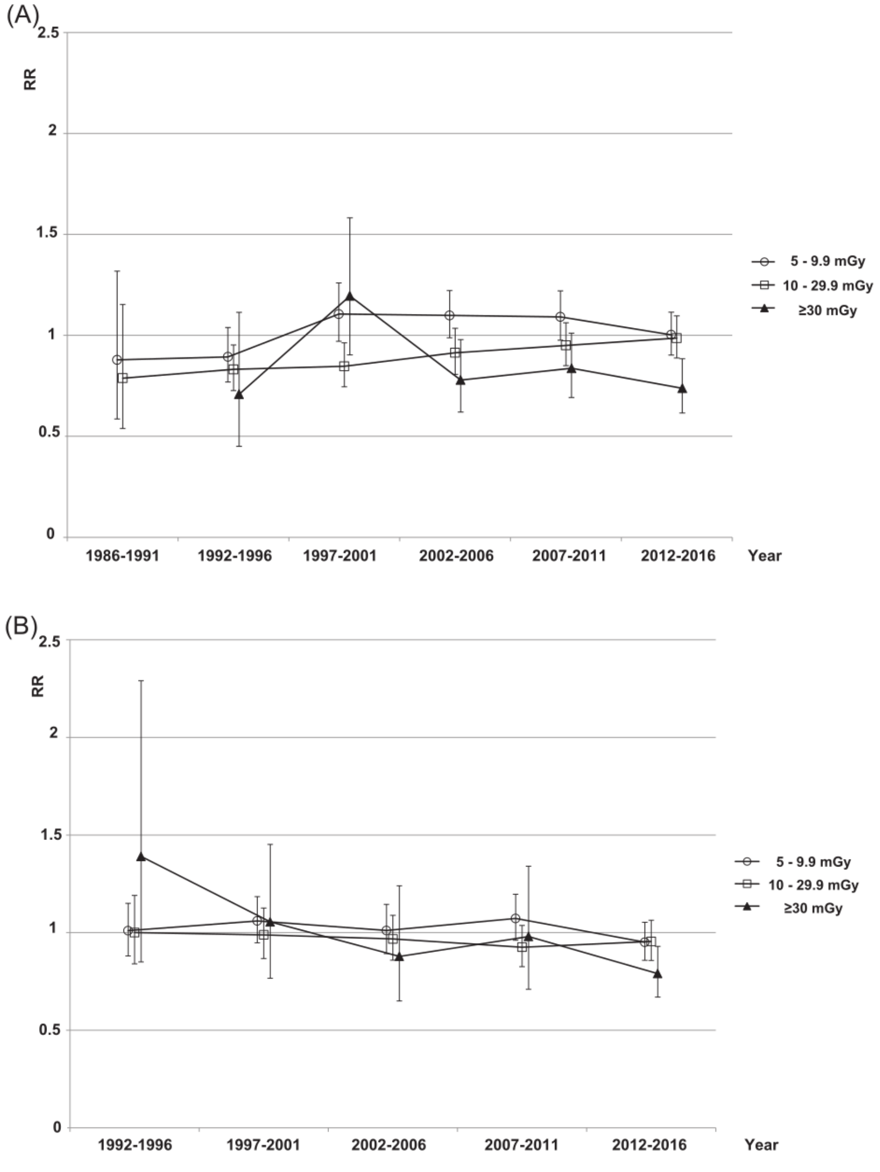


FIGURE 2 Breast cancer relative risk (RR) estimates by 5-year-lagged cumulative absorbed breast dose categories compared to the reference category with dose of <5.0 mGy (RR = 1.00) adjusted for attained age, urban/rural status and stratified by 5-year intervals in (A) Belarus and (B) Ukraine

Figure 6.15: Breast Cancer Relative Risk

6.6.11 The Liquidators

Over 200,000 men were brought in to clean up the mess. They became know as *liquidators*. From an ethical point of view, the liquidators should be deemed part of the public. Most were conscripted, and, while some of the management and engineers had direct or indirect ties to the nuclear power industry, they were not normally highly exposed.

The liquidator's dose profiles were quite different from those of the people living in the area. Kashcheev et al studied 67,500 Russian liquidators. Russians represented about 30% of the actual liquidators. Unfortunately, Kashcheev, a good LNTer, only collected data on the cumulative dose, Figure 6.16.[25]

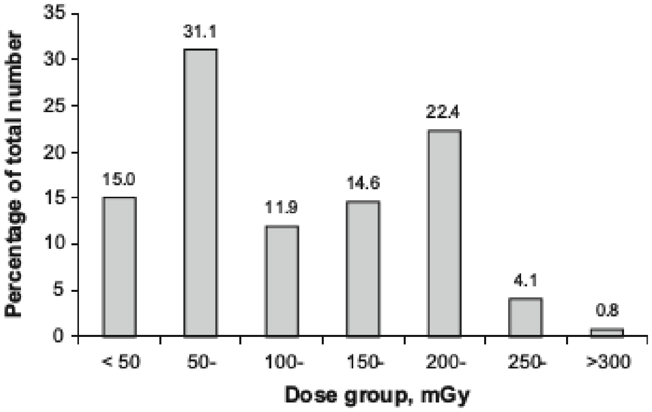


Figure 6.16: Kashcheev liquidator dose distribution

As SNTers we need the daily doses through time. The liquidator tour was four to eight weeks. However, as soon as you absorbed more than 250 mSv (later 100 mSv) you were supposed to be rotated out. For a variety or reasons, this did not always happen.

We do know that just under 4000 people were employed in cleaning off the Unit 3 roof. Most of these men received their dose in an hour or less; in many cases, a minute or two. The sarcophagus was constructed by three shifts of Sredmesh crews. There is some evidence that each of these shifts involved 11,000 people. Many of these men probably received a large portion of their dose acutely or nearly so.

The remaining 80% probably got their dose more or less evenly over their entire tour. Table 6.16 assumes 11,000 liquidators received their dose acutely, 25,000 acquired their dose over 7 days, and the rest evenly over four weeks. All 36,000 are assumed to come from the top end of Kashcheev's dose distribution. These arbitrary assumptions are almost certainly conservative. The resulting total LLE is 3,596 years. This LLE is roughly equivalent to 90 airplane crash

---

[25] This represents a major lost opportunity. The daily doses were recorded. Somebody has the actual dose profiles. This data would be an ideal test of the SNT model. And we could make a much more accurate estimate of the LLE.

victims. Under these assumptions, over 70% of the LLE is suffered by the 5% of the liquidators who got their dose acutely.

Table 6.16: Illustrative Liquidator LLE.

Dose mSv	Group Size	Acute Fraction	Acute LLE years	One Week Fraction	One Week LLE Years	Four Week LLE years
25.00	34000	0.00	0.0	0.00	0.0	1.9
75.00	70000	0.00	0.0	0.00	0.0	43.0
125.00	27000	0.00	0.0	0.00	0.0	50.5
175.00	33000	0.00	0.0	0.00	0.0	128.5
225.00	50000	0.11	1111.0	0.39	187.9	262.5
275.00	9000	0.50	1180.9	0.50	236.6	0.0
325.00	2000	0.50	318.6	0.50	75.1	0.0
TOTAL	225000		2610.4		499.6	486.3

The conservatism of our model is demonstrated by the fact that, while Kashcheev observed a 6% increase in cancer incidence in his sample of liquidators, the mortality within the group was ***lower*** than the Russian standard, probably due to earlier detection and better treatment.

6.6.12 Total LLE excluding thyroid cancer

Even if we accept all the conservatism, excluding thyroid cancer, Chernobyl is a casualty that, in terms of public Lost Life Expectancy ***due to radiation***, is roughly equivalent to 200 sure deaths.[26]

This assumes no evacuation, no behavioral changes, and poor control of contaminated food.[27] Since 1960, we've had 24 commercial airplane crashes that killed 200 or more people. Of the 6593 people killed in these crashes, 268 were on the ground, people who just happened to be in the wrong place when the aircraft came down. We tolerate this lost life in return for the benefits of air travel.

---

[26] The difference between this number and those in the UCS Table 6.6 is in part the result of:

1. The actual number of 1986/1987 liquidators was about 224,000 not 530,000. The 69,000 1988 and 1989 liquidators received far lower doses. The UCS number presumably is based on the number of people who were awarded liquidator certificates. Since liquidators received all sort of perks, politically connected people contrived to be called a liquidator. Many of these people were never anywhere near Chernobyl.
2. The "deaths" in Table 6.6 are *statistical deaths*. Our "equivalent air crash deaths" are the LLE in years divided by 40. Statistical deaths do not account for the fact that a cancer death shortens a life by about 12 years, not 40 years. If you adjust the 1323 statistical deaths in Table 6.6 by these two factors, you come up with 166 airplane crash deaths. The rough agreement is more coincidental than meaningful.

[27] It also assumes a callous approach to clean up. At Chernobyl, the Soviets hired two giant cranes. A crane could have reduced the doses on Unit 3 roof by a lot. But they decided to use both on the sarcophagus and were either unable or unwilling to bring in another crane.

Fractionation could also have mitigated harm. Instead of a single 250 mSv limit, it would have been better to have three 100 mSv limits separated by a day or two of repair.

6.7 SNT at Fukushima

6.7.1 Weekly doses at Fukushima

The Fukushima release was very roughly one-tenth the size of Chernobyl. Table 6.17 shows estimates of the activity released for the four most harmful isotopes.

Table 6.17: Four Most Harmful Isotopes at Fukushima

Isotope	Halflife	Release PBq	Photon fraction
131I	8.021d	120.0	0.622
134Cs	2.061y	9.0	0.180
137Cs	30.188y	8.8	0.083
132Te	3.230d	29.0	0.115

At Fukushima, the worst case public monitoring points outside the plant started out with an air dose rate of about 200 μGy/h, Figure 6.17. 5 to 10 kilometers from the plant all the readings are below 50 μGy/h. Once you get more than 10 kilometers from the plant most of the numbers are below 20 μGy/h.

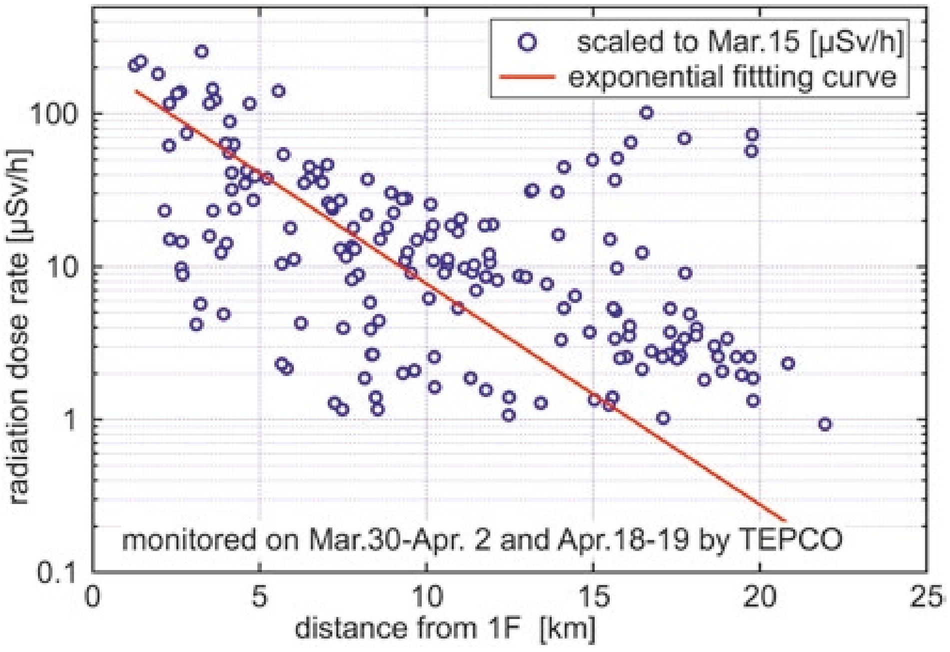


Figure 6.17: Initial air dose rates at Fukushima, μGy/h, reference [7][Fig 3.12]

Applying the Golikov model to Fukushima is obviously problematic. The behavior of the population groups near Fukushima is unlikely to be the same as the groups near Chernobyl. But we don't have the corresponding locale and occupancy factors for Fukushima, so it's the best we can do.[28] Once again the whole exercise is meant to be illustrative.

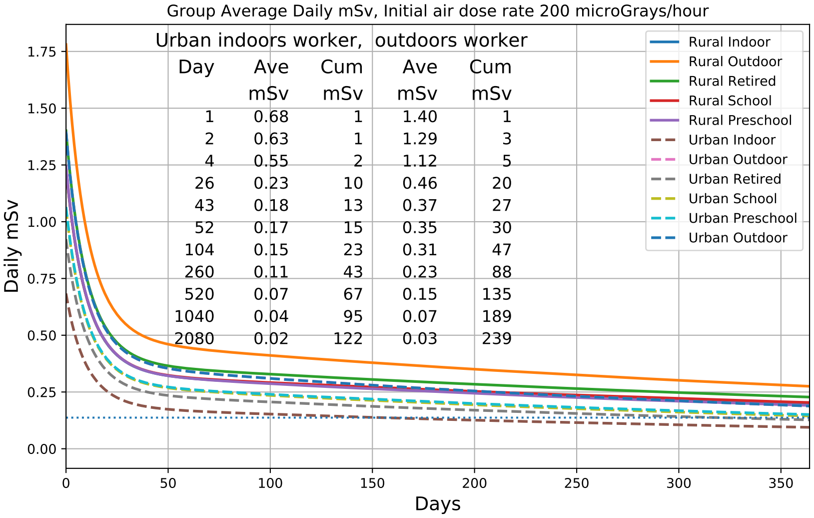
If we brazenly use the Golikov model, Figures 6.18 and 6.19 show the daily average dose rates by group for Fukushima locations than start out at an air dose rate 200 and 50 μGy/h respectively. These figures assume no evacuation and no modification of behavior. I've also assumed no internal exposure due to ingestion of contaminated food. At Fukushima this pathway was insignificant, in part due to strict food controls.

Qualitatively, the results are similar to Chernobyl, but the dose rates are much lower:

1. At Fukushima, about 70% of the initial air dose rate was due to ^{131}I and ^{132}I. The radioiodine was effectively gone in 8 weeks. After that, the daily dose falls off much less rapidly. The long term behavior is determined by ^{137}Cs and its weathering.
2. As at Chernobyl, the difference between the max dose group and the min dose group is about a factor of two. Modest changes in behavior can reduce dose significantly.
3. For 200 μGy/h locations, the max group average starts out at 2 mSv in the first day, but even this group is down to the pre-1950 tolerance dose in 8 days.
4. The Top 5% absorbed about double this dose; but at Fukushima, very few members of the public would have ever exceeded the pre-1950 NCRP tolerance rate of 1 mSv/day, if there had been no evacuation. And the handful that might have could have avoided doing so by spending more time indoors for a few days.
5. For 50 μGy/h locations, the first day peak is below the tolerance dose for everybody.

---

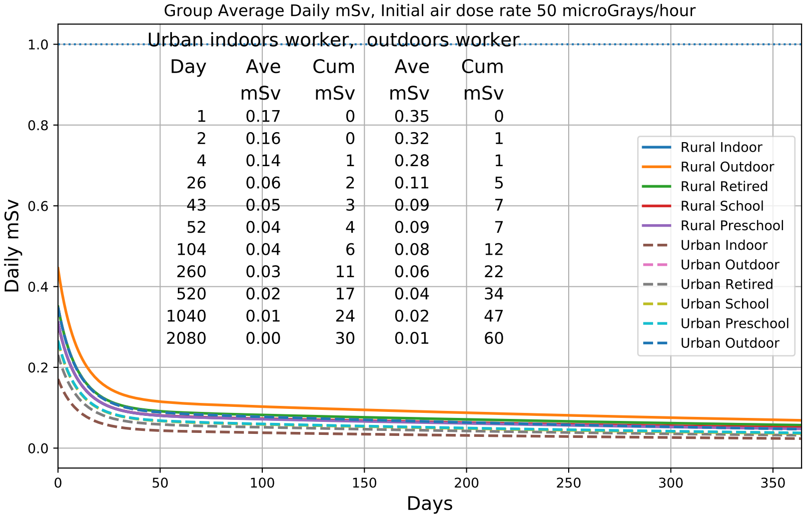
[28] And it may not be too bad. When you grind through the Golikov model, at the end of the day, the average absorbed dose over all groups is roughly 15-20% the air dose. When dosimeters were given to the citizens of Date-shi, just outside the evacuation zone, they found the absorbed dose was 0.15±0.03 the air dose.[118] Despite this, the Japanese government used a single air dose to absorbed dose conversion factor of 0.6, inflating the absorbed dose by as much as a factor of 4.



Urban indoors worker, outdoors worker

Day	Ave mSv	Cum mSv	Ave mSv	Cum mSv
1	0.68	1	1.40	1
2	0.63	1	1.29	3
4	0.55	2	1.12	5
26	0.23	10	0.46	20
43	0.18	13	0.37	27
52	0.17	15	0.35	30
104	0.15	23	0.31	47
260	0.11	43	0.23	88
520	0.07	67	0.15	135
1040	0.04	95	0.07	189
2080	0.02	122	0.03	239

Figure 6.18: Average Group Daily doses for a Fukushima location that starts out at 200 μGy/h.



Urban indoors worker, outdoors worker

Day	Ave mSv	Cum mSv	Ave mSv	Cum mSv
1	0.17	0	0.35	0
2	0.16	0	0.32	1
4	0.14	1	0.28	1
26	0.06	2	0.11	5
43	0.05	3	0.09	7
52	0.04	4	0.09	7
104	0.04	6	0.08	12
260	0.03	11	0.06	22
520	0.02	17	0.04	34
1040	0.01	24	0.02	47
2080	0.00	30	0.01	60

Figure 6.19: Average Group Daily doses for a Fukushima location that starts out at 50 μGy/h.

6.7.2 SNT Lost Life Expectancy

If we adopt the Sigmoid No Threshold model of cancer incidence, we can convert these daily dose rates to Lost Life Expectancy, for each population group. This has been done in Figures 6.20 and 6.21 for an initial air dose rate of 200 μGy/h, These figures make several points:

1. There are large differences between groups. An urban indoor worker on average will lose 8 times less LLE than a rural outdoor worker. This is due both to the more rapid weathering in towns and building shielding.
2. The Top 5 percentile in each group loses about 4 times more LLE than the SNT average.[29] The Top 5% receive about twice as much dose, and SNT non-linearity does the rest.
3. All the Fukushima LLE's are small. Under SNT, the worst case, top 5 percentile sub-group's LLE is about 2 days. This is about the same as the LLE from relaxing the 55 MPH speed limit.[51] The benefits of nuclear power are incomparably larger than the benefits of saving a few minutes in daily travel. And these max LLE's can be cut by a factor of 10 or more by spending more time indoors for a week or so. ***Nobody should have been forced to evacuate at Fukushima due to the release. Frail, elderly people most definitely should not have been evacuated.***

Figures 6.22 and 6.23 show the LLE's for an initial air dose rate of 50 μGy/h. The Lost Life Expectancies drop off sharply with decreasing initial dose rate. Halving the initial dose rate, cuts the group LLE's by more than a factor of four. Once the initial air dose is down to 50 μGy/h, the unevacuated LLE's are measured in minutes. No changes in behavior are needed.

---

[29] The SNT average is computed by calculating the LLE of each of the 20 sub-groups (0-5 percentile, 5-10, 10-15, etc.) and taking the average of those LLE's. This average reflects the non-linear character of SNT.

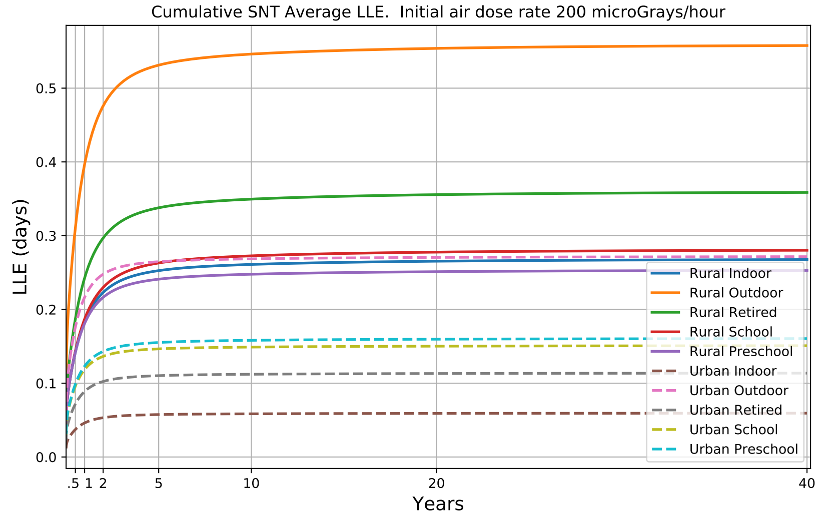


Figure 6.20: Fukushima average group LLE's, 200 μGy/h initial air dose rate.

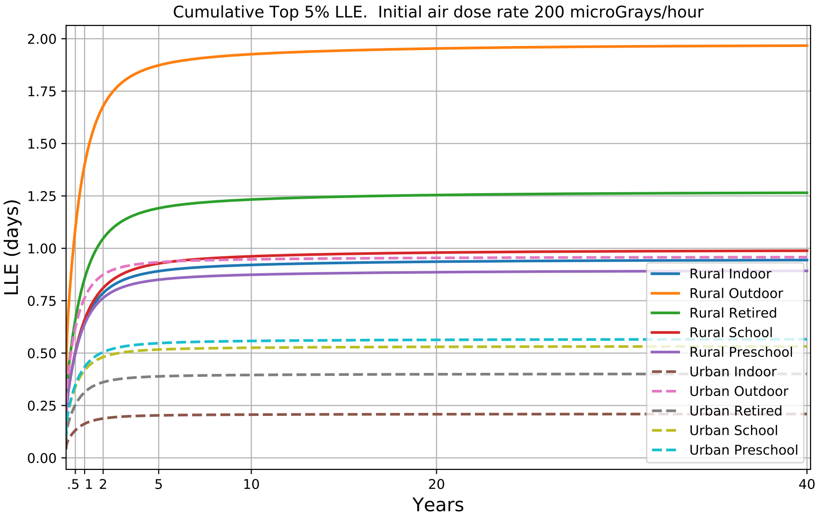


Figure 6.21: Fukushima top 5% sub-group LLE's, 200 μGy/h initial air dose rate.

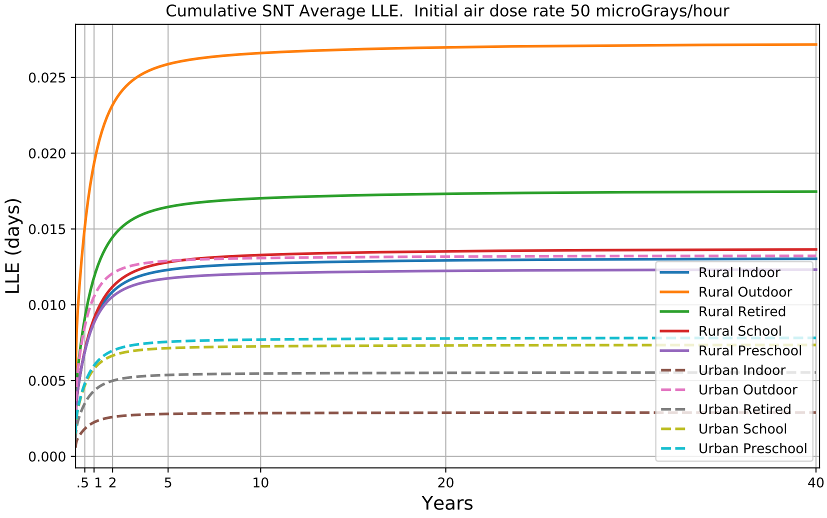


Figure 6.22: Fukushima average group LLE's, 50 μGy/h initial air dose rate.

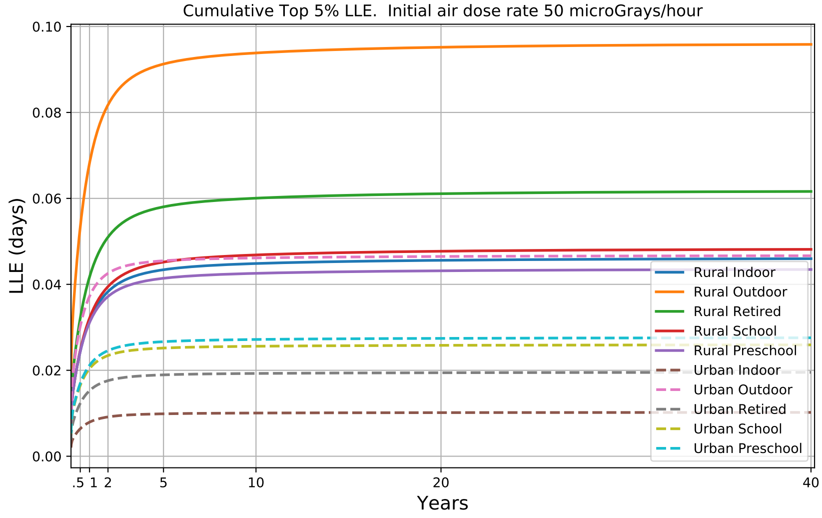


Figure 6.23: Fukushima top 5% sub-group LLE's, 50 μGy/h initial air dose rate.

6.7.3 Total Public Lost Life Expectancy at Fukushima

Looking at Figure 6.17, a conservative set of contamination assumptions might be:

1. All the area within 5 kilometers of the plant but outside the plant boundary started out at 200 μGy/h.[30] A large part of this area was below 50 μGy/h, but there are a few points farther out, that are in the 70 to 100 μGy/h range.
2. All the area between 5 and 10 kilometers from the plant started out at 50 μGy/h. The vertical scale in Figure 6.17 is logarithmic. Most of the points in this area are below 20 μGy/h, and some are below 2 μGy/h.
3. All the area between 10 and 20 kilometers from the plant started out at 20 μGy/h. Most of the points in this area are below 10 μGy/h.
4. All the area between 20 and 40 kilometers from the plant started out at 10 μGy/h. Most of the points in this area are below 5 μGy/h.

Based on the populations and areas of the towns near the plant, a rough estimate of the population density close to the plant is 150 people per square kilometer, dropping to perhaps 100 people/km2 as you move farther from the plant. Putting all these heroic assumptions together leads to Table 6.18.

Table 6.18: Guesstimated Population by Initial Air Dose

Radii	μGy/h	Area km2	People/ km2	Popul- lation
1 - 5	200	39	150	6000
5 -10	50	119	150	18000
10 -20	20	509	150	76000
20 -40	10	2004	100	200000

There's a lot of hand waving here; but for now suppose we accept these numbers, and we had a compensation schedule based on a Value of Life figure. An upper bound on this number might be the US dialysis standard which is \$129,000 per year or \$350 per day. Table 6.19 shows the group LLE's for the area within 5 kilometers of the plant. The Top 5 percentile of the most exposed group has an LLE of about 3 hours, worth about \$130.

Table 6.20 accumulates these LLE's over all groups in an area, and then over all areas. Under SNT, the total public LLE is about 400 days. At \$350 per day, the total compensation would be less than \$500,000. Most of that money would go to the 2% of the population with the highest dose rates.

---

[30] The Fukushima plant boundary is everywhere more than a kilometer from the three units that had releases.

Table 6.19: Fukushima Group LLE's for the 1 to 5 km area.

Area = 1-5 km Initial air dose rate μGy/h = 200.0
Internal f = 1 USD/LLE-day = 350 2023-09-26T22:40:38Z

Pop.=3000			Rural		
	Inside work	Outside work	Retired	School kids	Pre-school
Average LLE	0.05	0.11	0.07	0.05	0.05
Maximum LLE	0.18	0.37	0.24	0.19	0.17
Average EER	0.00001	0.00002	0.00002	0.00001	0.00001
Average mSv	467	626	540	490	433
Group pop.	600	1140	600	420	240
Group LLE	30	120	41	22	11
Group USD ave	10,594	41,948	14,201	7,767	4,004
Ave $/head	18	37	24	18	17
Max $/head	62	130	83	65	59
Group USD max	37,369	147,967	50,092	27,400	14,124
Pop.=3000			Urban		
	Inside work	Outside work	Retired	School kids	Pre-school
Average LLE	0.01	0.05	0.02	0.03	0.03
Maximum LLE	0.04	0.18	0.08	0.10	0.11
Average EER	0.00000	0.00001	0.00000	0.00001	0.00001
Average mSv	199	379	265	298	319
Group pop.	840	810	600	390	360
Group LLE	9	41	13	11	11
Group USD ave	3,285	14,490	4,492	3,876	3,807
Ave $/head	4	18	7	10	11
Max $/head	14	63	26	35	37
Group USD max	11,590	51,112	15,845	13,672	13,429

Table 6.20: Fukushima SNT Compensation at $127,000 per LLE year, 40 year cutoff.

fuku Internal factor = 1
Cancer LLE yrs: 12.00 $/life-day = 350

Area	Initial μSv/h	Population	LLE(days)	Compensation
1-5 km	200	6000	309.91	382,604
5-10 km	50	18000	45.28	55,896
10-20 km	20	76000	25.94	32,019
20-40 km	10	200000	15.06	18,594
Total		300000	396.18	489,115

Table 6.20 is illustrative only. In a real world analysis, we would use much more accurate numbers, based on the actual doses received. But I don't think the overall numbers are out of the ballpark. They are consistent with the UNSCEAR conclusion that, if there is any radiation impact on the public from the release, it will not be detectable.[261][31] Some will say the compensation is woefully puny. But the Montreal Treaty says a life killed by an airplane crash, an LLE of roughly 40 years, is worth about $170,000. And Table 6.20 is built on conservative assumption after conservative assumption. The table is overly generous by a long shot, ***provided there is no involuntary evacuation***.

Fukushima was a massive industrial casualty. The cost to TEPCO ratepayers, shareholders, and Japanese taxpayers from the loss of three large reactors and their electricity is in the many billions of dollars. And the Fukushima locals suffered not only horrible losses from the tsunami; but also the loss of jobs and local revenue that the three destroyed reactors would have created. But, sensibly handled, there would have been no significant off-site impact from the release of radioactive material at Fukushima. Sensibly handled the three undamaged reactors at Fukushima would have been back on line in a matter of weeks.

6.8 Buffer Zones

This last sentence needs to be qualified. At Chernobyl, the closest permanent residence to the plant was about 3 kilometers from Unit 4. At Fukushima, the closest permanent residence to the units that had containment breaches was more than 1 kilometer. The non-evacuation LLE numbers would have skyrocketed, if people had been living closer to the reactors.

Figure 6.24 shows the hourly dose rates through time at various measuring points near the Fukushima plant periphery. Figure 6.25 shows the location of the instruments. From March 13 to 15, the plume moved to the North and Northwest, after which the flow turned southwest. There is a sharp spike after each release event. If we assume a repair period of a day, we need daily dose rates. They peaked on the 16th at the Main Gate at about 83 mSv/d. This is clearly unacceptable for the public. The Main Gate is about 1 km from the damaged reactors. A buffer zone of at least 2 km is indicated.

There needs to be a buffer zone around any nuclear reactor. For a large reactor, there should be at least two kilometers to the nearest non-plant residence or place of work, unless there is a truly compelling reason not to. At both Fukushima and Chernobyl, Figure 6.7, the dose rates fell off by more than a factor of ten in the first two kilometers. If we accept SNT, the harm goes at better than the dose rate squared. By providing a 2 kilometer buffer zone, we reduce the peak public harm by at least a factor of 100.

The plant property itself can be part of the buffer zone. At Fukushima, it was the entire

---

[31] The 2021 UNSCEAR report confirmed and improved upon the results of the 2013 report. In particular, they found that cesium becomes immobilized in Japanese soil sooner than expected. The estimated thyroid doses are down sharply. And ten years on, UNSCEAR could detect no radiation related increase in cancer.

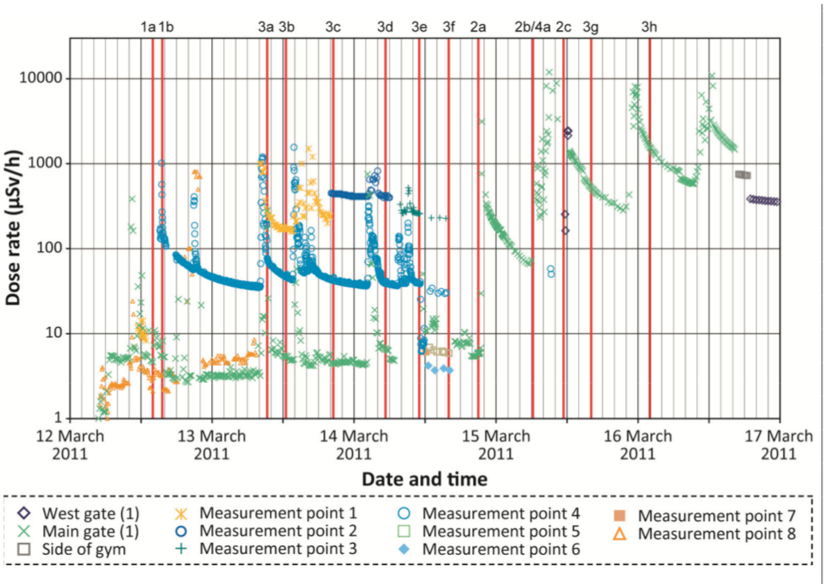


Figure 6.24: Dose rates at Fukushima Plant Boundary

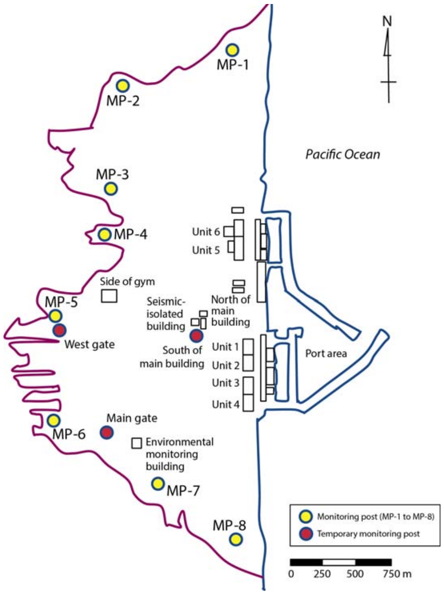


Figure 6.25: Fukushima Plant Layout

buffer zone. But the portion of the buffer zone outside the plant need not be fenced off. It could be a park or farmland, areas that people visit temporarily, areas that can easily be emptied of people with almost no disruption.[32] In a release, they should be advised to go home and shelter-in-place.

In the releases to date, the disruption and consequent physical and psychological stress due to evacuations has been far worse than the Lost Life Expectancy due to radiation harm. This was glaringly evident in the immediate deaths of some 50 frail, elderly people at Fukushima, Section 5.1.1. Buffer zones can help prevent such murderous tragedies. Instead of evacuation, a panicked, weak politician can tell the people to leave the buffer zone, go home, and shelter in place. He's done something without killing people.

By removing the need for evacuation, buffer zones can replace Emergency Planning Zones (EPZ). EPZ's are areas within which evacuation drills must take place. Holding up those drills was an effective delaying tactic of the anti-nukes in the late 1970's.

Buffer zones make it easier to allow controlled venting. At Fukshima, at 12:20 AM on March 12, the site manager, Maseo Yoshida wanted to vent Unit 1 and asked Tepco-Tokyo for permission. Tepco forwarded the request to Prime Minister Naoto Kan.[56] Kan said not until a 3 km radius around the plant has been fully evacuated. Evacuation of this area was not confirmed complete until around 9:00 AM, and venting did not start until 10:00 AM.

By then enough hydrogen had seeped into the outer building to cause the first explosion, which not only released a large amount of radioactive material, but also knocked out the mobile emergency diesel, which six minutes earlier had started sending power into Units 1 and 2, allowing high pressure water injection and core cooling. The debris also obstructed the attempt to get another mobile diesel generator to Unit 3. Without the delay in venting, Fukushima might have looked a lot like Three Mile Island.

With proper buffer zones, the plant management should be given discretion to vent, if they decide it is warranted.

The requirement for a buffer zone can be turned into a plus. Most nuclear plants are on the water. In the 1960's, the California state Resources Agency strongly supported nuclear. They realized that the buffer zones could be turned into state parks and beaches, assuring public access to the ocean.[277][p 123] That shorefront was protected from private development.

The requirement for a buffer zone, as well as other economies, will tend to group multiple plants at the same site. There is nothing wrong with this, as long as the layout is such that a casualty at one unit is extremely unlikely to spread to other units. At Fukushima, neighboring plants shared the same stack. This resulted in hydrogen released by Unit 3 causing an explosion in Unit 4, which was not even on-line at the time. At Chernobyl, four units not only shared the same building, but a pool of water in the basement. If the molten core hit had reached that

---

[32] Some industrial activities can be allowed in the buffer zone. Obvious candidates include electricity intensive processes such as CO2-free metals manufacture and hydrogen production. Wind and solar easily qualify for the buffer zone. The problem is, if nuclear is as cheap as it could be and as it needs to be, wind and solar will be economic almost nowhere. See Section A.6.

water before it was drained, it is likely the resulting steam explosion would have taken out the other units. Each unit should be independent and separated by mini-buffer zones from the other units.

This has implications for modular reactors. For example, NuScale places six or twelve 77 MW reactors in a single building. For the purpose of a buffer zone, a Nuscale six pack is a 462 MW plant, not six 77 MW plants. It's the total source term (amount of radioactive material) within each mini-buffer zone that counts. If and only if the mini-buffer rule is complied with, the buffer zone extent will not need to be changed when more plants are added to the site.

6.9 Windscale and Three Mile Island

What does all this say about Windscale and Three Mile Island, two other radioactive releases?[33] Table 6.21 compares the release amounts for these two casualties with Chernobyl and Fukushima.

Table 6.21: Four Main Isotopes at Four Big Releases

		Release in TBq			
Isotope	Half-life	Three Mile Island	Windscale	Fukushima	Chernobyl
^{131}I	8.02d	0.555	1800	120,000	1,760,000
^{137}Cs	30.19y	nil	180	8,800	79,500
^{134}Cs	2.06y	nil	?	9,000	54,000
^{132}Te	3.23d	?	1300	29,000	1,150,000

Windscale The Windscale release was very roughly one-fiftieth of Fukushima, Table 6.21. The maximum recorded dose rate was 0.84 mGy/d, 1 mile from the reactor.[145][p 100] Under SNT, the harm goes at better than the square of the release. To first order, Windscale harm was 1/2500th of Fukushima. The maximum public dose was 5-7 mSv. This dose received acutely, which it was not, has an LLE of 17 minutes. There is no point in doing the numbers. Since radioiodine totally dominated the Windscale release, if there were any impact, it would be in thyroid cancer. Attempts to detect any significant increase in this cancer due to the radiation have been unsuccessful.[163]

What's interesting about Windscale is the response. Or really the non-response. There was no evacuation voluntary or involuntary. Local milk was confiscated and destroyed.[34] This lasted about six weeks. The auxiliary buildings at Windscale continued to be occupied and operate.[35] Windscale, now called Sellafield, continues to be a center of British nuclear power activity. It is possible to have a release without a panic.

---

[33] Windscale, a 1957 release from a British atom bomb production reactor, was not a nuclear power plant release; but it is relevant to our subject.

[34] The milk could have been turned into cheese or butter and stored for a month or two. This was considered and rejected on PR grounds.[13] Bad decision. A missed educational opportunity.

[35] Construction on the neighboring Calder Hall site was shut down for a day.[13]

Three Mile Island The Three Mile Island release was about 1/2000th of the Windscale release. Three Mile Island showed that many of the assumptions of what happens in a core meltdown were just plain wrong. Contrary to the models, nil cesium was released. The ^{131}I release was one ten millionth of the ^{131}I in the reactor. Iodine and cesium compounds either dissolved in the water inside the buildings or condensed out on the piping and structure. This behavior has been observed in previous tests and in the SL-1 casualty; but pretty much ignored in the models.[145]. 0.555 TBq is about half the particle emission rate of a plutonium powered pacemaker, Section 2.1. The maximum dose to a member of the public was 0.37 mSv, which has an SNT LLE of about 2 seconds. From a radiation point of view, it was a non-event.

TMI probably should be the model for a “standard" meltdown. When Rockwell asked an NRC official after the fact why this was not the case, the guy replied “If I really thought that, I'd have to ask what I'm doing here".[218] Rockwell pointed out that's a question we should all ask ourselves.

But TMI was a multi-billion dollar industrial casualty. The utility, GPU, lost a nearly new 906 MWe power plant. Nuclear power plant owners have a very strong incentive to avoid a TMI, even if we ignore the release, as we should have been able to in this case. But only if the owners bear the cost of the casualty.

Response worse than the release? All releases of radioactive material are not created equal.[36] Chernobyl was a bad casualty by any definition, roughly equivalent to a major airplane crash in terms of Lost Life Expectancy due to radiation. And the harm was multiplied many times by unnecessary evacuations and senseless prohibitions against return.

Fukushima was a disaster for TEPCO rate payers and shareholders. And these economic losses would have had a serious impact on the local communities.[37] But the radioactive harm to the public will be undetectable. Properly handled, the release would have been a footnote to the tsunami and loss of three reactors. Instead, we shortened the lives of 1600+ people, unnecessarily disrupted the lives of 100,000 more, and imposed a 20 billion dollar per year fuel cost burden on all Japanese by shutting down all nuclear power, which imbecility spread to Germany and elsewhere.

Windscale is a lesson in how a radioactive release should be handled. As a result, the damage was limited to the loss of a poorly designed, outmoded, weapons reactor.

Three Mile Island was the opposite. A non-event in terms of public radiation harm, which showed that many of the assumptions underlying release analysis were incorrectly pessimistic, turned the American public against nuclear power. Opposition to nuclear power rose from less than 30% to more 50%.[222] I think this was rational behavior. The fact that there was no harm

---

[36] The IAEA might beg to differ. They have a rating system called INES (International Nuclear and Radiological Event Scale). According to INES, Chernobyl and Fukushima rate the same. Both are 7's. This is consistent with the any-big-release-is-a-catastrophe dogma.

[37] An entirely valid criticism of nuclear power is its lack of resilience. If you do have a casualty, it tends to be outrageously expensive compared with other sources of electricity, even without unjustified responses to a release. This is a cost that nuclear power must internalize. Some of the new technologies promise to reduce these costs substantially, by making all or portions of the reactor replaceable.

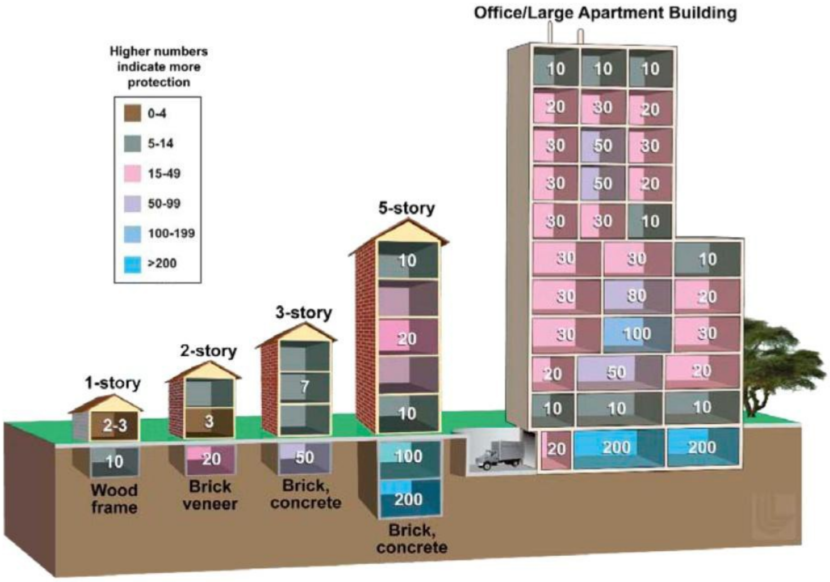


Figure 6.26: EPA estimate of dose reduction from staying in doors during Early Phase. 10 means the indoor dose is one-tenth the outdoor dose.

was almost irrelevant. Americans understood they could no longer trust a nuclear establishment that had lied to them.[38]

6.10 Sigmoid No Threshold and the EPA

The US Environmental Protection Agency issues Protective Action Guidelines(PAG) for responding to a release of radioactive material. The current version was published in 2017.[5] Per unchallengable EPA rules, the guidelines are based on a strict interpretation of LNT. The PAG manual divides the response into

1. Early Phase
2. Intermediate Phase
3. Late Phase

Early Phase is while the release is on going and the plume has yet to move passed a point. During the Early Phase most of the dose is from the plume. During the Early Phase there is a great deal of uncertainty about the amount and temporal and spatial distribution of the dose rate. Intermediate Phase starts after the release has stopped and ends when clean up starts. During

---

[38] Something similar happened at the THTR reactor in Hamm-Uentrop, Germany in May, 1986. The release was tiny, something like 0.0003 TBq. It wasn't the release; it was the lie.

this phase, the amount and spatial distribution of the radionuclides are pretty well known. Most of the dose is from material deposited on the ground, known as *groundshine*. The Late Phase is when clean up starts. The split between Intermediate and Late strikes me as arbitrary and unnecessary.

The Guidelines correctly put a great deal of emphasis on shelter-in-place. The manual has a nice drawing, Figure 6.26, showing the order of magnitude reduction in photon dose from staying indoors during the plume. It says "shelter-in-place should be preferred to evacuation whenever it produces equal or greater protection".

For the early phase, the PAG manual recommends shelter-in-place or evacuation if the projected dose rate is greater than 10 mSv in 4 days. This is based on accepting a probability of 0.0002 of mortal cancer from the dose.[39] From Table 6.1, that's an LNT Lost Life Expectancy(LLE) of about 1 day. The manual also says when the projected dose is less than 10 mSv for the first four days, evacuation is ***not*** recommended, although shelter-in-place should be considered. The manual references the evacuation deaths from the 2005 Gulf Coast hurricanes and Fukushima, which apparently changed EPA's view on the risks of evacuation.

For the Intermediate Phase, the guideline is *relocation* if the projected whole body dose is greater than 20 mSv in the first year or greater than 5 mSv in any subsequent year. The document distinguishes between evacuation and relocation and emphasizes that relocation should be done deliberately, not hurried.[40]

Imagine a world in which EPA magically switched from LNT to SNT but kept the same acceptable LLE's. For now let's focus on the first year. According to LNT, 20 mSv has an Excess Relative Risk (ERR) of 0.001, meaning 25 mSv increases your probability of developing fatal cancer by 1 chance in 1000. The corresponding LLE is 4.2 days. EPA accepts this given the risks and costs of relocation. This is a fairly aggressive first year ERR. Figure 6.27 shows that everybody at Chernobyl in locations that started out at 600 μGy/h, had an average first year LLE of less than 4.2 days.

A glance at Figures 6.20 and 6.21 shows that, under the PAG, the EPA would have evacuated nobody at Fukushima, to avoid the first year dose. An SNT-based EPA and I are on the same page here.

But the EPA's Guideline to relocate, if the dose rate in the follow on years is more than 5 mSv per year, is far, far tighter, ridiculously so. By this logic, a wide swath of the US mountain west including Denver should be depopulated, Figure 6.28. According to EPA's own numbers, eight states average more than 5 mSv/y.[162] At 5 mSv/year (14 μSv/d), the SNT LLE per year is 13.5 seconds. People who were told not to evacuate in the first year and accept an LLE of 4 days, are now told to evacuate to avoid an LLE per year that is 30,000 times smaller.

---

[39] The PAG manual assumes rather arbitrarily that evacuation or shelter-in-place will reduce the dose by half, so the avoided dose is 5 mSv.

[40] The shift in EPA policy makes the concept of an Emergency Planning Zone (EPZ) largely obsolete. The main purpose of the EPZ is to facilitate rapid evacuation, which the EPA no longer supports.

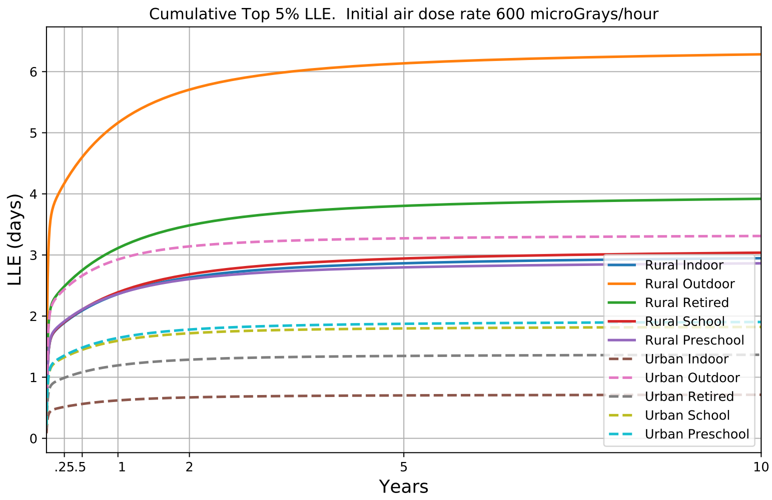


Figure 6.27: Max Subgroup LLE's at Chernobyl for initial air dose rate of 600 μSv/h.

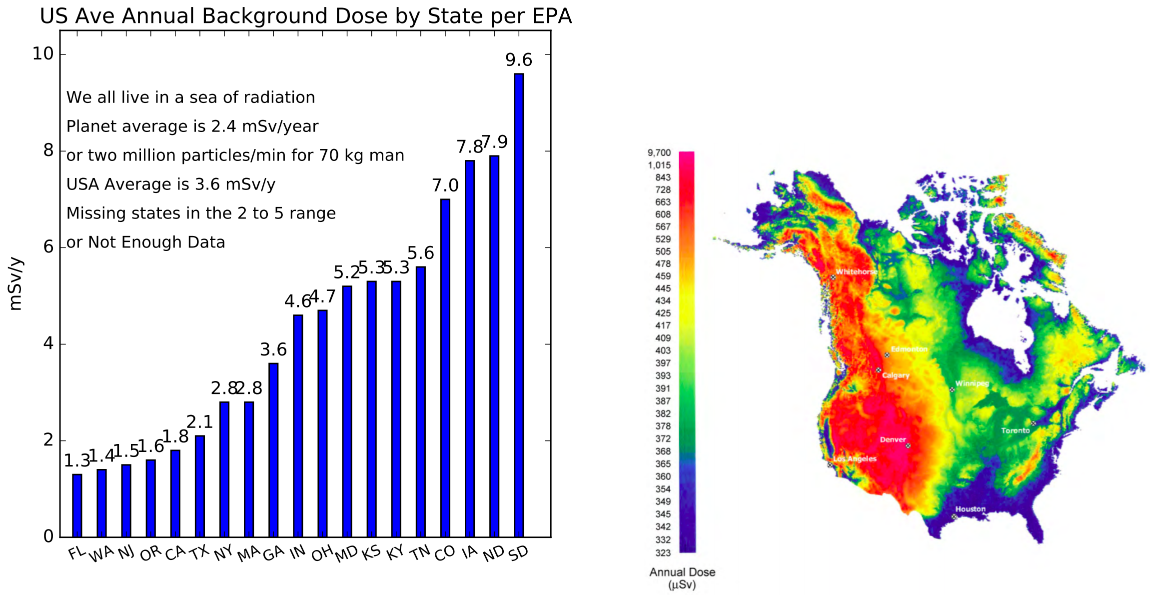
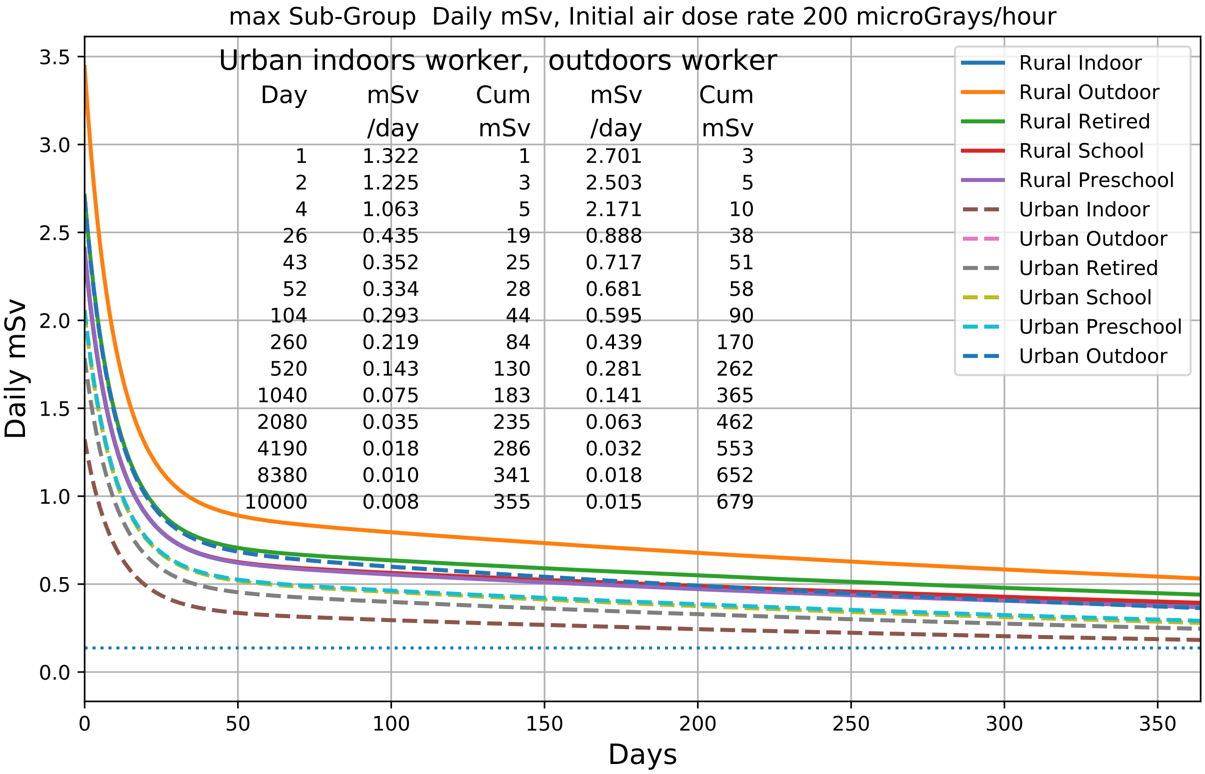


Figure 6.28: North American background dose rates

And expect some very prolonged evacuations. The Fukushima 200 μGy/h groups were told not to evacuate in the first year. But to avoid 14 μSv/d, some groups must evacuate for more than 10 years thereafter, Figure 6.29. Fortunately, the background rates at Fukushima are low or we would never get there. Places like Pripyat are proscribed for close to 100 years.



Urban indoors worker, outdoors worker

Day	mSv /day	Cum mSv	mSv /day	Cum mSv
1	1.322	1	2.701	3
2	1.225	3	2.503	5
4	1.063	5	2.171	10
26	0.435	19	0.888	38
43	0.352	25	0.717	51
52	0.334	28	0.681	58
104	0.293	44	0.595	90
260	0.219	84	0.439	170
520	0.143	130	0.281	262
1040	0.075	183	0.141	365
2080	0.035	235	0.063	462
4190	0.018	286	0.032	553
8380	0.010	341	0.018	652
10000	0.008	355	0.015	679

Figure 6.29: Fukushima max Sub-group mSv's for initial air dose rate of 200 μSv/h.
Dotted blue line is 5 mSv/y.

This nonsense is a product of LNT's obsession with cumulative dose. ***Unless we adopt a dose-response model that is consistent with the facts, a large release really is catastrophic in terms of dislocation cost.*** If we accept a dose-rate based model, the dislocation costs disappear, even in a Fukushima size release.

6.11 Linear No Threshold versus Sigmoid No Threshold

I'd be the last to claim that Sigmoid No Threshold is an accurate model of the exceedingly complex biology that is involved in radiation damage and repair.[41] But the competition here is not perfection but LNT. Table 6.22 summarizes the score in that contest.

Table 6.22: Linear No Threshold vs Sigmoid No Threshold

	Linear No Threshold	Sigmoid No Threshold
Models extremely high dose in a reasonable manner	No	Yes
Models mid-range dose in a way that is consistent with universally accepted radiotherapy practice	No	Yes
Is consistent with the no perfectly safe dose doctrine	Yes	Yes
Is consistent with the risk observed at acute dose of 100 mSv and above	Yes	Yes
Is consistent with modern understanding of DNA damage and repair.	No	Yes
Is consistent with the lack of discernible increase in cancer in high background radiation areas	No	Yes

It is the last two rows that should concern the supporters of LNT. At both Chernobyl and Fukushima, the mental and physical stress caused by fear of radiation far outweighed the increase in cancer caused by the release. At Fukushima, over 1600 people were killed unnecessarily. Much of this must be laid at the feet of LNT and its promoters. These promoters have seen the human suffering and death that LNT has caused at least twice. They must know that LNT is not consistent with either our current understanding of radiation damage and repair nor cancer incidence in high background dose rate areas. If there is a workable alternative that avoids these critical defects and they choose not to support it, they must share responsibility in the unnecessary suffering that will occur in the next release. Primum non nocere.

6.12 Postscript: The Muller Threshold Trap

SNT has been rejected by almost all anti-LNT pro-nukes. The main reason is SNT accepts the no-perfectly-harmless-dose premise. These people think the public is too stupid to understand that there is no practical difference between a negligible dose and zero dose. They are wrong. All of us accept negligible risks every time we walk out the door.

---

[41] I'd also be the last to claim that I have done a good job of implementing Sigmoid No Threshold. Somebody far better qualified needs to do a much better job of fitting logistic curves to the REFR data and other data sets. For one thing, SNT depends on the background level. Strictly speaking, my fit only applies to areas with the same background levels as Hiroshima/Nagasaki.

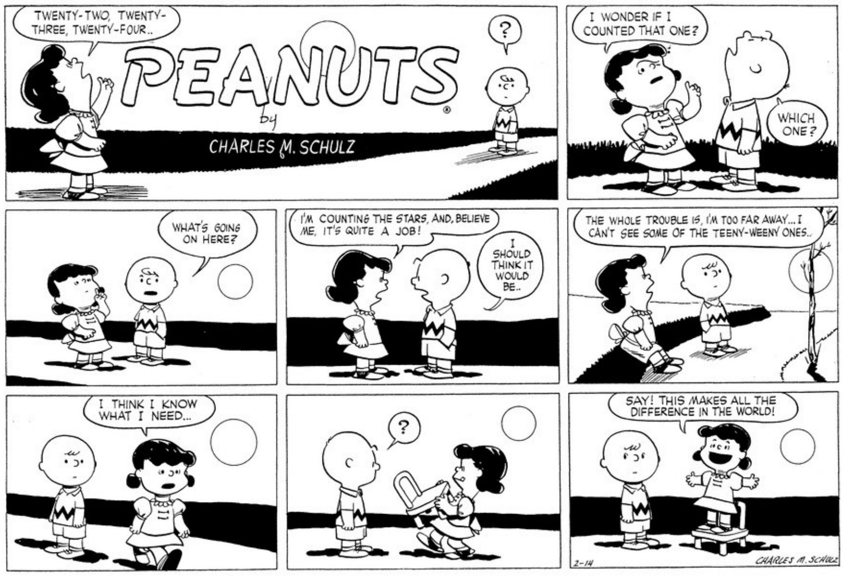


Figure 6.30: Lucy and the meaning of the word negligible

In the Peanuts comic strip, Lucy is counting the stars. But she realizes she can't see the teeny-weeny ones. She's too far away. So she grabs a chair and stands on it to get closer. Her logic is impeccable. But everyone gets the joke, even Charlie Brown; and everyone who gets that joke understands the meaning of the word negligible.

If you don't accept the no-perfectly-safe-dose premise, you must argue that there is a threshold below which there is absolutely zero harm. This sets up a false dichotomy. Either there is such a threshold or LNT. The LNTers pounce on this. They don't defend LNT. They can't. Rather they attack the concept of a threshold as unproven and unprovable, putting a nearly impossible burden on the thresholders.[42] If the thresholders cannot successfully argue for a threshold, then by their own logic, we are left with LNT, no matter how lousy LNT is at describing radiation harm.

---

[42] A recent example of the false dichotomy is the 2021 UN study, Life Cycle Assessment of Electricity Generation Options. This study is generally favorable to nuclear power, but falls into the Muller fallacy of the converse when talking about LNT. LNT implies no-lower-threshold; therefore, no-lower-threshold implies LNT.

> The 'no lower threshold' assumption leads to the accounting of health effects from the first becquerel emitted by a radionuclide — in other words, if a certain dose of radiation is found to cause one extra case of cancer in a given population, then one tenth of that dose will cause one extra case in ten times the population size.[254][p 51]

In plain english, no lower threshold is the same as LNT. The report goes on to claim we cannot be sure that LNT is wrong, because we lack the statistical power to do so. As we have seen, this is just plain false. The correct statement is we can't be sure that "no lower threshold" is wrong because of lack of statistical power.

Appendix: Technical Exposition of SNT Model

The Five Parameter Logistic

The Five Parameter Logistic is a generalization of a normal logistic, which allows the low end hook to be smaller than the high end. This is essential in modelling radiation harm.

$$H(d) = H_{inf} + \frac{H_0 - H_{inf}}{\left[1 + \left(\frac{d}{d_{mid}}\right)^s\right]^g} \qquad s > 1.0, \quad d_{mid}, g > 0.0$$

If we assume zero harm at zero dose ($H_0 = 0.0$), and 100% harm at a very large (infinite) dose ($H_{inf} = 1.0$), we have three free parameters. d_{mid}, the location of the inflection point of the S. g, the asymmetry. $g = 1$, standard symmetric logistic. $g < 1$, low end hook smaller than high end. s, the slope parameter. For the standard logistic, s is the slope at the inflection point. For all g, it is the slope of the low end curve in log-log space, as we shall see.

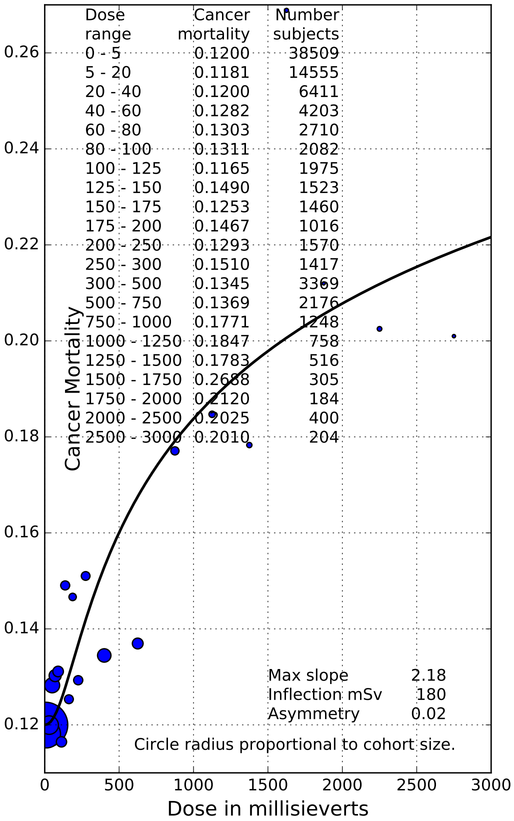
There is nothing radical or original here. The logistic is the standard dose-response model everywhere except in radiation.

Fitting the Logistic to the RERF Data.

The Radiation Effects Research Foundation (RERF) has studied the cancer mortality of 86,611 survivors of the Hiroshima and Nagasaki atom bombs. Figure 6.31 shows a fit of the 5PLogistic to the RERF cancer mortality data. The parameters for this fit are $g = 0.02$, $d_{mid} = 180$ mSv, $s = 2.18$. A $g = 0.02$ means the low end hook is far smaller than the high end.

This is an eyeball fit. The RERF data is a total mess. It bounces up and down like a slinky. This is not normal scatter. Each one of the circles below 1000 mSv is the mean of thousand or more data points. How can the average response for 5000 people between 300 and 500 mSv be far below the average response of 6000 people between 125 and 300 mSv? The eyeball fit purposely gives less weight to the numbers that make the least sense.

But no one can claim that it is too optimistic. There are 34,642 data points below the curve, and 13,440 above. This fit is purposely biased to the high side.



Dose range	Cancer mortality	Number subjects
0 - 5	0.1200	38509
5 - 20	0.1181	14555
20 - 40	0.1200	6411
40 - 60	0.1282	4203
60 - 80	0.1303	2710
80 - 100	0.1311	2082
100 - 125	0.1165	1975
125 - 150	0.1490	1523
150 - 175	0.1253	1460
175 - 200	0.1467	1016
200 - 250	0.1293	1570
250 - 300	0.1510	1417
300 - 500	0.1345	3369
500 - 750	0.1369	2176
750 - 1000	0.1771	1248
1000 - 1250	0.1847	758
1250 - 1500	0.1783	516
1500 - 1750	0.2688	305
1750 - 2000	0.2120	184
2000 - 2500	0.2025	400
2500 - 3000	0.2010	204

Figure 6.31: RERF cancer mortality

Low end asymptotic behavior

From the broad perspective of Figure 6.31, the low end hook is barely visible. But for nuclear power plant releases, where the daily doses to the public are rarely above 1 millisievert, all we are interested in is the very low end, Figure 6.32. Our fit is slightly above the data below 40 mSv but not outrageously so.

The 5PLogistic exhibits a surprising asymptotic behavior at the low dose end. It turns into a power law in which the exponent is the slope parameter, s.

Letting $\delta = (\frac{d}{d_{mid}})^s$, our harm model can be written

$$H = 1 - (1 + \delta)^{-g}$$

If $\delta \ll 1$, then by Taylor's Theorem,

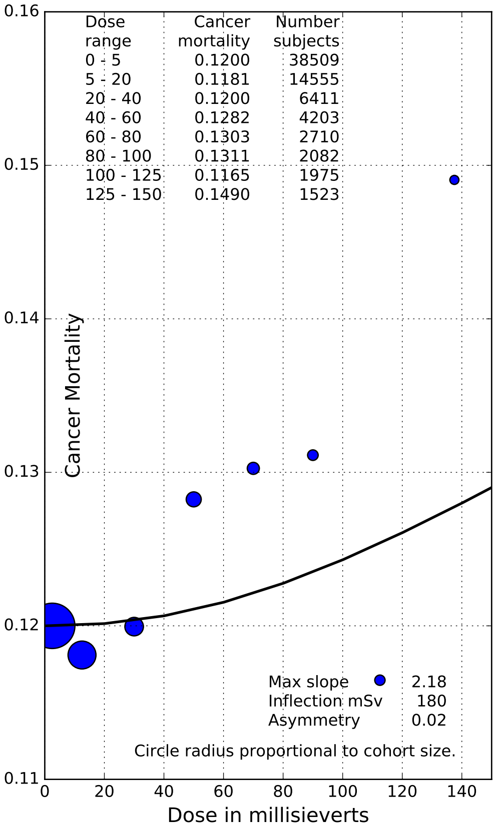
$$(1 + \delta)^{-g} \cong (1 - g\delta)$$

Substituting this approximation into the equation for harm,

$$H = g\delta = g(\frac{d}{d_{mid}})^s$$

At the low end, moving the inflection point down, increases the harm. A smaller hook goes the other way.[43]

For our fit, the low end harm goes as the 2.18 power of the repair period dose.



Dose range	Cancer mortality	Number subjects
0 - 5	0.1200	38509
5 - 20	0.1181	14555
20 - 40	0.1200	6411
40 - 60	0.1282	4203
60 - 80	0.1303	2710
80 - 100	0.1311	2082
100 - 125	0.1165	1975
125 - 150	0.1490	1523

Figure 6.32: Bomb survivor cancer mortality, 0 to 150 mSv

---

[43] Corollary: for the slope to go to zero as d goes to zero, s must be greater than 1.0. By a similar argument, at the high end, the 5PLogistic becomes a power law whose exponent is gs. At the high end, LNT comes up with probabilities that are greater than 1.00, which is mathematical nonsense.

Figure 6.33 is a log-log view of our SNT curve. This power law approximation sets in pretty quickly. The curve is pretty much a straight line in log-log space from 100 mSv (about half the inflection point dose) on down.

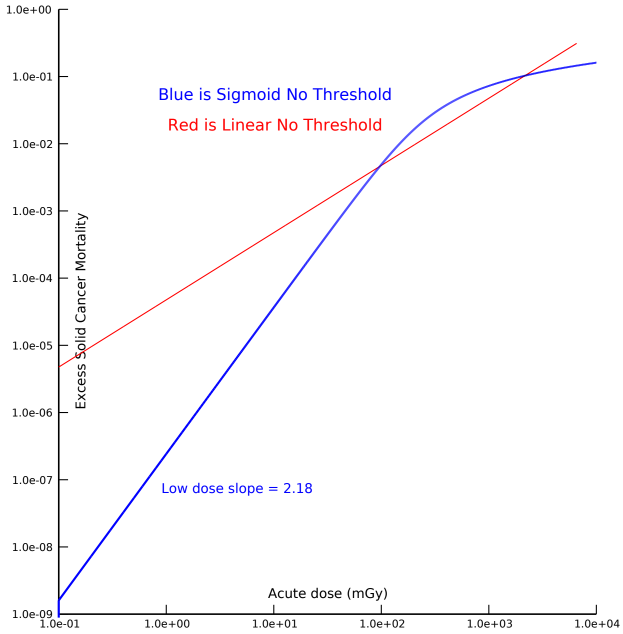


Figure 6.33: Log-log view SNT 5Pl curve

This has an important implication. According to SNT in any real world release, the harm goes at about the inverse 2.2 power of the dose within the repair period. But to first order the dose rate is inversely quadratic with the distance from the source of the release. This means the harm tends to drop off at better than the fourth power of the distance from the source. A rough rule of thumb is doubling the distance from the source will reduce the harm by about a factor of 18.[44]

---

[44] Really large NPP releases such as Fukushima and Chernobyl tend to be spread over a week or more. During that period, the wind will move around. At any time, locations at the middle of the plume will see a roughly cubic drop off in momentary harm with plume distance from the source.

Repair Period Choice

Since SNT harm is a bit more than quadratic in repair period dose, if we double the repair period, the repair period harm, is increased by a bit more than a factor of four. But we have half as many repair periods, so the overall harm is roughly doubled. To first order, the SNT harm is linear in the length of the repair period. Longer legislative repair periods are more conservative.

However, society should base the legal repair period on biology. Biology tells us that DNA repair is almost always complete in 12 hours.[183] By that time, the repair has either succeeded or failed. A repair period of a day is already on the high side. Also shorter repair periods allow a more accurate description of a rapidly changing dose rate profiles. If society wants to be more generous to the downwinders, the payment per Lost Life Day can be increased.

Chapter 7

Thyroid Cancer

It is now time to talk about radiation and childhood thyroid cancer. There are two reasons for separating thyroid cancer from the other long terms effects of a release:

1. Thanks to the ability of the thyroid gland to concentrate iodine in a tiny organ, the dose rate to the thyroid can be magnified by a factor of 1000 or more. Thyroid dose rates of over a 1000 mSv/day can easily occur if a child drinks ^{131}I contaminated milk.
2. It is not necessary to prevent a release to avoid these harmful dose rates. It is only necessary to prevent children from drinking and eating ^{131}I contaminated food. This requirement disappears in about 8 weeks.

7.1 Childhood Thyroid Cancer at Chernobyl

In the three major releases of radioactive material to date from nuclear power plants, the only statistically significant harm to the public that has been detected is a dramatic increase in thyroid cancer to the young who were living near Chernobyl, Figure 7.1.

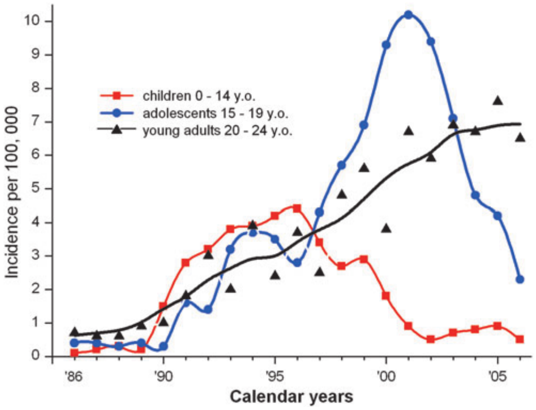


Figure 7.1: Childhood thyroid incidence in Belarus, 1986-2006

At Fukushima, about 300,000 children received intensive thyroid screening. 191 thyroid cancer cases were operated on.[284][Table 2] With no special screening, the childhood thyroid cancer incidence rate is around 1 per million. The Fukushima incidence was 0.00064 or 640 in a million. Intense screening resulted in a 600-fold increase in diagnosed cases.

However, there is no evidence that radiation has anything to do with this. Thanks to stringent control of contaminated food, almost all these kids received low to zero thyroid doses. There were no locational differences between kids closer to the plant and those farther. The age distribution was inconsistent with a radiation induced spike. When a control program was instituted in Aomori, Yamanashi, and Nagasaki prefectures, nowhere near Fukushima, the detection rates were similar.[103] Toki et al did a detailed study of the Fukushima child thyroid data.[252] They found no statistically significant relationship between thyroid incidence and ^{131}I contamination.

They did find a relationship between air dose rates, almost all from cesium, in the towns where the kids lived and thyroid cancer. This made no sense since the thyroid dose from ^{131}I (not to mention dose rate) was far higher than the thyroid dose from cesium. The authors called this “puzzling”. The best they could come up with was the kids from the higher — but still tiny in terms of radiation harm — dose rate towns were under more psychological stress, and psychological stress can cause cancer among other ailments. Be that at it may, the Fukushima thyroid cases were not caused by radiation damage.

However in a Belarus study, 16,213 kids were screened, and 87 had thyroid cancer, Table 7.1.[287] Assuming their screening was as intense as the Japanese, we would have expected 0.00064* 16213 = 10.5. In a Ukrainian, 13,127 kids were screened, and 45 had thyroid cancer, Table 7.2.[253] We would have expected 0.00064* 13127 = 8.5. And there was a strong relationship between dose and cancer incidence. Probably 90% of these cancers was radiation related.

Most of the thyroid dose has been traced to the consumption of milk contaminated with ^{131}I. 20 to 30% of any iodine that is ingested ends up in the thyroid gland. An adult thyroid gland has a mass of only 15 grams, one five thousandths of a 70 kg body, and a child’s thyroid is smaller still. ***The thyroid dose is concentrated by a factor of 1000.*** At Chernobyl doses to the thyroid ranged as high as 48,000 mGy.

More importantly, ^{131}I has a half-life of 8.04 days, and weathering cut the half-life of iodine in the milk to about 5 days.[1] These high doses were incurred over a relatively short time, a few weeks. ***The dose rates could be as high as 2000 mGy/d.***

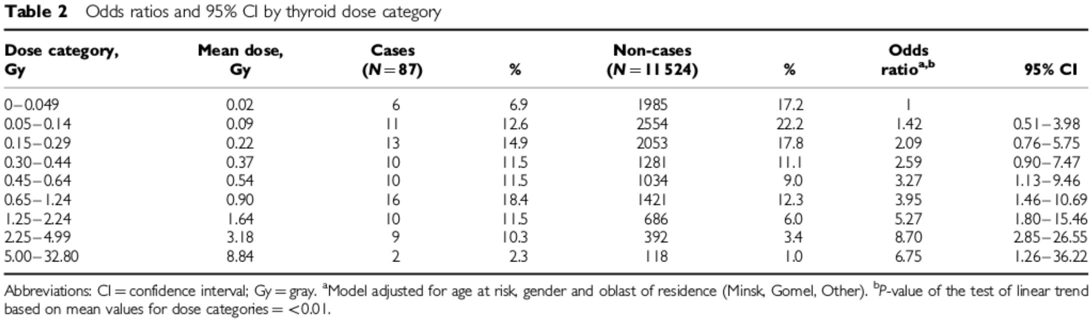


Table 2 Odds ratios and 95% CI by thyroid dose category

Dose category, Gy	Mean dose, Gy	Cases (N=87)	%	Non-cases (N=11 524)	%	Odds ratio^{a,b}	95% CI
0–0.049	0.02	6	6.9	1985	17.2	1	
0.05–0.14	0.09	11	12.6	2554	22.2	1.42	0.51–3.98
0.15–0.29	0.22	13	14.9	2053	17.8	2.09	0.76–5.75
0.30–0.44	0.37	10	11.5	1281	11.1	2.59	0.90–7.47
0.45–0.64	0.54	10	11.5	1034	9.0	3.27	1.13–9.46
0.65–1.24	0.90	16	18.4	1421	12.3	3.95	1.46–10.69
1.25–2.24	1.64	10	11.5	686	6.0	5.27	1.80–15.46
2.25–4.99	3.18	9	10.3	392	3.4	8.70	2.85–26.55
5.00–32.80	8.84	2	2.3	118	1.0	6.75	1.26–36.22

Abbreviations: CI = confidence interval; Gy = gray. ^{a}Model adjusted for age at risk, gender and oblast of residence (Minsk, Gomel, Other). ^{b}P-value of the test of linear trend based on mean values for dose categories = <0.01.

Table 7.1: Zablotska breakdown of Belarussian thyroid cancer data

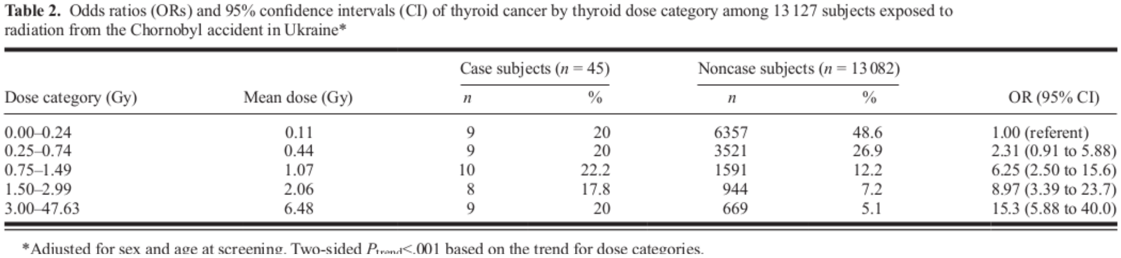


Table 2. Odds ratios (ORs) and 95% confidence intervals (CI) of thyroid cancer by thyroid dose category among 13 127 subjects exposed to radiation from the Chornobyl accident in Ukraine*

		Case subjects (n = 45)		Noncase subjects (n = 13 082)		
Dose category (Gy)	Mean dose (Gy)	n	%	n	%	OR (95% CI)
0.00–0.24	0.11	9	20	6357	48.6	1.00 (referent)
0.25–0.74	0.44	9	20	3521	26.9	2.31 (0.91 to 5.88)
0.75–1.49	1.07	10	22.2	1591	12.2	6.25 (2.50 to 15.6)
1.50–2.99	2.06	8	17.8	944	7.2	8.97 (3.39 to 23.7)
3.00–47.63	6.48	9	20	669	5.1	15.3 (5.88 to 40.0)

*Adjusted for sex and age at screening. Two-sided P_{trend}<.001 based on the trend for dose categories.

Table 7.2: Tronko breakdown of Ukrainian thyroid cancer data

---

[1] Biological half-life of ^{131}I in the thyroid is 120 days. The effective half-life is 7.5 days.

7.2 Thyroid Dose Rate Profiles

Unfortunately, no one has attempted to measure the daily dose profiles, which is what SNT needs to estimate the harm to these kids. To try to fill that gap, I used a model which takes as input:

1. The peak ^{131}I concentration in the milk.
2. The ramp time in days it takes to get to that peak.
3. The time in days it stays at that peak. During this period, the increase in concentration is assumed to be matched by the decay. After this period, the milk contamination decays at the effective half-life of ^{131}I.
4. Thyroid mass and uptake.
5. The amount of milk consumed per day,

The first three parameters allows us to compute an idealized milk contamination profile. These are shown as the dashed lines in Figure 7.2. The last two parameters allow us to convert that contamination profile into a thyroid dose rate profile, the solid lines in Figure 7.2.

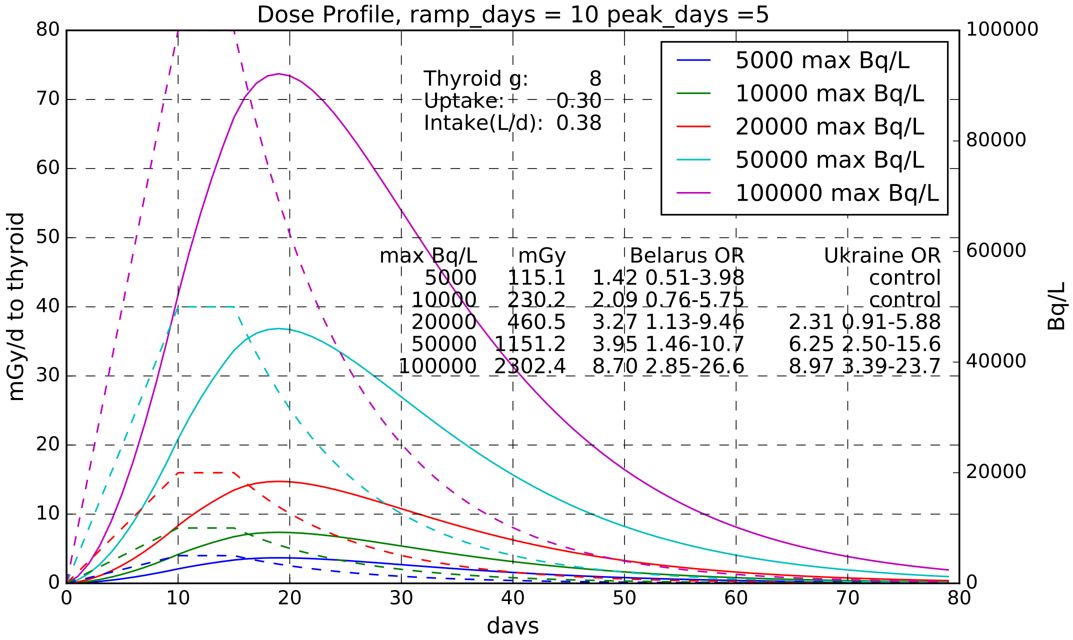


Figure 7.2: Milk Contamination (read right) and Thyroid Dose (read left) Profiles

Zablotska et al screened 11,600 Belarussian kids from the area around Chernobyl and found a mean thyroid dose of 560 mGy.[287] Tronko did the same for 13,127 Ukrainian kids and came up with a mean dose of 730 mGy.[253] Close to 3000 children were above 1500 mGy. The highest measured dose was 47000 mGy. Figure 7.2 shows that, under our assumptions, it would take something like 30,000 to 40,000 Bq/L milk to get to the mean numbers. For the high end kids, the milk must have been well above 100,000 Bq/L.

At Windscale, the highest milk contamination was 50,000 Bq/L on a farm 15 km from the reactor.[106][page 126] Chernobyl released 1000 times more ^{131}I than Windscale.[68][p 166] I have been unable to find any milk contamination numbers for the areas close to Chernobyl. But in the Plavsk region of Russian, 500 kilometers from Chernobyl, 1000 to 5000 Bq/L were measured.[114] I would expect contaminations at least 20 times higher 30 km from the plant, on the edge of the Exclusion Zone.

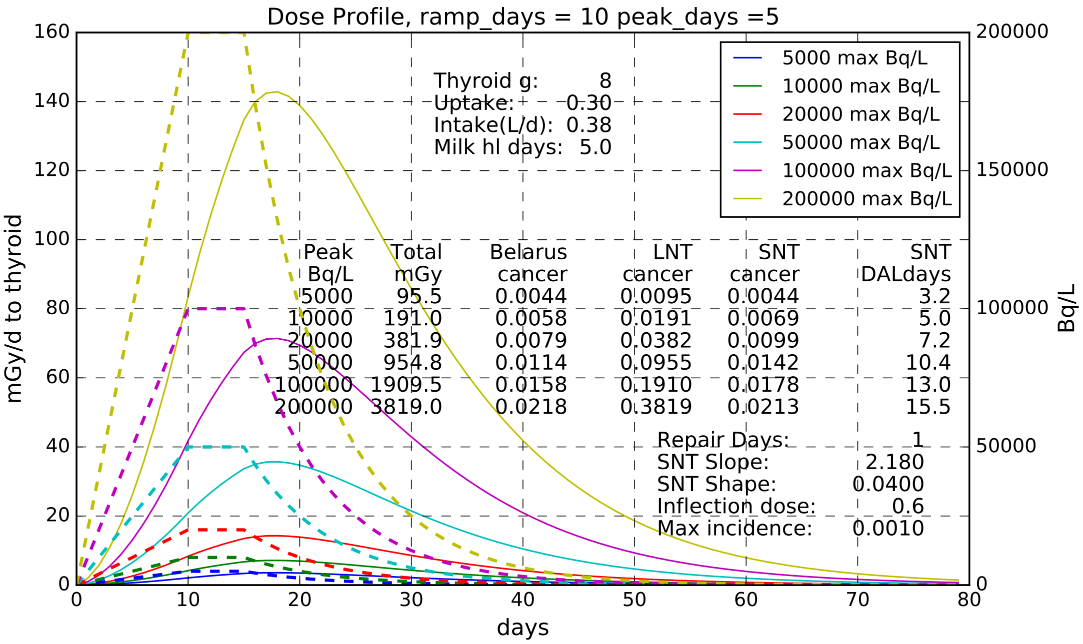
The most important feature of Figure 7.2 are the dose rates. The 50,000 Bq/L profile peaks out at just under 40 mGy/day. The kids who were drinking 100,000 Bq/L milk, got over 70 mGy per day. The Odds Ratio for the Zablotska and Tronko studies are shown on the graph. Because the incidence is low, the statistical power is quite poor. But we start seeing clearly significant increase in cancer at around 20,000 Bq/L. This corresponds to thyroid dose rates in the 10 to 15 mGy/d.

The cumulative doses in these dose profiles, shown in the column labeled mGy, are still far below the worst case thyroid doses observed at Chernobyl. The average dose in the Belarus cohort was 560 mGy. Under the assumptions of Figure 7.2, this corresponds to a peak milk contamination of 29,500 Bq/L and a peak dose rate of 21 mGy/d.

A lot of kids around Chernobyl exceeded 20 mSv/d to the thyroid. As a result, we have seen as many as 4000 thyroid cancers, and may end up with as many as 160 premature deaths. ***The one thing we must do in a release is prevent kids from drinking highly contaminated milk.***

7.3 An SNT Model of Thyroid Cancer

We have fitted a 5 parameter logistic to the Belarus thyroid cancer data. The fit is based on assuming the dose profiles of Figure 7.2 are realistic, and then searching for the SNT parameters that result in the observed cancer incidence for those dose profiles.



Thyroid g: 8
Uptake: 0.30
Intake(L/d): 0.38
Milk hl days: 5.0

Peak Bq/L	Total mGy	Belarus cancer	LNT cancer	SNT cancer	SNT DALdays
5000	95.5	0.0044	0.0095	0.0044	3.2
10000	191.0	0.0058	0.0191	0.0069	5.0
20000	381.9	0.0079	0.0382	0.0099	7.2
50000	954.8	0.0114	0.0955	0.0142	10.4
100000	1909.5	0.0158	0.1910	0.0178	13.0
200000	3819.0	0.0218	0.3819	0.0213	15.5

Repair Days: 1
SNT Slope: 2.180
SNT Shape: 0.0400
Inflection dose: 0.6
Max incidence: 0.0010

Figure 7.3: SNT versus LNT on thyroid cancer

The results are shown in the lower right corner of Figure 7.3. Astonishingly, it turns out the best fit is to assume a repair period of a day and use a curve, which for all practical purposes is an exponential with an upper asymptote of only 0.0010, meaning even if the kid got an infinite dose in a day, the increase in cancer incidence for that day would be 0.0010. The lower hook is there; but it is so small compared to the thyroid doses these kids got it plays almost no role.

Focusing on the cancer incidence columns in Figure 7.3, we see that LNT does an extremely poor job of replicating the thyroid cancer data. There is no LNT slope that can fix this. The 5 parameter logistic has no problem fitting the data.

The authors of the Belarus paper also found that an exponential fitted their data far better than linear, Figure 7.4. In fact, a linear fit was statistically rejected[287][page 183] They then proceeded to ignore that inconvenient fact, by focusing only on the low end, where the data is very roughly linear, the opposite of the usual LNT ploy. If you narrow the dose range of interest enough, you can always find a portion of the curve that is sort of linear.

The ^{131}I thyroid harm is completely different from the whole body, primarily cesium based harm.

1. The peak childhood thyroid dose rates are 100 times higher than the peak public cesium based dose rates, creating easily detectable increases in cancer. The cesium whole body dose rates are so low that, even at Chernobyl, we see no increases in other cancers in the public.
2. For the non-thyroid cancers, we are down in the bottom hook of the S, where the response is roughly quadratic in the repair period dose. For the thyroid cancers and the upper end of the doses these kids got, we are well up into the upper hook of the S, where the response is far lower than linear in repair period dose.

The obvious question is why do we see this counter-intuitive behavior? One possibility is really high dose rates wipe out any pre-existing thyroid nodules like an ablation. So they do as much good as harm. At this point, this is just speculation. But one thing we cannot do is ignore the data, and pretend the response is linear.

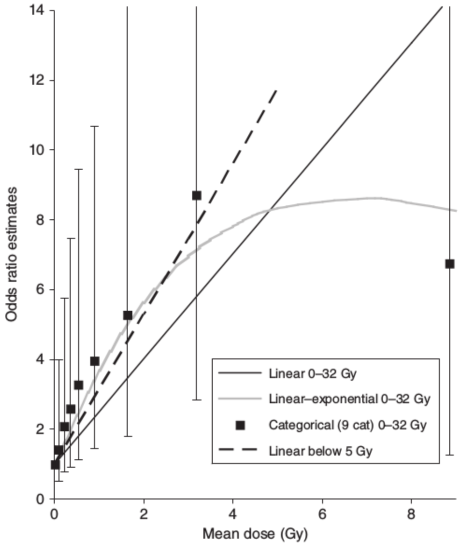


Figure 2 Categorical odds ratios and fitted dose–response lines

Figure 7.4: Exponential response to thyroid dose, Zablotska Figure 2.

7.4 Compensation

Thyroid cancer is often dismissed on the basis that it is "treatable" and has a low mortality rate of about 1%. But the usual treatment is a thyroidectomy, which means hormone treatments for the remainder of the patient's life, and likely a shorter life span. The WHO puts the Disability Adjusted Life Years (DALY) associated with thyroid cancer is two years.[186] If we apply that DALY to the SNT increase in cancer, we obtain the rightmost column in Figure 7.3. The expected Disability Adjusted Life Days for the Belarus cohort ranges from 3 to 15 days. Using the US dialysis standard, that a life day is worth \$350, the compensation at Chernobyl would run from about \$1000 to \$5000 per child. If we assume 50,000 children were involved, the total compensation would be very roughly \$150,000,000. It would have been far better to prevent the consumption of contaminated food.

Chapter 8

Fear Induced Deaths

8.1 Chernobyl

Along with just about everybody else, I've glossed over the most grievous impact that nuclear power has had on public health, the Lost Life Expectancy and Lost Life Quality due to fear of radiation.

In reviewing Chernobyl, the World Health Organization came to the conclusion "The mental health impact of Chernobyl is the largest public health problem caused by the accident to date."[20][page 95] These effects are hard to quantify. Anecdotal stories abound of depression, anxiety, medically unexplained disorders, and increased alcoholism. These problems need not be related to actual dose. One interesting study asked 499 villagers to agree/disagree/not sure to "I think I have an illness due to radiation."[93] 263 were from contaminated villages. 236 were from uncontaminated villages. 41% from the contaminated villages agreed, 10% disagreed. 28% from the uncontaminated villages agreed, 22% disagreed.

But studies meeting western medical standards are few. They pretty clearly show increased morbidity in females, particularly mothers. A significant excess suicide rate was found in Estonian liquidators, who were forced into this service. Bromet and Haveanaar summarize their 2007 survey of the information

> Chernobyl was a complex, high impact disaster and its emotional toll was substantial and protracted. It took the form of depressive, anxiety, and somatic symptoms, and increased use of medical services among the exposed population, although there is no evidence that it led to increased rates of psychiatric disorders per se or organic brain involvement in exposed children or clean up workers. The highest risk group appear to be women with young children although evidence about a high incidence of suicide in clean up workers suggest they too comprise a high risk group.[26]

Others are no so restrained. Kate Brown's book "Manual for Survival" paints a very different picture.[28] This writer spent years in Russia and the Ukraine, pored over stacks of government documents, interviewed 100's if not 1000's of people affected by Chernobyl. Her conclusion is that the impact of Chernobyl has been vastly understated, not just with respect to cancer, but to a wide range of other diseases and ailments, which she attributes to radiation. Her writing style is prolix and florid. My favorite "The leaping, bounding, galloping rates of maladies took shape, a dark horseman riding across the Chernobyl territories."[28][p 195]

Brown is not much interested in western science which is beholden to the same people that brought us the atom bomb. She calls them the "physicists" and contrasts them to Russian doctors who have cared for radiation patients from casualties in the Russian nuclear weapons program. She is particularly taken with Dr. Angelina Gus'kova.

> No one in the world had treated more patients with radiation illness than Gus'kova.
>
> Working on hundreds of patients suffering from radiation exposure over three decades, Gus'kova developed a compendium of knowledge on radiation medicine that had no equivalent in the world.[28][p 13,15]

Everywhere Brown goes she finds evidence of wide spread harm that the establishment has failed to recognize. She has no problem finding interviewee after interviewee who is certain his or her ailment is caused by radiation. She has no problem uncovering the clumsy attempts by the apparat to downplay the disaster.

But she just as clumsily overstates her case. Brown claims that "the ill-advised detonation of nuclear weapons in Nevada delivered to milk drinking Americans across the the U.S continent an average collective dose of radioactive iodine similar to that of people living in the Chernobyl area."[28][p 311] Where are all the Chernobyl area health problems in these milk drinking Americans?

Brown makes almost no mention of background radiation. It's as if she is not aware that we are bathing in radiation our whole life. She has either learned nothing about her subject or is pretending this is the case.

The book is awash in contamination rates: ground contamination, milk contamination, berry contamination, wool contamination. But she rarely gets into dose rates. When she does, it's not pretty. After the first few years, the main source of radiation was Cesium-137. She claims that half of ^{137}Cs will still be around for 180 to 320 years.[28][p 302] In fact the decay half-life of ^{137}Cs is 30.4 years. In 180 years, more than 98% of ^{137}Cs will have decayed to non-radioactive barium. And weathering will isolate much of the cesium far sooner.

Speaking of contamination, in 1990, four years after the explosion, the Soviets ordered the relocation of any area contaminated with more than 137,000 Bq/m2 of ^{137}Cs. Sounds like a big number, but the external dose from this cesium is about 1.8 mSv in the first year with a lifetime dose of 6 mSv.[258][p 647] The first year dose is well below natural background in large parts of the planet, and the lifetime dose is a small fraction of the lifetime dose that all of us will be exposed to. 220,000 people were needlessly forced out of their homes.[1]

One of Brown's main claims is that the ingestion of food contaminated with ^{137}Cs spread illnesses far and wide. It is true that, after the Unit 4 sarcophagus was completed, a large portion of the doses in the contaminated areas was from ingestion of Cesium-137. The uptake of ingested cesium is high; about 80% is absorbed into the body. This is not included in the last paragraph. Bouville and Drozdovitch of the National Cancer Institute say "The relative contributions of external and internal radiation to the dose from ^{137}Cs were on average about equal, but they depended on the type of soil, on the type of diet, and on countermeasures."[23] So the total dose in a 137,000 Bq/m2 area is roughly 4 mSv in the first year and 12 mSv lifetime. In ordering the 1990 relocation, the government very belatedly told everybody that this dose is so dangerous that it is worth uprooting people from their homes. No wonder they were scared.

Brown never mentions the fact that the biological half-life, the time it takes half of any ingested cesium to leave the body, is between 70 and 110 days.[105][p 163] Instead we are told "Radioactive isotopes do not readily leave the body". Bouville and Drozdovitch say "Internal radiation from ^{137}Cs is uniformly distributed in all soft tissues of the body (not in the skeleton) and is eliminated from the body within a few months."[23] Of course, the ^{137}Cs does not disappear, at least not immediately. It will be recycled through the environment and a portion could be ingested again.

Without support, Brown claims that 5 mSv/y is unsafe.[28][p 197] As we have seen, millions of humans live in areas where the background radiation is more than 5 mSv/y. Yet we cannot see any increase in cancer.

Brown claims with absolutely no support that a chronic dose "slow drip of beta [electrons] and alpha particles ... over many years" is worse than the same acute dose.[28][p 213] ***Not once does she mention the repair processes with which evolution has equipped us.***

She claims that radiation is the only known cause of myeloid leukemia, a flat falsehood.

Here's how Brown describes the radium dial painter cancers.

> When a few radium dial workers died and their relatives filed lawsuits, managers at the Radium Dial Company and U.S. Radium claimed the women's doses were too low to cause health problems. They had the backing of university researchers and local public health officials, both of whom in 1920s generally bowed before the power of corporations. After several more women died and others became invalids, company officials hired their own medical doctors to investigate. When those physicians ruled that radium could indeed be a factor, the company managers hid the reports or found other less competent "experts' to vouch for worker safety. When the lawsuits picked up speed, company businessmen courted public health officials, lobbied for restricting workmen's compensation laws, produced their own misleading health statements, and hired teams of lawyers who did their best to sow confusion and stall legal rulings.

---

[1] The initial evacuation of the area immediately around the plant involved 116,000 people.

> ...
>
> It took fourteen years for the women to win the first lawsuit. A medical researcher, Robley Evans, studied the radium dial workers in the 1930s and determined that trace amounts, as little as two micrograms of radium caused death.[28][page 92]

There is no mention of the doses involved. Nor the fact that the same Dr. Evans pointed out that there were no cancers in women who had received less than 160,000 mSv, a dose that is a 500 times higher than the Chernobyl exposures with the exception of 100 or so first responders.

In 2015, Deryabina et al published a census of wild life in the Belarus sector of the exclusion zone. It showed that large mammals were thriving. Relative abundances of elk, roe deer and wild boars were similar to those in four uncontaminated nature preserves and wolf abundance was 7 times higher.[66] Unsurprisingly, animal tracks showed that the wild life were not avoiding the most highly contaminated areas. One of the coauthors of this study was an English ecologist, Jim Smith. Here's how Brown tells the story.

> In 2015, the physicist, James Smith, made headlines by publishing a short letter stating that long term census data revealed abundant wildlife populations in the Zone of Alienation. The story went viral. Major media ventures picked up Smith's two page letter in an academic journal and repackaged it. For a few weeks, Smith became a media darling.
>
> I contacted Jim Smith to ask him if I could follow him on his next trip to the Zone. He replied he had no plans to visit. ... He did not need to go to the Zone. Computational studies combined with levels of radioactivity told him what he needed to know.

The careful wording clearly implies the Smith has never been to the Zone without actually saying so. In fact, Smith had been to the Zone over 40 times.[235] The paper is supported by 18 pages of supplementary data. In Brown's footnotes, the paper is listed as "Smith et al" when in fact the lead author is the Belarussian Tatiana Deryabina. The term physicist is used almost as an epithet.[2] What's lost in all this blatant obfuscation is that Brown makes no attempt to refute Deryabina et al's findings. Nor could she. The Zone of Alienation has become the major tourist attraction in the region.

Brown claims that many of the liquidators suffered from the same non-cancer ARS symptoms as the staff and the first responders did. The problem for Brown is her hero expert, the caring Dr. Gus'kova, has a different opinion.

---

[2] In Brown's world, the western radiation protection establishment is a bunch of grant obsessed physicists while the Russian professionals are real doctors caring for real patients. In fact, many of the western radiation specialists are practicing physicians, and Russia and other Eastern European countries are well represented on the international bodies dealing with radiation.

> In contrast, to the first group [the 134 ARS victims] this second group of individuals working within the 30 km zone, just as the population exposed to radiation, did not exhibit any manifestations of radiation sickness.[100]

Brown's book is a polemic. Brown herself is a propagandist, every bit the master of the half-truth and the misleading statement that she accuses the nuclear establishment of being.[3] But Brown's work does document the extent of the anxiety and the impacts of that anxiety on the region. The WHO was right. The psychological impacts on the region and their consequences were even greater than the enormous direct impacts.

8.2 Fukushima

Whatever the fear induced impacts of Chernobyl, there is no doubt that the fear induced effects at Fukushima completely overwhelmed the non-fear-induced sure deaths and any radiation related cancer deaths. Two plant employees were killed when the tsunami came ashore and flooded the turbine hall. The WHO using LNT expects that any increase in cancer mortality due to radiation will be so low that we will not be able to reliably measure it.[276][p 10-11][4] Our own estimate, assuming no evacuation, is a public Lost Life Expectancy due to radiation of 6 years.

According to Section 5.1.1, approximately 1600 elderly people died in the botched, unnecessary evacuation, most of them within a week or two. Some sources now put the total toll among

---

[3] Prof. Brown has now gone on to explore the history of "indigenes, peasants and maverick scientists who understood long before others that plants communicate, have sensory capacities, and possess the capacity for memory and intelligence."

[4] In 2018, the Japanese government awarded compensation to a Fukushima plant worker in his 50's who died of lung cancer. Unsurprisingly this generated headlines such as "Japan confirms first Fukushima worker death from radiation" (BBC) and "Japan says Fukushima Radiation caused worker's death" (New York Times).

The man was diagnosed with the disease in February, 2016, which would be an unusually short latency if the release caused his death. Available information is sketchy; but it appears the man received 34 mSv in the 9 months after the release, and another 40 mSv in the next four years. We are told the total exposure for his 28 year career was 195 mSv, which would be an average of 3.8 mSv for the other 23 years All these dose rates are well below background in Kerala except the first month or two after the release.

Lung cancer was not highly elevated in the bomb survivors. Table 24 in reference [210] says they observed 101 cases of lung cancer in the RERF cohort that received 100 to 200 mSv against an expected 99 cases. Despite this clearly insignificant difference, Preston et al using LNT say we should attribute 9.8% of lung cancer deaths in this cohort to radiation. Using Preston's way off LNT fit, there is a 90% chance that the man did not die from his exposure.

Not only does LNT not match the RERF data in this category, but the bomb survivors received almost all their dose in matter of minutes. This man experienced dose rates that were many orders of magnitude less. If we apply SNT to this man, arbitrarily assuming 20 mSv in the 1st month after the release, 7 mSv in the next month, and 1 mSv per month for the next 7 months, and 0.833 mSv per month for the next 4 years, his excess risk would be 0.03%. Under these assumptions, there is a 99.97% probability, the exposure did not cause his death. The Japanese have a rule that says compensation is due if the worker receives more than a 100 mSv cumulative and the cancer shows up more than 5 years after exposure. This guy qualified; so radiation caused his death.

the evacuees at more than 3000 based on increased mortality rates. And on top of this, we have all the quality of life impacts including the very real psychological distress on some 160,000 evacuees and indeed anyone who believes his life has been seriously affected to the dose rates he has been exposed to, ***regardless of the fact that in all but a handful of cases those dose rates were below background dose rates on a sizable portion of the planet.***[5] As of 2015, 85,000 people had not returned to their homes.[248]

An important feature of the Fukushima panic is that it was driven not by anti-nukes, but by the government, by portions of the nuclear power establishment. The strangely named Ministry of Education, Culture, Sports, and Technology (MEXT) issued weird proclamation after proclamation. Transport of gravel was "safe" only if it's activity was less than 100 Bq/kg. As Table 8.1 shows, all sorts of substances have an activity exceeding 100 Bq/kg.

Table 8.1: Radioactive Activity in Every Day Stuff

Material	Bq/kg	Material	Bq/kg
Humans	70-100	Milk Powder	450
Beef	125	Instant Coffee	945
Banana	140	Granite	1000+
Potatoes	165	Coal Ash	200-1000
Cat Litter	175	Phosphate Fertilizer	600-1200
Fish	56-260	Salt Substitute	16000
Mushrooms	30-400		

MEXT pronounced swimming "safe" if the activity of the water was less than 10 Becquerels per liter. Normal seawater has an activity of 12 Bq/L. The nuclear establishment panicked and in the process panicked the public.[6]

Perhaps the worst move was the government's policy of "remediating" any area in which the dose rate is 1 mSv/year above background. In practice, this means removing valuable top soil at great expense and putting it somewhere where it cannot be used, denuding and uglifying the countryside. This clearly tells any would be returnee that 1 mSv/year above background must be dangerous. But what about 0.75 mSv/year about which the government is doing nothing. If

---

[5] There is a good chance that the severity of the release was magnified by orders of magnitude by misplaced fear.[56] At 12:20 AM on March 12, the site manager, Maseo Yoshida wanted to vent Unit 1 and asked Tepco-Tokyo for permission. Tepco forwarded the request to Prime Minister Kan. But Kan delayed the venting until a 3 km radius around the plant has been fully evacuated. By then enough hydrogen had leaked into the outer building to cause a big explosion, which not only released a large amount of radioactive material, but also knocked out the mobile emergency diesel which six minutes earlier had started sending power into Units 1 and 2, to begin core cooling. The debris also obstructed the attempt to get another mobile diesel generator to Unit 3. Without the delay in venting, Fukushima might have looked a lot like Three Mile Island.

To compound Kan's error, the winds were blowing out to sea on March 11th and predicted to stay offshore for another two days, something he knew or should have known.

[6] The Japanese nuclear establishment had plenty of company. The Italians evacuated their Tokyo embassy to Rome where the dose rates are nearly four times those in Tokyo. The NRC said that, if the release had happened in the US, they would evacuate everybody within 50 miles of the plant. The NRC would have compounded the tragedy far worse than the Japanese did.

I thought the government's policy was rational, I wouldn't return either.

The establishment then further compounded the mess by shutting down all 54 Japanese reactors, when only 15 were at risk from tsunami. Not only did this impose a severe economic burden on Japan and expose the population to fossil fuel pollution, but it was further proof that nuclear power is unsafe. But the establishment was in a bind. It had told the public that a release would not happen. The lie had been revealed. It knew whatever it did it would not be trusted. So it flailed about desperately, hoping that this somehow would make up for the lie. Didn't work. The Japanese even have a word for the no-release lie. They call it *anzen shinwa*, the safety myth.

8.3 Three Mile Island

It goes without saying that the fear induced effects of Three Mile Island were far, far greater than any health risk associated with the release, since for practical purposes there were none. The best estimate of the average extra dose to the 2.2 million people living near the plant is 0.015 mSv.[16] That's a bit less than a one-way flight from New York to Los Angeles. This number assumes no evacuation and a number of other purposely conservative assumptions. The official LNT estimate of the number of additional fatal cancers to these 2 million people is 0.7.[128][p 12] For us non-LNTers, what we are interested in is the dose to the most exposed individual. That would be 1 mSv if a person stood next to the highest reading off-site dosimeter from March 28 to April 7.[7] The TMI study group did find one member of the public who they thought received a dose of 0.37 mSv. His SNT Lost Life Expectancy is 2 seconds.

But there was a panicked evacuation and wide spread concern.[8] I have a great deal of sympathy for the evacuees. There was not just fear. There was anger. These people had been lied to. Now they don't know whom to believe. They are not going to move their kids out of harm's way because they are supposed to believe the same people who told them this would not happen?

The lying continued during the accident. In a press release, issued for the evening news on the first day of the casualty, the NRC said:

> ... Low levels of radiation have been measured off the plant site. ... It is believed that this is principly direct radiation from radioactive material within the reactor containment building, rather than from release of radioactive material from the containment.

The NRC concocted that whopper because they were unwilling to admit that a release had occurred. Hard to imagine a stupider lie. Here's how NBC's Tom Brokaw interpreted this:

---

[7] The TMI release was almost all Xe-133 and some I-131. Xe-133, a noble gas, has a half-life of 5.3 days. I-131 has a half-life of 8 days. A combination of decay and dispersion meant the dose rates died off quickly.

[8] Bishop Keeler of Harrisburg was so convinced his flock faced imminent annihilation that he declared general absolution. Father Keeler was later promoted to Cardinal.

> The Nuclear Regulatory Commission in Washington says radiation penetrated through walls that were four feet thick, and it spread as far as 10 to 16 miles from the plant.

Brokaw may have imbellished a bit, but he had an impeccable source. At least 3 of the 5 NRC commissioners cleared this nonsensical falsehood.[220]

This is just one of many blunders during TMI that exposed the incompetence and bureaucratic malaise of the NRC.[97, 128, 220] The proximate cause of the meltdown was the operators shutting down the emergency injection pumps, which is precisely what they had been trained to do. The NRC had received and sat on several clear warnings, that the instructions that the operators had been given were dangerously wrong. The most obvious was the nearly identical casualty at Davis Besse 18 months earlier, in which the operators managed to save the day by going against their training, Section 4.1. But no one was willing to rock the boat. You do not make yourself popular in a bureaucracy by saying there is something wrong with the system. And there is no penalty for remaining silent. The First Rule of Bureaucratic Advancement is: don't let the shit flow uphill.

After the meltdown happened, the NRC's most damaging screw up was to make a statement that the hydrogen bubble in the top of the reactor vessel could explode. Up until that point the residents has remained surprisingly calm, despite a nearly continuous stream of conflicting statements coming from the NRC. But the hydrogen explosion story changed everything. The locals had had enough. The bishop declared general absolution. Tens of thousands threw their kids in the car and got the hell out of there.

The journalists themselves were terrorized. Some 400 had flocked to the story. Few if any knew any thing about nuclear power. When the hydrogen bubble story spread, they joined in the exodus. Their stories reflected their own fright.[29][p 397-398] Anything that scared the hell out of a war correspondent must be really bad.

The theory was nonsense. There was no oxygen in the hydrogen bubble. The hydrogen in the bubble would immediately convert any oxygen created in the reactor back to water. This would have been obvious to anyone with even the most basic technical competence.

Both the official semi-independent reports on Three Mile Island, the Kemeny Report[128] and the Rogovin Report[220] were extremely critical of the NRC. But the solution is more regulators and more procedures, and most importantly more paperwork. The safety-critical QA program failed, so we need a more comprehensive QA program. The single failure based PRA failed, so we need more comprehensive PRA. This illustrates the First Rule of Bureaucratic Expansion: screw up and you get bigger. In a competitive market, screw up and you disappear.

About a year after the meltdown, some gas still trapped in containment needed to be released so that recovery work could begin. No one would be exposed to as much as 0.01 mSv. A poll taken prior to the release indicated there was substantial fear of the release among the locals. So the NRC undertook a careful public education campaign to explain how trivial the health risks were. A poll taken after the campaign showed that the fear had increased. The nuclear establishment was dumbfounded.[50][p 71] Somehow an exposed, unapologetic, serial liar expected to be believed by the victims of his lies.

At the same time, it is impossible to have any sympathy for journalists who scream “RADIATION" as the one word headline in a Boston newspaper did after TMI, with no mention of the fact that the extra dose was about four days worth of normal background. Journalists know the importance of numbers. Just about every car wreck or airplane crash headline starts off with a number “89 Killed, 12 Hurt in ....". Yet numbers are rare to non-existent in the reporting of radioactive releases or contamination.[9] This is inexplicable since radiation is ubiquitous. The only interesting question is: how much? I could shout “RADIATION" any time, any where and be correct.

8.4 Can we have a release without panic?

After World War II, the British were desperate to get the bomb. They needed weapons grade plutonium. But the Special Relationship with the USA did not include sharing secrets on plutonium production. They were on their own. What they came us with was two enormous, klutzy piles of graphite in northwest England at a place called Windscale. Cartridges contain uranium were pushed into holes in the graphite on one side, pushing the irradiated cartridge already in the hole out the other. The reactors were air cooled.

The graphite was used to slow the neutrons down to create a self-sustaining chain reaction. Unfortunately, the British knew very little about the behavior of graphite under radiation. Under the right conditions, irradiated graphite can store energy, which if not released properly can start a fire. Releasing this energy requires *annealing*, which is done by increasing the reactor temperature.

The Cold War was at its peak. Windscale was under intense pressure to produce more and more isotopes. Ad hoc modifications were made to increase plutonium production. Later they started making tritium for an H-bomb using magnesium/lithium cartridges. This required increasing the enrichment of the uranium fuel. The poorly designed facility experienced continuing problems, stuck and broken cartridges, unexplained temperature excursions, and sporadic leaks.

On October 8, 1957, Windscale 1 caught fire during an attempted anneal. The culprit was probably the magnesium/lithium cartridges.[10] The fire destroyed the reactor. Radioactive material spewed out of the 410 foot high cooling stack, and spread out over the Cumbrian countryside. Table 8.2 compares the amounts released at Windscale with those at Three Mile Island. At TMI, almost all the iodine and cesium stayed dissolved in water within the containment. And the gases that were vented passed through a high performance filter. Based on ^{131}I, if we had to put a number on it, we might say the Windscale release was 1500 to 3000 times worse than TMI.

So what happened at Windscale? Not much. There was no evacuation, voluntary or involuntary. Milk produced in the neighboring area (about 500 square kilometers) was condemned and

---

[9] It is perhaps defensible that TV and news reporters don’t talk about millisieverts. But they could easily relate the extra dose to background levels or that received in activities such as flying or eating bananas. Bananas are high in potassium. Potassium-40 is a photon emitter. The photon dose from eating one banana is roughly 0.1 μSv. The average extra dose at TMI was about 150 banana doses.

[10] The man most responsible for putting out the fire was Tom Tuohy. In the process, he intentionally exposed himself to large amounts of radiation multiple times. Predictably, top management in the British weapons program

Isotope	Three Mile Island	Windscale Beattie[a]	Windscale Garland[b]	Fukushima	Chernobyl
	Release in TBq				
^{131}I	0.555	740	1800	120,000	1,760,000
^{137}Cs	nil	22	180	8,800	79,500
^{134}Cs	nil	?	?	9,000	54,000

Table 8.2: Release magnitudes

[a] 1963, Low end estimates.

[b] 2007, High end estimates.[91]

destroyed, and the farmers compensated. This lasted for a little over a month. The maximum dose to the public was put in the 7 to 9 mSv range.[121][page 4] This included some ^{210}Po.[11] We can be sure that the public SNT Lost Life Expectancy was far smaller than Fukushima.[12] The Windscale auxiliary buildings continued to be used for offices and shops. The site was renamed Sellafield. It remains a center of British nuclear activity. It is possible to have a release without a panic.

8.4.1 The LNT is Prudent Argument

LNT is often defended by people who accept that it is probably wrong at the low dose/low dose rate end; but think it should still be used for regulatory purposes, because it is simple and conservative, a safe fiction. But a model that is conservative by orders of magnitude at the dose profiles experienced in a nuclear power plant release brings with it enormous costs to humanity.

This regulatory convenience is inevitably taken to be a real measure of cancer incidence as the UCS have done, Table 6.6. If leading scientists misuse these “regulatory limits" in this manner, we cannot expect politicians and the general public to do otherwise. This leads to panicked, destructive responses to a release and prohibitively expensive regulation in an attempt to prevent a release. And it leads to psychological anxiety which has very real mental and physical health consequences.

---

attempted to blame the fire on operator error. Tuohy called them “a shower of bastards." Tom Tuohy died at age 90. RIP.

[11] Polonium-210 is a prolific alpha emitter, with a half-life of 138 days. It is the isotope that the Russians used to kill the defector Litvinenko in 2006, by putting it in his tea. The British made it to trigger their bombs, by inserting cartridges containing bismuth into the Windscale piles. ^{210}Po is not a fission product. It is not normally produced by a commercial nuclear reactor.

[12] Since ^{131}I dominated the release, if we were going to have any effect, it would be in thyroid cancer to people who were young at the time of the release. McNally et al found a slightly increased thyroid cancer incidence among Cumbrians who were less than 20 at the time, relative to the rest of England.[163] But they found essentially the same increase in Cumbrians who were born between 1959 and 1963, who had no exposure to the Windscale release. They also found considerable clustering. When the clustering was allowed for, none of the differences were statistically significant.

More fundamentally, if LNT imposed costs result in nuclear power being replaced by fossil fuel sources then LNT is responsible for the health impact of those alternate sources. It is easy to show that coal, oil and gas have a far higher Lost Life Expectancy per electricity generated.[159]

In this vein, the NCRP also justifies LNT on the basis of *prudence*.

> ... no alternative dose-response relationship appears more pragmatic or prudent for radiation protection purposes than the LNT model.[180][p 9]
>
> The LNT model is practical because it is easy to apply and prudent because it is unlikely to underestimate risk at low doses.[180][p 10]

But the NCRP offers no cost-benefit analysis supporting this claim of prudence. In theory, the radiation protection establishment accepts the fundamental principle that radiation protection measures should do more good than harm.[262] This is called *justification*. But in practice, the definition of prudence is minimizing radiation exposure regardless of other costs, a myopic definition that has killed thousands of people and could kill the planet.

8.5 Who is to blame

If these fear induced impacts are inherent in nuclear electricity, then we have to view these consequences very seriously. On the basis of sure deaths, Fukushima moves up from 2 to something like 1600, or 5th on Table's 5.2 list of deadliest energy related casualties. Unless people become convinced that the dose rates that will be experienced in a release as large as Fukushima will have no measurable impact on their health, simply estimating radiation induced cancer deaths greatly underestimates the social cost of a release. Conversely, if people were to accept this fact, then nuclear electricity can be regulated in much the same manner as a coal plant, accepting a tiny detrimental health impact in return for all the benefits of reliable, CO2 free electricity.

But they won't be convinced by a nuclear establishment that

1. nonchalantly accepted LNT in 1959, blithely proclaiming to one and all that release level dose rates are orders of magnitude more dangerous than they are;
2. bases its claim to safety on bogus release probabilities, destroying any right to credibility.

It's time to look at the history of nuclear electricity and why people are so fearful of low dose radiation. It turns out this fear has been abetted and promoted by the nuclear power regulatory/industrial complex itself.

Chapter 9

The Gold Standard, ALARA, and the Cost of Nuclear Power

> Nuclear power is one of the chief long-term hopes for conservation. ... Cheap energy in unlimited quantities is one of the chief factors in allowing a large rapidly growing population to preserve wild lands, open space, and lands of high scenic value. ... With energy we can afford the luxury of setting aside lands from productive uses.[David Siri, Sierra Club Director, 1966]

Cost is key to solving the Gordian knot of electricity poverty and global warming. Cost is not dollars. Rather it is a measure of the amount of the planet's precious resources that is consumed by an activity. The job is immense. We must not only supply reliable electricity to the billions that desperately need it; we must also replace a large portion of the current non-electrical energy system. Unless we do this in an extremely economic manner, in plain english, very cheaply, we will fail and ravish the planet in the attempt.

Currently nuclear electricity is not cheap. In large parts of the world, nuclear power cannot even compete with coal. If this is inherent in the technology, then nuclear is off the table. But if nuclear costliness is manmade, then it can be unmanmade.

This chapter argues not only is nuclear power not inherently costly; it is inherently cheap. But it also argues that the same regulatory system that priced the existing nuclear technology out of the market, will also price any new nuclear technology out of the market, regardless of how inherently cheap or safe that technology is. That regulatory system is called the Gold Standard.

9.1 Unless you are cheaper than coal, don't bother

A modern coal plant, Figure 9.1, is a marvelous piece of engineering.

Figure 9.1: Manjung 4, A Modern 1 GW electric coal plant. Turbine(green) in the foreground. Boiler in the background.

To generate a gigawatt of electricity, the 100 meter high boiler will consume roughly 7,000 tons of coal a day to produce 3200 tons per hour of 282 bar (4000 psi), 600C (1100F) steam, which will be expanded through a 70 meter long turbine.[1]

This coal is fed from a 30 hectare (70 acre) yard, Figure 9.2, dried, pulverized, and mixed

---

[1] These coal numbers are based on a good (6700 kcal/kg), low sulfur Australian Thermal Coal.[110][p 91] For a sub-bituminous coal the numbers will be considerably larger.

Figure 9.2: Manjung4 layout looking landward (top) and seaward (bottom)

with over 77,000 tons per day of heated air that has been pushed into the furnace by immense forced draft fans.[2] The coal yard in turn must be fed by a 100 car train nearly every day or a 150,000 ton bulk carrier every two or three weeks. Often the coal has been transported thousands of miles from a huge open pit mine.

For an average good coal, the process produces roughly 1100 tons a day of solid waste (mostly fly ash) and 200 tons per day of sulfur dioxide. The 84,000 tons per day of stack gas is pulled though an air heater, a SCR unit to remove most of the NO2, a giant baghouse or electrostatic precipitators to remove most of the particulates, and pushed into a scrubber to remove most of the SO2 by immense induced draft fans. SCR (Selective Catalytic Reduction) requires ammonia be sprayed into hot flue gas, and then the gas be directed through a catalytic honeycomb which must be kept free of plugging with sootblowers and sonic horns. The baghouse or precipitators require shakers or rappers to remove the ash, most of which goes to landfills or slurry ponds. Scrubbers require about two tons of pulverized limestone per ton of sulfur in the flue gas. They are high maintenance, energy intensive units. They add a little CO2 to the stack gas. Finally, 18,000 tons per day of CO2, and about 10% of the Gross Calorific Value of the coal is spewed out of the top of a 170 m high stack. The stack height is required to dilute the remaining pollutants in the gas.

Amazingly, a modern coal plant can do all this and produce electricity at about 5 cents per kilowatt-hour.[3] For most of the world, this is the cheapest form of dispatchable power. The problem for natural gas is transportation. Liquifying the gas, transporting it in cryogenic LNG carriers, and regasifying it is enormously expensive. Even in a world where massive amounts of gas are being flared in west Texas, the delivered cost of gas in most parts of the world results in an electricity price of 7 or 8 cents per kWh. Unless you have access to a great deal of pipeline gas, coal is cheaper. Oil is way more expensive. Because oil is so valuable as a transportation fuel, the cost of electricity power produced by oil is in excess of 20 cents per kilowatt-hour.

In Figure 9.1, the turbine hall is in front of the boiler. The boiler towers over the turbine hall. But what we don't see in Figure 9.1 is all the stack gas treatment equipment which is on the other side of the boiler. Figure 9.3 shows that this equipment takes up even more space than the boiler. Very roughly, one third of the cost of a coal plant is power conversion (the turbine hall and the electrical switchyard), one third is the boiler and coal handling, and one third is stack gas treatment. The power conversion portion costs about $500 per kW. The remainder, the steam generation side, costs between $1000 and $1500 depending on how tight the air pollution

---

[2] The reason a coal plant needs 11 tons of air per ton of fuel is nitrogen. Air is 80% nitrogen. Nitrogen contributes nothing to the combustion process. It just comes along for the ride, consuming energy, and creating some NOx (aka smog) in the process.

[3] One argument you will hear is that the reason that nuclear plants are so expensive is the contractors do not have the necessary skills. Physically and technically building a nuclear plant requires the same skills as building a coal plant. In fact, the contractors and vendors are the same in both cases. So the outfits that have no problem building a coal plant quickly and efficiently, suddenly become incompetents when building a nuclear plant.

requirements are. According to the IPCC median estimate, life cycle, a coal plant will produce 1001 grams of CO2 equivalent gas per kWh.[171][Table A.II.4]

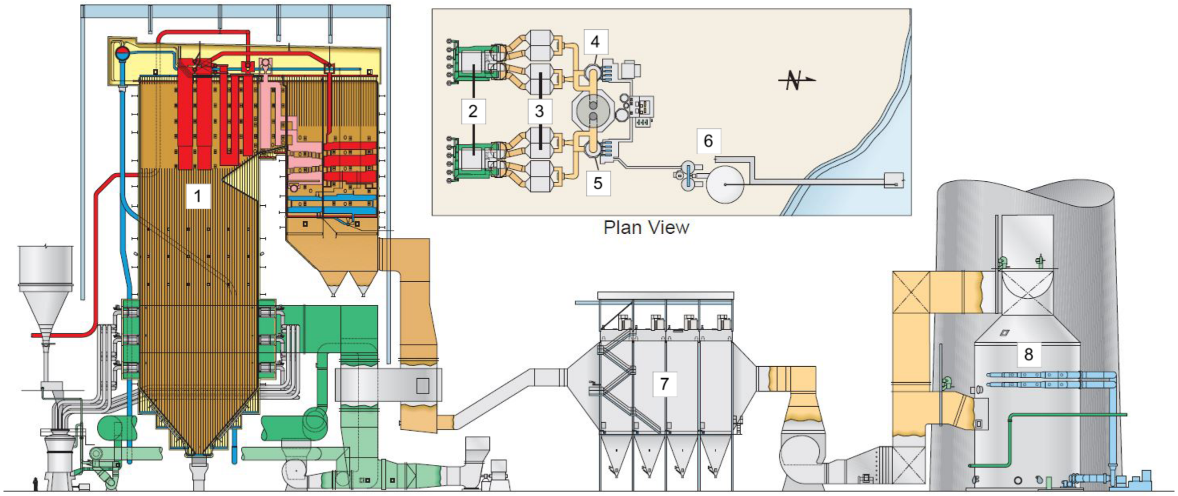


Figure 9.3: 660 MW Tanjung Jati boiler and gas handling equipment. 1. Furnace, 2. boiler house, 3,7. Electrostatic Precipitators (modern baghouse), 4,5,8 scrubbers, 6. wet scrubber limestone silo

9.2 Nuclear Plant Anatomy

Like a coal plant, a nuclear plant boils water to make high pressure steam and expands that steam through a turbine to generate electricity. A nuclear power plant replaces the boiler, the coal reception, storage, and preparation system, the air handling gear, stack gas treatment equipment, and the ash handling system, with a reactor and a steam generator. The nuclear steam generation system is far more compact than the coal steam generation system.

The Department of Energy estimates that both the steel and concrete requirements of a current conventional nuclear plant are lower than those for a coal plant with the same output, Figure 9.4. Interestingly, nuclear steel per megawatt is nearly twice what it was in 1970. Concrete has gone up by close to a factor of three.[207] We will explore this retrograde performance later in the book. For now, the point is that even now a nuclear plant requires less material than a coal plant.

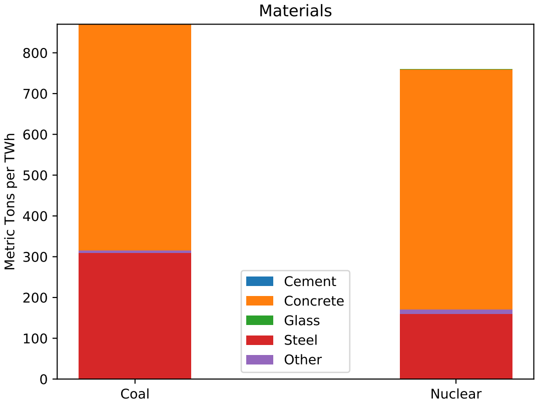


Figure 9.4: Concrete and steel, coal versus nuclear.[192][Table 10.4]

Figure 9.5 is a cutaway view of a modern nuclear power plant, the ESBWR from GE-Hitachi.

The nuclear island in the foreground is the steam generation system. It is roughly half the size of the turbine hall. For a coal plant, the opposite is true. The actual boiler is the gold vertical cylinder in the center of the nuclear island. It contains both the reactor and the boiler. It is 28 meters tall and 7 meters in diameter. This is all we need to boil the steam required to generate 1.5 GW of electricity, 50% more than Manjung 4. The rest of the nuclear island is devoted to refueling and systems for coping with casualties such as loss of plant power, and loss of coolant.

This plant will consume 82 kg of fuel per day, about 100,000 times less than an equivalent coal plant. It will produce about 100 kg of solid waste per day about 10,000 or more times less than an equivalent coal plant. Nuclear used fuel is roughly 10 times denser than coal plant ash.

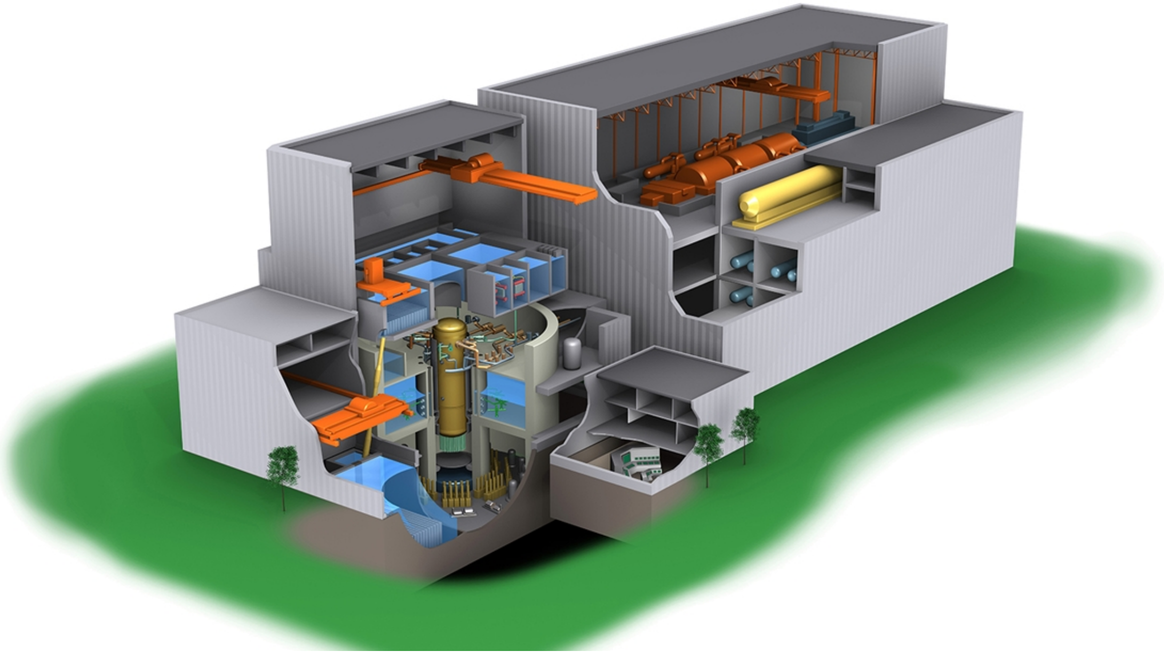


Figure 9.5: 1500 MW ESBWR power plant.

The used fuel volume is at least 100,000 times smaller than the coal ash volume. The plant will emit practically no air pollution. According to the UN Economic Commission for Europe, life cycle, given the current power mix, the plant will produce 5.5 grams of CO2/kWh, 186 times less than the coal plant.[254] In an nearly all nuclear grid, the ESBWR will produce less than 0.5% of the CO2 of the coal plant.

If a Martian were to step out of her space ship and be asked which plant is more expensive, Manjung 4 (Figures 9.1 and 9.2) or the ESBWR, Figure 9.5, which do you think she'd say? After she says, "probably Manjung 4". Then you'd have to tell her "No. Not even close. The coal plant costs $1500/kW. The ESBWR costs more than $5000/kW." Whereupon she asks "How can this be?".

That indeed is the question.

9.3 The Birth of the Gold Standard

Nuclear power has a more than 500,000 to 1 advantage in energy intensity over fossil fuels. So why is nuclear not cheaper than burning coal or oil or gas? Hidden in Figure 9.6 is the answer. In the mid 1960's oil prices were dropping to all time lows in real terms. Massive new finds in the Middle East plus rapidly dropping transportation costs as tanker size doubled every few years pushed the landed cost of oil below \$3.00 per barrel in mid-60's dollars. Gasoline was selling in the US at 25 cents a gallon. The majors were buying crude in the Middle East for less than 4 cents per gallon, less than a penny per liter.

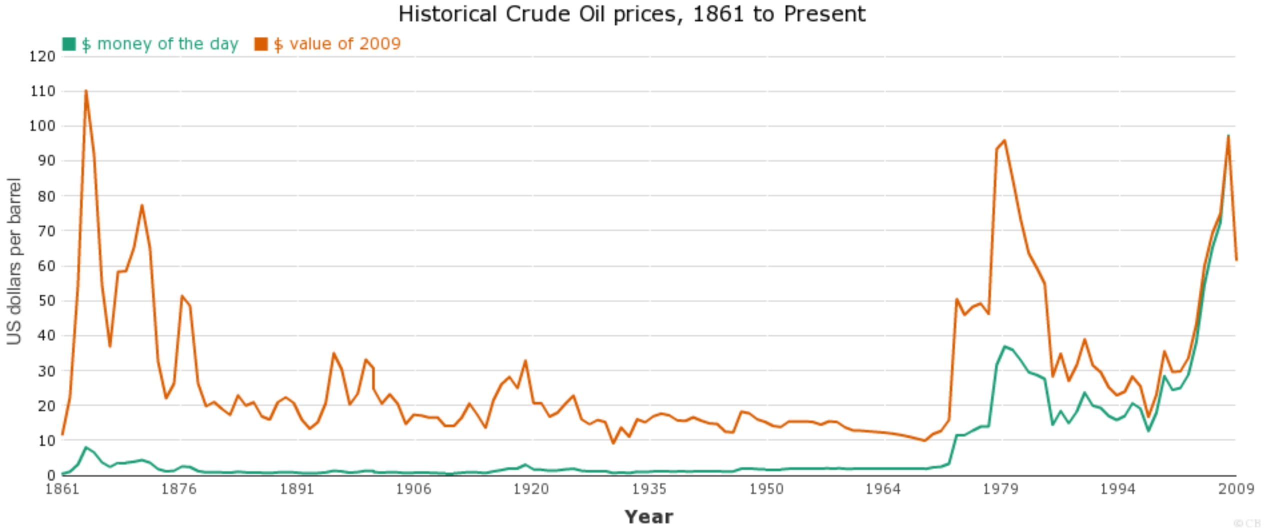


Figure 9.6: Oil price 1861 to 2009, BP Statistical Review of World Energy

Oil was so cheap that it was pushing into electricity generation, long the preserve of coal. This competition in turn was forcing down the cost of coal, Figure 9.7. Coal responded with hydraulic cutters, bigger draglines, and longwall techniques. But despite coal's best efforts, coal was losing market share to oil in power generation especially in Europe and Japan. By the end of the 1960's oil had risen from near zero to over 15% of US electricity generation, Figure 9.8. In Europe, oil's penetration was even deeper and more rapid. In 1971 over 20% of European power was generated by oil.[4]

It is impossible to imagine a more cut throat, more difficult market for a fledgling technology that had not existed a decade earlier to try to enter and compete in. ***Yet that is precisely what nuclear did.***

---

[4] During the 60's the American domestic crude price was about a dollar above the world price thanks to an import quota system. One result of the drain-American-first policy is that the domestic price of oil lagged world price when prices started to rise.

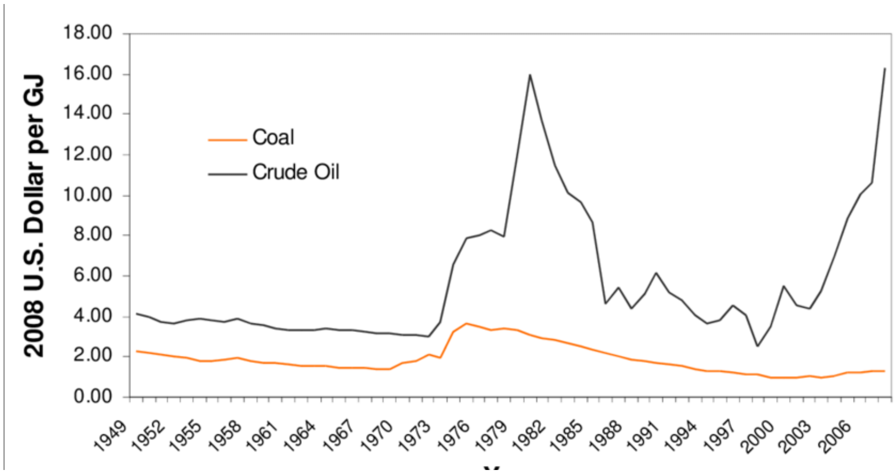


Figure 9.7: USA coal and oil prices, 1949 to 2009, reference [109][page 16]

A growing trickle of orders in the early 60's blossomed into the bandwagon market of the mid-late 60's, In 1966 and 1967 alone, US utilities ordered 49 nuclear power plants totally 39,732 MW of capacity. By the end of 1967, US utilities had ordered 75 plants totalling more than 45 GW of power. At the time, the US was consuming about 170 GW.

Why did this happen? Part of the explanation was a strong push from government especially big government liberals including Scoop Jackson and Albert Gore Sr.[50][p 269] Support for nuclear power was plank Number 1 in JFK's 1960 Democratic party platform.[15][p 181] Part of it was a growing concern over coal plant pollution. Part of it was aggressive pricing on the part of the vendors to gain market share, work their way down the learning curve toward a well-moated market.[85][p 62-63] Part of it was the herd instinct which gave the market its name.

But in order to pull this off, sceptical, conservative utility managers first had to be convinced that nuclear was cost competitive with coal and oil. In 1964, Albert Tergen, president of General Public Utilities, told his shareholders it was "no longer economic to build fossil fuel plants on the Eastern Seaboard."[271][page 30] In 1965, GE had to show TVA that it would produce electricity for less than 3.7 mills per kilowatt hour.[30][page 90] ***That's about 2.7 cents in current dollars.*** And indeed Komanoff, no friend of nuclear, claims this was the case. In 1971 Komanoff estimates nuclear CAPEX at 366 1979 dollars per kW, coal without scrubbers at $346/kW.[132][p 20] Nuclear's fuel cost advantage tipped the LCOE in favor of nuclear. In 1970, Paul Ehrlich, a determined foe of nuclear on Malthusian grounds,[5] complained "Contrary to widely held belief, nuclear power is not now 'dirt cheap'. ... At best, both [nuclear and coal] produce power for approximately 4-5 mills per kilowatt-hour."[78][p 57]

But still it was a near-run thing. With oil and coal price at near all time lows in real terms, with little or no pollution regulation, with big jumps in coal plant thermal efficiency, infant

---

[5] Ehrlich's view of nuclear power and humans was "giving society cheap, abundant energy at this point would be the moral equivalent of giving an idiot child a machine gun".[77]

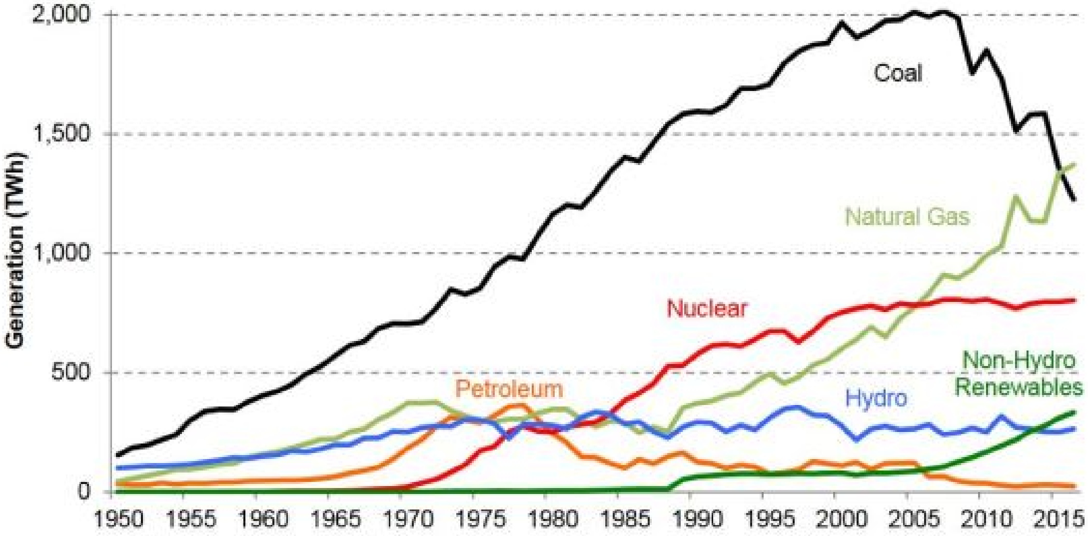


Figure 9.8: USA electricity generation by fuel from reference [53]

nuclear power was at best barely competitive with fossil fuel. The utility managers that held off on buying nuclear were probably right to do so.

Then came the miracle that should have been nuclear's salvation.

In September, 1969, an unknown manic-depressive Army captain takes over in Libya, and promotes himself to colonel. Qaddafi demands an immediate 43 cent increase in the posted price of oil, a brazen ultimatum that should not have worked. The majors refuse, but they also refuse to supply oil to Occidental Oil which has a critically large stake in Libya. Occidental caves. The weakness of the buyers' position is revealed. Oil prices start leap frogging. In 1971, posted price up another 90 cents. Mid 1973, posted price is now $2.90 almost double the mid-60's price.

But the real killer was the Yom Kippur War. On October 6th, 1973, Egypt attacks Israel. Israel caught napping and quickly has her back against the wall. She is running out of munitions. The USA tries to fly in replacement supplies at night, but the aircraft end up arriving in daylight, and the assistance is exposed.[285][p 584-587]

On the 16th, OPEC raises the posted price to $5.11 per barrel. On the 17th, Arab nations impose an embargo on the US and Holland. Worse they cut back production, 5% from September and vow to keeping cutting back 5% per month, until the US stops “interfering" in Israel. Israel heroically regains the upper hand, a truce is declared, and in March, 1974 the embargo is lifted. But by that time the damage has been done. The price of oil is now $11 per barrel, five times what it was in 1968.

The result is a boom in coal and nuclear. The already completed nuclear plants were raking in money and providing some of the cheapest electricity ever generated. The people who made the dubious decision to invest in a fledgling industry now look like prophets. Everybody scrambles over themselves to get new coal and nuclear plants built.

But curiously coal prices are tracking oil prices. As coal demand blossoms, marginal mines are brought back into production, and coal works its way up the supply curve. The process is abetted by new regulation and more importantly miner strikes as labor now senses it has the upper hand. The first Mine Health and Safety Act is passed in 1969, and strengthened in 1977. Major UMW strikes in 1974 and 1977 were accompanied by wildcat strikes throughout the decade. Ellerman estimates that real labor cost per unit of output rose 70% between 1968 and 1979.[79][Figure 9] Heavy fuel oil in March 1975 was 282% above its price in June 1973. "During the same month, the spot coal index rose 216% above its June, 1973 level.[30][p 93] The real price of coal in 1977 was 2.5 times that of 1970, Figure 9.9. On top of this, coal plants were facing increasing pollution control costs imposed by the Clean Air Act of 1970, which inter alia restricted the use of high sulfur eastern coal. The Clean Air Act of 1977 effectively mandated scrubbers even if the plant used western coal.

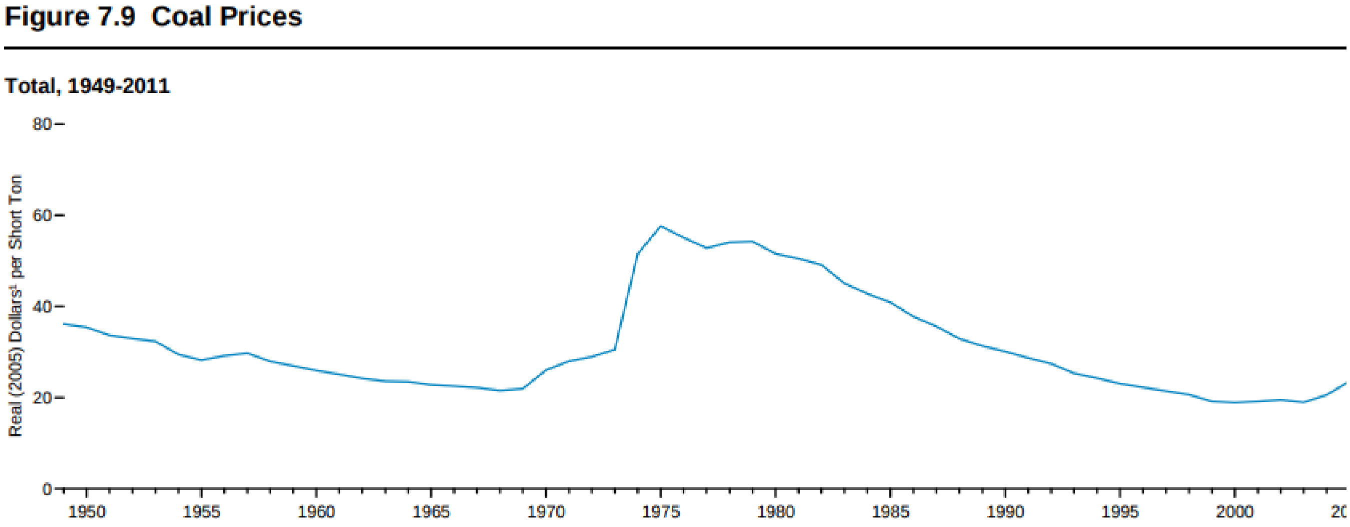


Figure 9.9: USA coal prices, 1950 to 2005, Source: EIA, Annual Energy Review 2011

Events could not be breaking better for nuclear. Unfortunately, there is an iron law of empirical economics. ***Cost rises to meet price.*** We see this in cyclic markets. Whenever a cyclic market goes into boom, the suppliers scramble to expand and in the process they lose control of their costs. This has happened in the Oil Patch at least two times in my life time. It happens in the shipbuilding market about every ten years. The law also applies to monopolies, although the process can take longer. In the 1950's and 1960's Eastern Airlines had an effective monopoly on the lucrative Northeast to Florida market. It was sitting on a gold mine. But costs began their inexorable rise. Aircraft mechanics were making pilot salaries. Baggage handlers were being paid aircraft mechanics wages. Eastern jobs were handed down within Eastern families. Eastern Airlines was the first major American airline to go broke.

The same thing happened to coal and nuclear in the 1970's. Bupp and Derian note in some wonderment

> Coal seemed to be *just competitive* with nuclear power from light water reactors at about 25 to 30 cents/mbtu in 1970; it still seems to be *competitive* at about four times that price in 1976.[30][page 97] [Emphasis in the original.]

It apparently never occurred to these authors that there might be a causal relationship.

But notice what happened to coal prices after 1978. They began a long decline and by 2000 were as low as they were in 1970 in real terms. Coal got its act together. The combination of greatly reduced demand growth — produced in part by the 1970's price jumps — stringent competition, the weeding out of high price sources, and technological advances, has been such that coal can now produce electricity as cheaply as it ever could in real terms. This too is the rule in cyclic markets. The survivors get their act together, and eventually we find out what the product really costs.

But nuclear did not follow that recovery pattern. The cause is pretty clear. When a market goes into boom, not only is it difficult for the players to resist cost increases from vendors and labor, but it is also nearly impossible to resist regulatory cost increases.

Nuclear is unique among all sources of electricity in that it was developed almost entirely by national governments. Until 1954, the federal government by law had an absolute monopoly on nuclear power in the USA. Truman thought atomic energy was “too important to be made the subject of profiteering".[85][p 41] This is still the case in many countries. When Congress allowed private firms to build nuclear power plants, it made sure that the federal government via the Atomic Energy Commission (AEC) retained total control over the process. The magic word is *license.* To build and operate a nuclear power plant, you must obtain a license from the federal government.

This is quite different from the situation that fossil fuel faced. Coal and oil were developed by private enterprises to solve local problems: pump out a mine, power a mill. To build a coal plant, the most a developer had to do was convince local pro-growth politicians — by fair means or foul — that the plant was in the interest of their district, something they could brag about at the next election. And in the rare cases they met resistance, they would move to a more “reasonable" venue. But for nuclear, the developer's fate was in the hands of a monocratic bureaucracy which had no stake in and received no benefit from the provision of electricity to the area in question.

Up until the late 1960's, AEC regulation was a tug of war. Attempts to impose regulatory costs were not only strongly resisted by the industry which was in life or death competition with coal and oil, but the AEC itself was caught between its promotional function and its regulatory function. But the result was a balance, and the plants that were built under that balance have a pretty good safety record. No member of the public has been harmed in some 50 years of operation.

But with the doubling and tripling in coal prices, industry's goal became do whatever you have to do to get the plants built. The cost constraint practically disappeared. At the same time the AEC regulatory process was becoming more codified, more bureaucratic. In 1970, the AEC inaugurated a series of Regulatory Guides,[132][p 51] four in 1970, 21 in 1971, and 33 in 1972. The Guides were not regulations and not vetted as such.[6] They were meant to be guidance to the staff of what they might ask for. But with little or no push back from the industry, the Guides quickly evolved into requirements.

> Staff usually insisted upon close adherence to the practices outlined in the guides, and applicants 'volunteered' to conform rather than engage in time-consuming negotiations. As a consultant report to the NRC noted, 'Utilities often conclude that proposing alternatives to approaches identified in NRC guidance would be too costly. In those cases, the NRC guidance serves as defacto regulation'.[132][page 51]

As soon as one applicant agreed to a guide, that became the floor for the next applicant. Requirements ratcheted upward with each application. And often locked in a particular practice or process whether or not it was efficient or economic. An example was a prohibition against multiplexing, resulting in thousands of sensor wires leading to a large space called a cable spreading room. Multiplexing would have cut the number of wires by orders of magnitude while at the same time providing better safety by multiple, redundant paths.

Another example was the acceptance in 1972 of the Double-Ended-Guillotine-Break (DEGB) as a credible failure. In this scenario, any section of the primary loop piping instantaneously disappears. Steel cannot fail in this manner. As usual Ted Rockwell put it best, "We can't simulate instantaneous double ended breaks because things don't break that way."[271][p 179] Designing to handle this impossible casualty imposed very severe requirements on pipe whip restraints, spray shields, sizing of Emergency Core Cooling Systems, emergency diesel start up times (11 seconds to load), etc, requirements so severe that it pushed the designers into using developmental, unrobust technology.[197][page 138] A far saner approach is Leak Before Break by which the designer ensures that a stable crack will penetrate the piping before larger scale failure.[7]

The boom in regulation continued throughout the decade.

> As of January 1, 1971, the United States had some hundred codes and standards applicable to nuclear plant design and construction; by 1975, the number had surpassed 1,600; and by 1978, 1.3 new regulatory or statutory requirements, on average, were being imposed on the nuclear industry every working day.[233][page 36]

---

[6] For the most part, the Guides were and are a hodge pogue of ad hoc reactions to specific problems as they cropped up. Were the Guides a premeditated tactic to avoid the normal regulatory process? I don't know.

[7] The impossible DEGB is still with us. It is the main reason that drove mPower, NuScale, GE, Westinghouse and Holtec to come up with designs that use integral pressure vessels to virtually eliminate primary loop piping. It is easier and cheaper to manufacture smaller, separate pressure vessels for the reactor, pressurizer, and steam generators, and connect them with pipes, than to cram everything into a single, tall vessel. But under the DEGB, the more expensive and much harder to maintain single vessel wins.[1]

9.4 The Arrival of ALARA

In 1971, the AEC proposed a radically new regulatory philosophy requiring all nuclear plants be designed to hold all radioactive emissions to levels such that 'exposures were as low as practicable'[30][p154] In other words, there is no limit. And the criteria is not whether the benefit of further reduction outweighs the cost. The criteria is: can you afford the reduction?[8]

This was such a departure from standard regulation that it did produce push back from industry. But after considerable debate the policy was formally adopted in 1975 with the wording changed slightly to "as low as reasonably achievable" or ALARA. But ALARA is still an explicit mandate to the regulators to raise cost to whatever the applicant can afford regardless of how small the benefit, if any. ALARA guaranteed that nuclear's cost would rise to whatever the competition's cost was. Bupp and Derian need not have been surprised.

In the 1970's, nuclear could afford a lot of cost raising. Tables 9.1, 9.2, 9.3 from reference [208] show just how much.

Table 9.1: Escalation of codes,standards and guides, 1970-1978

Year	Standards	NRC Guides
1970	400	4
1973	1074	68
1975	1624	157
1978	1800	304

Table 9.2: Change in material requirements, 1973-1978

Year	Concrete Cubic yards	Steel Short tons	Cable Yards	Cable tray Yards	Conduit Yards
1973	90,000	15,400	670,000	8,400	58,000
1978	162,000	34,200	1,267,000	27,000	77,000

What blows my mind about Table 9.2 is the cabling. This was a period in which the world was switching from analog to digital. With bandwidth exploding and multiplexing feasible, the cabling requirement should have been dropping precipitously.

Table 9.3: Escalation of labor employed, 1967-1980

	man-hours/kW		
Year	Engineering	Craft	Total
1967	1.3	3.5	4.8
1972	3.4	6.2	9.6
1978	5.5	13.0	18.5
1980	9.2	19.3	28.5

---

[8] In a sense, ALARA was just a codification of what the regulators were already doing. Congress had not specified any limits. So the regulators kept testing to see how far they could push. But ALARA made that push mandatory and made "there are no limits" official, explicit policy.

Table 9.3 is the craziest of all. This was an era in which engineering productivity was skyrocketing thanks to the computer. Yet in 1980 a plant required 2.6 times as many engineering hours as it took real labor to build the damn thing in 1967. Preposterous. But this shows how far regulation had to go to push nuclear's cost up to coal. It shows the power of ALARA.

The chickens came home to roost in 1979. The problem was not Three Mile Island. The problem was the Iranian Revolution and the disappearance of 5 million barrels per day of Iranian oil from the market. Oil prices tripled again. Oil was now ten times as expensive as it was in 1970. Coal prices hardly responded at all. Oil was now decoupled from coal and nuclear. But the second oil shock threw the world economy into a deep recession. On top of this the long term effects of the 1973 price rise were now really showing up in power demand growth. At the start of the 70's, electricity demand was growing at 7% per year. In 1979 and the 1980's this dropped to flat to 2% per year. There was simply too much generating capacity and capacity factors plummeted.[9] Ordering halted, Figure 9.10, and the inevitable weeding out process began.

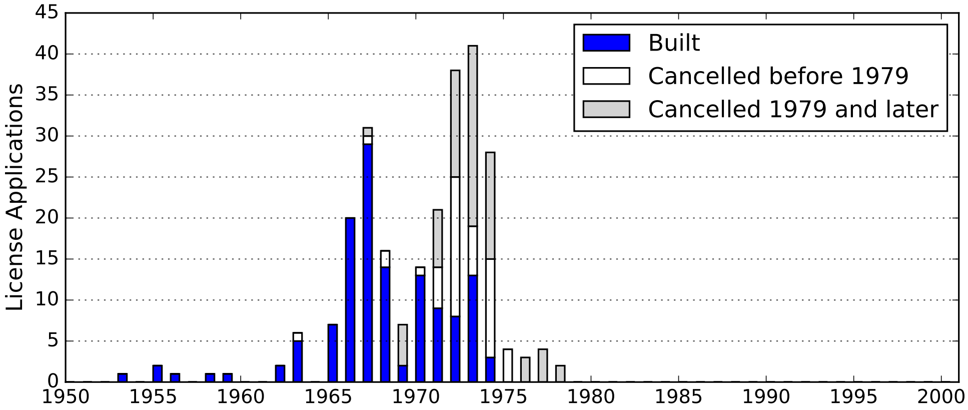


Figure 9.10: USA Nuclear Power Plant Orders, reference [2][Table C-1]

But while you can shut down high cost mines, lay off all but your best workers, and push desperate vendor's prices down to rock bottom, the regulatory ratchet only works one way. Nuclear was left stranded with top of the boom costs while coal reacted to the new reality and steadily reduced its costs in the 1980's and 1990's despite increasing regulation.

Nuclear power with its 500,000 to 1 advantage in energy intensity is not inherently expensive. It is inherently cheap. So cheap that even when it was barely starting down a steep learning curve, it was competitive with coal and oil when they were as cheap as they ever were. Unfortunately, at the very worst time in its development, competitive pressures disappeared producing regulatory bloat from which nuclear power has never recovered. In polite nuclear circles, this regulatory bloat is called *the Gold Standard*.

---

[9] Capacity factor is the ratio of actual output to nameplate output. In the late 80's and 1990's, nuclear's capacity factor improved significantly. The industry spent a lot of time congratulating itself; but all that had happened is demand had caught up with supply.

9.5 The American Plume and non-American experience

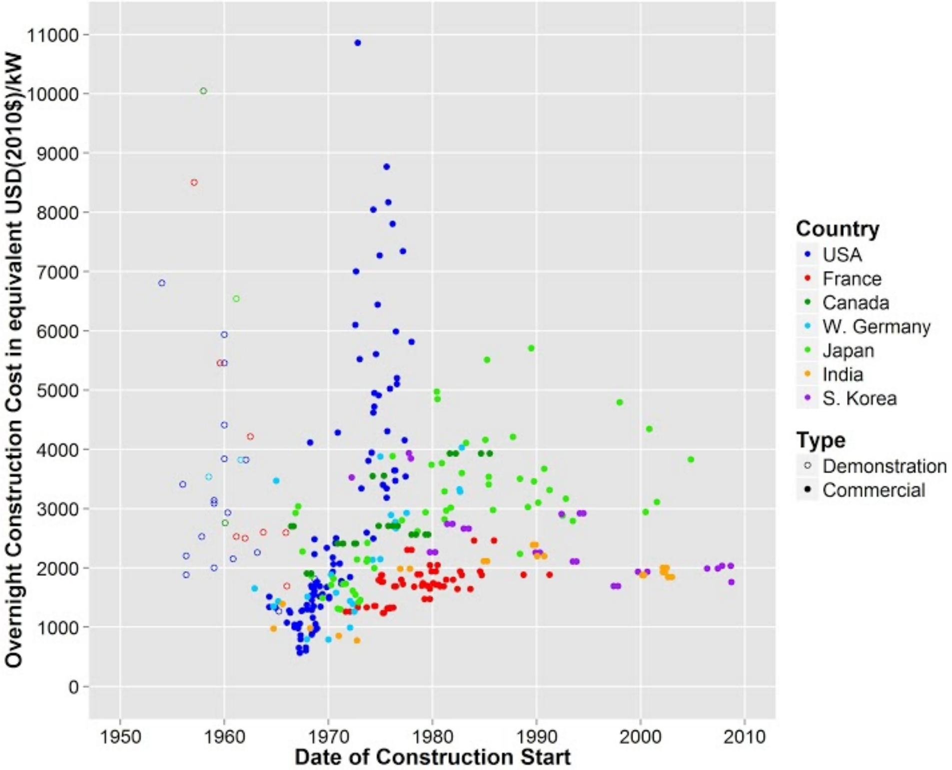


Figure 9.11: Overnight nuclear plant cost as a function of start of construction from [151]

Figure 9.11 from Lovering et al, reference [151], summarizes the carnage. This scatter diagram of plant overnight costs versus start of construction makes a number of points:

1. The USA about face started in the very late 1960's and by the mid-1970's the "best" plants has a real overnight cost of \$3000 per kW, four times that of the late 60's plants. We have seen what caused this mind-blowing increase.
2. There is a plume of US plants spiraling up toward \$10,000 per kW in the mid-70's. This plume cannot be explained by fossil fuel price increases. It is the result of regulated monopolies being able to pass on their costs whatever they are to the rate payer, which costs they can roll into their rate base, increasing shareholder profits. Once costs got out of control, there was nothing to stop them from going higher. In theory, the utility regulators should have refused the rate increases, stopping construction of any plant that was not competitive. But regulatory theory and human nature are two entirely different animals.[10]

---

[10] A particularly debilitating feature of the continually tightening requirements under ALARA was *backfitting*.

3. The plume carried away the American nuclear dream. By the mid 70's, the USA nuclear boom was over. Only 13 nuclear power plants were proposed in the USA in the 20th century after 1974, Figure 9.10.[64] ***This was five years before Three Mile Island.***
4. Qualitatively other countries followed a similar pattern to the US with a slight lag: decreasing real cost up to about 1970 and sharply increasing cost thereafter. Canadian cost went up a factor of three or more in the 70's. West Germany and Japan about the same. The jump in fossil fuel prices applied everywhere. However, these countries stuck with nuclear longer than the US and for the most part avoided a plume. This may reflect more concern about the availability of fossil fuel and more centralized control of the utilities.
5. The extreme example of this is France. France made a top level decision to become independent of fossil fuel, and to a large extent carried it through. Between 1974 and 1985, France built 58 large nuclear plants which supply about 75% of the country's electricity.[11] The key to this was strong dirigisme from the top. EDF, the national utility, had total control of the project. There was no independent regulatory body.[12] For practical purposes, EDF regulated itself.[99] There was no regulatory uncertainty, no rule changes after a design was certified, no backfitting. In the early-1970's, France was building reactors at an overnight cost of around $1400/kW 2020 dollars.[99][Figure 12]

   But even in France there was an erosion in real cost. France could not totally isolate herself from the increase in fossil fuel price, in part because she had decided to base her plan on American technology. France "held" her cost increase to about a factor of two. France did a less worse job of controlling costs than the others; but a doubling in real cost over ten years would be regarded as dismal performance anywhere but nuclear.
6. Korea, the purple dots in Figure 9.11, is an instructive outlier. As late as 2013, post-Fukushima, South Korea was able to produce the APR1400 at less than $2500 per KW,

---

The new rules would be imposed on plants already under construction. A 1974 study by the General Accountability Office of the Sequoyah plant documented 23 changes "where a structure or component had to be torn out and rebuilt or added because of required changes."[85][p 208] The Sequoyah plant began construction in 1968, with a scheduled completion date of 1973 at a cost of $300 million. It actually went into operation in 1981 and cost $1700 million. This was a typical experience.

In regulated markets, utilities have a perverse incentive to welcome such changes. They offered weak or no pushback. The regulators were faced with the Hobson's choice of either accepting a nauseating rate increase or writing off all the rate payer money that had already been spent on the plant.

Another casualty of regulatory uncertainty was the turnkey contract. With the exception of Shippingport, the first ten or so US plants were built under fixed price contracts in which the reactor manufacturer took full responsibility for delivering the plant per spec.[30, 132][p 19, p 17] But such contracts cannot exist in a world in which the rules can be changed after the contract is written. They were quickly abandoned in favor of cost-plus contracts, which allowed the cost of the changes to be pushed onto the ratepayer. The reactor builders became component vendors. Since few utilities had the technical competence to manage a nuclear plant build, this led to the development of third party managers called EPC contractors to perform this function. But nobody other than the ratepayer in this system has an incentive to keep costs down. Coal plants are still built under turnkey contracts.

[11] Sweden replaced essentially all her fossil fuel plants with nuclear in slightly less time.[94][p 22-25]

[12] This was not changed until 2006 when the Autorite de Surete Nucleaire was set up.

Table 9.4. The APR1400 is a 1.4 GW, standard Pressurized Water Reactor which has been certified by the NRC. For a PWR, a CAPEX of $2500 results in a Levelized Cost of Electricity of 3.5 to 4 cents/kWh. This is fully competitive with coal which costs about 5 cents/kWh, even if we don't factor in the pollution and CO2. South Korea at least until very recently had much of the 1970's French dirigisme structure, a country largely run by a technological elite which recognized that resource-poor Korea had to go nuclear. The Korean experience proves you can build a PWR for $2500/kW even in the 21st century.[13]

APR 1400 Capital Cost
Millions of US Dollars at 1150 Won/$

	Shin Kori 3,4 2008-2017	Shin Hanul 1,2 2012-2018
Nuclear Steam Supply	1434	1248
Turbogenerators	314	321
Balance of Plant	1124	1177
Erection	1220	1057
A/E Cost	371	457
Administrative Cost	184	171
Foreign Capital Mgmt	12	23
Land Cost	21	8
Contingency	219	183
Overnight Cost	4899	4647
Interest	880	757
Total Budgetted Cost	5799	5404
Actual Cost(KHNP)	6460	7100
Actual $/kW	2307	2535

Table 9.4: Korean APR1400 cost, reference [42][Table 5]

But the local Gold Standard had pushed costs up to where there was not much margin. The Gold Standard fosters an uncompetitive environment which focuses on very expensive paperwork. This creates a strong incentive to fudge the paperwork. In 2012, it came out that thousands of special nuclear certificates on non-safety critical equipment had been forged.[14] This begs the question: why are special nuclear certificates required on non-safety critical equipment? The answer is: that's the way the Gold Standard works.

In 2013, the scandal spilled over to some safety critical cabling. There is little evidence that the cables themselves were substandard although one anonymous whistle blower alleged that components which had failed a test were falsely certified to claim otherwise. The result was long construction delays while equipment was replaced, and a new level of oversight that has pushed costs up further. In 2016, the pro-nuclear government was ousted by a

---

[13] China may be approaching the same cost level. China National Nuclear Corp claims Hualong Two will come in at 13,000 CNY/KW ($1990/KW) down from 17,000 CNY/KW ($2600/KW) for Hualong One.[117]

[14] In a properly functioning competitive market, there is little money to bribe people to forge documents.

populist who announced that South Korea would replace its nuclear plants with wind and solar, neither of which the country has much of. The South Korean nuclear program is now stalled; but not because nuclear power is inherently expensive. ***It's the Gold Standard that is inherently expensive.***

9.6 The Lack of a Learning Curve

Komanoff found a nearly linear relationship (R = 0.92) in the 1970's between the increase in USA plant cost and sector size, which he defines as amount of capacity operating and under construction (aka issued licenses)[132][page 26]. This is counter intuitive. In competitive markets for highly engineered products, increases in volume invariably result in decreases in price. This behavior is usually called *the learning curve*, although volume itself creates opportunities for cost reduction. Komanoff argues that this anomalous behavior was due to a conscious policy of keeping the probability of a major casualty constant regardless of the amount of nuclear capacity. There is some AEC documentation supporting his claim; but, if so, this was a nonsensical policy.

There are two major problems with such a policy:

1. It ignores the benefit side. Doubling capacity doubles the amount of clean, CO2-free power. If one plant is safe enough, then two plants with the same casualty probabilities are safe enough. This is implicit in just about all our safety metrics. Airlines brag about low fatalities per passenger mile. Car safety improvements are valued by their effect on accidents per mile traveled. Power plant safety is measured in deaths per terawatt-hour.
2. It assumes an increase in plant cost results in a compensatory decrease in major casualty probability. In fact, such expenditures run into very sharply decreasing benefit. Cohen estimates that by the 1980's nuclear plant regulation had pushed the marginal cost of saving a single life up to 2.5 billion dollars.[50][page 142] The goal to make the probability of a casualty independent of sector size is unobtainable at any cost and that should have been obvious to everybody.

If this was the policy, there is little evidence that it was effective. The cheap pre-1970 plants have the same superlative safety record as the far more expensive later plants. Three Mile Island 2 was the youngest power plant in the USA fleet, when it suffered the only core meltdown in US commercial plant history.

As a matter of history, there was a learning curve. Nuclear power plant costs were declining through the 1950s and 1960's and fairly quickly. Lang finds that unit overnight capital costs were reducing at about 25% for every doubling of capacity, Figure 9.12.[138][p 7]

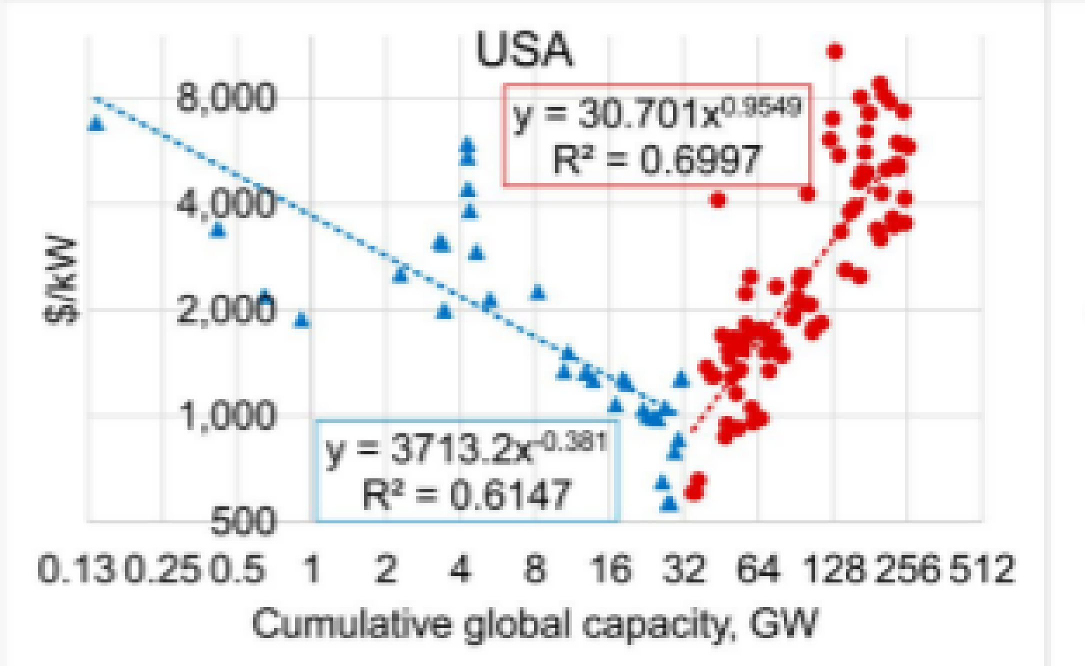


Figure 9.12: USA Unit cost versus capacity [from Lang-2017]

If people were worried about sector casualty probability prior to the late sixties, it did not show up in plant cost. Right around 1970, something changed. The learning rate turned sharply negative, and unit costs started skyrocketing. A simpler explanation for the near linear increase in cost with number of applications after 1970 is that, once cost pressures are removed, the regulatory ratchet operates in roughly equal steps.

9.7 Post-1980 Plant Labor Costs

Table 9.5: Breakdown of 1987 USA Power Plant Labor Costs 1987 $/kW, [50][page 148]

Account	Median USA Experience	Best USA Experience	USA Coal
Structural Craft	150	91	76
Mechanical Craft	210	100	180
Electrical Craft	80	48	52
Real Labor Subtotal	440	239	308
Construction Services			
(Indirect cost)	170	86	38
Engineering	410	170	56
Field Supervision	320	65	50
Other Professional	58	27	6
Insurance/taxes	115	65	65
Paper Labor Subtotal	1073	413	215
Labor Total	1513	652	523

Table 9.5 compares nuclear and coal labor cost numbers for 1987. This is well after the merde had hit the fan in the 1970's during which both coal and nuclear lost control of their costs. And after the crash in 1979 and 1980, after which coal started getting their costs back under control. Several features of this table stand out.

1. The enormous range in nuclear plant costs. The difference between the low and the median is a factor of 2.5. God knows where the worst is. This can't happen in a competitive market. In a competitive market, the best price is the only price.
2. But here's what is surprising. ***Even in 1987 after all that had gone down, with ALARA in full swing, the lowest cost nuclear plants were much cheaper than coal when it comes to real labor costs.*** Even in 1987, the inherent energy density and the lack of pollution and waste control equipment trumped the need for radiation protection as far as real labor is concerned. Even the Median nuclear plant was not that far above coal in this category, which means a lot of the nuclear plants were competitive with coal with respect to people who are actually making stuff.
3. Where nuclear gets clobbered is paperwork. It took twice as many paperwork hours as real labor hours to get the plants built. Even the best nuclear plant had twice the paper work labor as coal. The median numbers are off the charts. And the US coal paperwork numbers are horrible. World class shipyards figure they need to keep engineering and production control labor to less than 5% of the ship price.

Inherent cheapness is no guarantee of competitiveness in an ALARA driven regulatory system.

9.8 Role of the Anti-Nuclear Movements

The 1950's saw growing opposition to nuclear ***weapons*** and in particular nuclear weapons testing, mainly among the intelligentsia initially led largely by atom bomb developers.[15] The motivation behind the effort was fear of a nuclear war. But the organizers thought they needed something more than a potential threat, something more immediate to persuade the general public to join the effort. They chose the health hazards associated with radioactive fallout.

The problem was that with a few local but dramatic exceptions, the dose rates resulting from weapons testing were well below background. Figure 9.13 shows that fallout dose rates in the U.K. peaked at 0.15 mSv/y.[8][Figure 23] The solution, Section 5.3, was to argue that mortality was linear in dose however small and cumulative over both time and population. The solution was LNT.

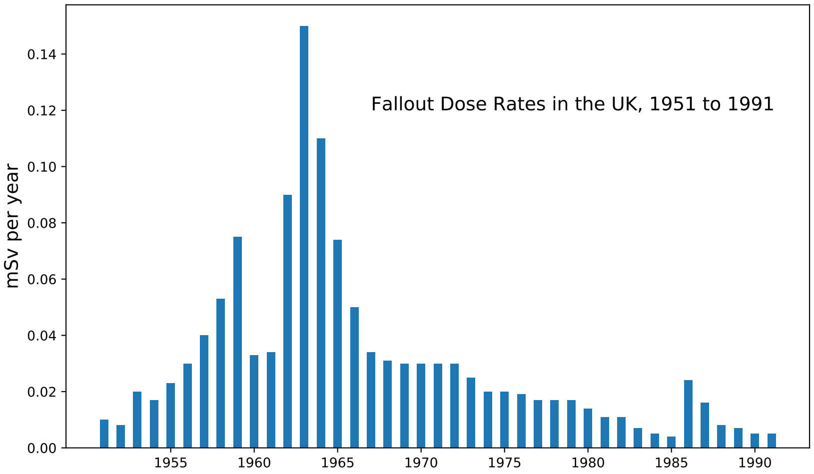


Figure 9.13: UK Fallout Dose Rates, 1951-1991. Peak was in 1963 as weapons states got as much atmospheric testing in as possible before the ban. Chernobyl shows up as a blip in 1986/1987.

---

[15] Almost to a man the early activists against nuclear weapons were strong supporters of nuclear electricity. Their quandary was captured by Karl Darrow, an important member of the Manhattan Project, who wrote to a colleague: “I take it that there are two main objects. One is to please the public with the prospect of beneficial uses of atomic power, and the other is to scare it out of its boots by threatening it with new weapons." Darrow doubted this would work. Indeed it was not long before the founders of the movement to control nuclear weapons turned away from a group that increasingly did not distinguish between nuclear weapons and nuclear power.

LNT conflicted sharply with the radiation safety limits that radiobiologists had developed over 60 years. ***The solution was to lower those limits by over a factor of 2 in 1951 and by another factor of 30 in 1957.*** Through 1951, the International Commission on Radiological Protection (ICRP) dose rate limit for the general public was 1 mSv/d. However, in 1951, the ICRP changed the recommended limit to 3 mSv/week. This was based on claims of genetic mutations at low doses which turned out to have no foundation, Section 5.3. In 1957, the American counterpart of the ICRP, the National Council for Radiation Protection(NCRP), added a limit of 50 mSv/y for nuclear workers and 5 mSv/y for the public. As the NCRP itself acknowledged, this humongous change was not based on any new data.

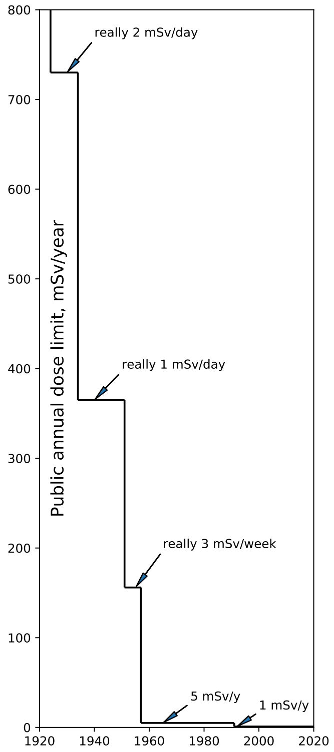


Figure 9.14: US Dose Limits

> The changes in the accumulated MPD [Maximum Permissible Dose] are not the result of positive evidence of damage due to use of earlier permissible dose levels but rather are based on the desire to bring the MPD into accord with the trends of scientific opinion.[179, page 1]

Opinion trends that are not based on data are hardly scientific.[16]

These machinations allowed the test opposition to aggregate tiny dose rates over long periods and hemispherical populations, and claim that a large number of people were being invisibly killed by weapons testing. The public was unpersuaded. In 1977-1978, less than 30% of Americans opposed nuclear power.[222][17] But, with a major boost

---

[16] Lauriston Taylor's first hand history, reference [245], makes it clear that the "opinion trends" at the time were still dominated by Muller's theory of genetic hazard, a hypothesis already contradicted by Caspari's fruit fly results and Neel's bomb victim data, Section 5.3.

Taylor points out that, before issuing the new recommendations, the NCRP checked with the AEC to find out what dose rates the AEC workers were actually receiving.[245][p 47] They were told the workers rarely exceeded 15 mSv/y. The new limits were a form of ALARA. Kocher flat out states that the 1950's NCRP and ICRP recommendations were ALARA based targets, not harm based limits.[130]

Taylor does not explain the reasoning for the shift from a daily limit, to a weekly limit, and then to an annual limit, which is inconsistent with radiotherapy and everything we know about the repair period. But he does say the Committee was worried about 'overruns'. If the NCRP had asked the AEC what the daily maximums were, they would have gotten back numbers in the 1 mSv and higher range. Most of the annual dose was received in far shorter periods. By pushing the regulatory limit period out, they were able to push the dose limit down without interfering with AEC operations, a sort of ALARA in reverse. But I do not have documentary evidence that this was the motivation.

[17] This rose to over 50% after Three Mile Island exposed the release probability lie. It was not anti-nuke

from the Cuban missile crisis, the movement was able to achieve a limited test ban treaty in 1963, pushing most weapons testing underground.

These efforts certainly caught the attention of the nuclear power industry and of the AEC. Industry was worried about the implications for liability. If a plant had a release, it would easily create local dose rates far higher than those associated with weapons testing fallout. In 1957, the decision was made to commission a report by the Brookhaven National Lab, dubbed WASH-740, which included a scenario in which a large number (3000) of people were killed by Acute Radiation Sickness. This scenario combined a *cold release* of half the radioactive material in a nuclear plant directly upwind of a sizable city in the form of 1 micron particles during an inversion. A cold (70F) release combined with an inversion guarantees that all the material stays close to the ground. Brookhaven does not say how a casualty that exploded through the containment could operate at 70F.[18] In all their *hot release* (300F) scenarios, very few people were killed.[22][p 12-14]

The AEC/industry strategy seems to have been:

1. Concoct a casualty with horrific results to demonstrate the need for a limit on liability.
2. Argue that the probability of such a casualty is so low that as a practical matter nobody has to worry about it.

This contradictory plan backfired. The only thing anybody remembers about WASH-740 is 3000 killed and the fact that industry took these numbers seriously enough to demand protection from the consequences of a release. It fell on the regulatory side of the AEC to try and fulfill the false implication that a large release would never happen.

But outside industry circles, the public remained largely unconcerned about nuclear ***power*** safety at least through the 1960's. As late as 1969, the Sierra Club voted to support nuclear power.[19] The bandwagon market of 1966/1967 would not have happened had utility executives felt a ground swell of opposition to nuclear power. The Union of Concerned Scientists, just about the first group to raise questions about nuclear power safety outside the industry, was founded in 1969. The UCS was founded to challenge misuse of technology in Vietnam and the arms race. It did not turn its attention to nuclear power until 1971. Daniel Ford, the UCS's Executive

---

propaganda that turned the American public against nuclear power; it was the lie.

[18] Presumably the reactor has suffered a meltdown, which for uranium oxide fuel means temperatures in excess of 3500F.

[19] This generated a split in the Club with the anti-nuclear power faction forming Friends of the Earth. The issue was not cost or safety. Quite the opposite. The fear was that cheap, abundant power would attract more people to California. When Martin Litton, one of the leaders of the anti-nuclear faction, was asked if he worried about nuclear power accidents he replied, "No, I really didn't care because there are too many people anyway." It was not until 1974 that the Sierra Club officially became anti-nuclear power.

Earlier the club, which had been formed to preserve California's wilderness, had been strongly supportive of nuclear power, running an "Atoms not Dams" campaign. In 1966, Sierra Club Director William Siri wrote "Nuclear power is one of the chief long-term hopes for conservation. ... Cheap energy in unlimited quantities is one of the chief factors in allowing a large rapidly growing population to preserve wild lands, open space, and lands of high scenic value. ... With energy we can afford the luxury of setting aside lands from productive uses."

Director, writes that in 1972 “Nuclear power still enjoyed strong support in Congress and in the general public."[85][p 116] Historian Brian Balogh puts it this way:

> What scholars have failed to explain to date is why significant public doubt about the safety of commercial nuclear power did not materialize until the early 1970's. For more than twenty years, nuclear experts fretted over public opposition to commercial nuclear power that consistently failed to materialize.[15][p 234]

In October, 1971, the whole town of Midland, Michigan turned out for a rally in support of two nuclear plants in the town, and a protest against the AEC, where the construction license application was languishing.[236] Local rock bands played and state politicians, GOP and Dem, bloviated. The rally ended with everybody singing:

> Cleaner air and water for the mid-state is our stand,
> For the welfare of our people and the future of our land.
> Let us tell the folks in Washington, a license we demand.
> We need nuclear power now.

as combined high school bands played The Battle Hymn of the Republic.

It was not until the mid-70's that sporadic NIMBY opposition to the siting of a particular plant coalesced into something approaching an organized campaign against nuclear power. Even then the movement in the US was largely made up of leftist veterans of the anti-Vietnam protests, keeping the party going.[20] The target was the social structure, the Man, as much as nuclear power.[21] The general public was not much involved. In 1976, US activists sponsored voter initiatives in a half-dozen states, calling for a moratorium on nuclear plant construction. All were soundly defeated.[278][p 199].

---

[20] After Three Mile Island in 1979, a anti-nuclear power rally was held in DC. 75,000 people showed up, including the aforementioned Komanoff, Nader, Tom Hayden, Jane Fonda and other luminaries of the anti-Vietnam protests. “What a fantastic day!" enthused Hayden. “It reminds me of the best days of the 1960's."[272][p 197]

[21] The environmental organizations were originally wilderness conservation groups. But some of them developed a distinctly misanthropic edge. People were the problem. Technological developments that allowed more humans on this planet were bad, not good. And that means a technology that promised cheap, nearly unlimited electricity would be a catastrophe.

> Giving society cheap, abundant energy would be the equivalent of giving an idiot child a machine gun[Paul Ehrlich]

> It would be little short of disastrous for us to discover the source of clean, cheap, abundant energy because of what we might do with it.[Amory Lovins]

Oh and by the way, the people that are pushing this disastrous technology are the same bastards that gave us the bomb. It all fit. Large parts of the conservation movement became counter-culture greens. These people were far less interested in the environment than they were in changing the system. When planet heating warnings were issued by atom bomb developers like Edward Teller and Albert Weinberg, they were dismissed both because of the evil source and because it was an argument for nuclear power.

The first real non-NIMBY protest against nuclear power was at Wyhl in Germany in 1975. The RAND corporation did not start chronicling US nuclear plant protests until 1977.[62] By that time nuclear power had already lost the war. All the anti-nuclear ***power*** movement did was delay and in one or two cases prevent the startup of unneeded plants.

But the radiation health issues raised by the anti-***weapons*** testing campaign in the 1950's did have a profound effect on the AEC regulatory apparat. LNT was accepted by the AEC with little or no discussion. This led to ALARA. More fundamentally, the regulators became convinced that if there were a major release there would be hell to pay. This was strong motivation to push as hard as they could to make sure they did not get blamed. Which is what they did.

9.9 The Gold Standard and the Future

For anyone who believes that nuclear power is important if not critical to solving the closely coupled problems of electricity poverty in the emerging economies and global warming, the implications of this history should be sobering. The light water reactor (LWR) is a klunky, brute force technology combining high pressure, low temperature, and solid fuel. It was never regarded as much more than a stop gap by most of the early giants in nuclear power, including its inventors.[275][p 132]

A range of other technologies exist that avoid some or all of the three major drawbacks of a LWR. Some of these technologies are walkaway safe. On any over-temperature the reactor will shut itself down and cool the decay heat passively. They require no power to do so. There is nothing a confused operator or a malfunctioning control system can do to prevent this shutdown and cooling. Such designs can operate without any human supervision.

In a sense, these designs will not be any safer than current reactors. You cannot be safer than zero which is the number of people that have been killed by radiation from commercial light water reactors in the free world. But they could be cheaper while providing even better radiation release resistance than current plants.

But as we have seen, even the klunky, light water reactor was as cheap as coal or oil when coal and oil were as cheap as they ever were and the LWR was in its infancy. The Gold Standard quickly put an end to that, while at the same time stifling any attempts at improvement.

And the Gold Standard will do the same to the new entrants. The two key reasons are: (a) regulator incentives, and (b) ALARA.

Regulator Incentives People respond rationally (aka selfishly) to the incentives that they are presented with. Let's look at the issue from the point of view of the regulator. In the USA and most other countries, he has nearly absolute control over whether or not a plant gets built.

- He gets no credit for approving a successful plant. No matter how much cheap, pollution-free, CO2-free electricity it produces, he sees none of these benefits. All the benefits go to the rate payers, the investors, and the planet.
- He owns any problems. A big problem will get him fired, especially if he is high up in the regulatory structure.

The rational response is to approve nothing. But this response is tempered by the need for applicants. If all players realize they will not get approval, then there will be no applicants, and the regulator will not have a job. So the rule becomes approve as little as you can without totally shutting down the application stream.[22]

---

[22] This does not mean that the regulators are anti-nuclear. In fact, at places like the NRC just about everybody is strongly pro-nuclear. These people went into nuclear power because they believed in it. But they have been put into a system in which nuclear cannot be too safe. It's their job to implement that rule. If they don't do that job diligently, they will be fired or at least passed over.

In NRC-like systems in which the applicant pays the regulator to review his application, the problem is exacerbated in an interesting fashion. The applicant becomes the direct source of the regulator's funding at something close to $300 per man-hour. In a fully developed system, the applicant will be paying for scores of high priced bureaucrats. The total bill can easily run into hundreds of millions of dollars. But when the application is approved, this funding stops.[23] The regulator will have to lay off dozens of friends and colleagues. He may even lose his own job.

The rational response is to strongly encourage applications. But once you have enticed an application, prolong the process just as long as you can. Continually reassure the applicant. "It's looking good. We just need one more analysis." Lather, rinse, and repeat. An accomplished regulator can keep this process going for the better part of a decade.[24]

ALARA When you combine these incentives with ALARA, then things become disastrous for new nuke. ALARA means there are no limits on the regulator's power. Worse, if the regs include ALARA, it is not only in the regulator's selfish interest to push ALARA as far as he possibly can without forcing the applicant to withdraw his application; but that's exactly what ALARA explicitly mandates him to do. If he does otherwise, he will expose himself to the claim that he is in cahoots with the applicant, which in a way he is. If a technology is cheaper or safer, it just means he has more room to push the limits down and the costs up.

This is not just a hypothesis. Recently Terrestrial Energy presented their graphite moderated design to Canadian regulators.[25] Canada is the home of the CANDU heavy water moderated reactor. Heavy water reactors produces 60 times the amount of the weakly radioactive hydrogen isotope, ^{3}H (aka tritium), as a light water reactor.[26] Terrestrial's design produces an order of magnitude less tritium than CANDU, so they easily met the CANDU-based tritium requirements, which according to the regulators more than adequately protect the public. The regulators, invoking ALARA, said not good enough, and ended up requiring much lower tritium emissions from the Terrestrial design than from a CANDU.

ALARA is inherently biased against the cheap and the safe. Over time ALARA will push the cost of any technology, however cheap, at least up to the point where it is barely competitive.

The conclusion is obvious: under the Gold Standard there will be no new nuke.

---

[23] A reader points out this is a little misleading. An operating plant pays a fee to the NRC. Currently that fee is $4.6 million per year. But that dollar flow is far smaller than that resulting from a full blown application review process, and goes to a different part of the bureaucracy.

[24] In order to keep this process going for as long as possible, the American nuclear power establishment has one more trick up its sleeve. The DOE funnels taxpayer money to politically connected applicants calling it something like "Advanced Reactor Demonstration Program". The applicant then uses that money to pay the NRC application fees. The taxpayer becomes the unwilling funder of the bureaucracy circulating her money to itself.

[25] The neutrons created by a fission are moving at speeds which are so fast that they are unlikely to be absorbed and create another fission. So most reactor designs use a *moderator* to slow the neutrons down.

[26] More on tritium in Section 11.5.3

Figure 9.15: Eemshaven: 2 by 800 MW USC coal plant, 46.2% efficiency

9.10 The Lousy Contractor Argument

Whenever anyone points to ALARA-based regulation as the cause of the prohibitive cost of nuclear power, the almost automatic response is: it's not the regulation, it's the contractors. They don't have the skills to design, plan, and build a nuclear power plant. If they would just do a better job, the problem would go away.

But from a purely technical point of view, the skills required to construct a nuclear power plant are the skills required to build a coal plant. And in fact the contractors are the same, and their vendors are the same. In many respects, a coal plant is tougher and more complicated. The temperatures are higher. The pressures are higher. You must handle a 100,000 times as much fuel. And for every unit of fuel, you have more than 10 times as much pollutant laden stack gas. Technically, the nuclear plant is the simpler problem.

In 2015, the Dutch utility RWE commissioned their Eemshaven plant in the northeast corner of Holland at a cost of 2.2 billion euros. This is a little under $1500/kW for a 2 by 800 MW plant. This is for the latest and greatest ultra-super-critical plant meeting stringent EU pollution limits.

But the same people who have no problem throwing up a coal plant on a fixed price, turn key basis, all of a sudden turn into incompetents when they are faced with a nuclear plant. The same people who built nuclear plants in the late 1960's for less than 3 cents per kWh in current dollars can't complete a plant in 2020 for triple that, despite all the technical advances we have had in the last 60 years. What turns these smoothly functioning coal plant engineers into hopeless bumblers when they try and do a nuclear plant? Whatever that disease is, it wasn't around in the 1960's.

9.11 Big Oil and Nuclear

Another attempt to explain nuclear's abject failure to live up to its promise is to blame sinister fossil fuel interests. To examine this claim, we must divide fossil fuel into coal, oil, and gas. There has never been much overlap between coal and oil and, until recently, not much overlap between oil and gas.

Coal Coal and nuclear have been in direct competition since the inception of nuclear power. Coal interests have fought hard against nuclear, concentrating on the support that nuclear was getting from the government. Their biggest victory was closing a loophole in the Atomic Energy Act by which commercial plants could claim to be demonstration plants to get more favorable licensing procedures and subsidized fuel. Unfortunately, they closed the loophole in a way that effectively precludes extended full scale prototype testing. But aside from that win, coal's main role has been to put an upper bound on the cost of nuclear. But that upper bound rose precipitously during the early 70's as coal simultaneously battled miner strikes, pollution regulation, and the costs of rapid expansion. Nuclear's cost rose in lock step and ALARA based regulation locked in nuclear's cost at the peak.

Oil Oil took a very different view of nuclear. For oil men, the heavy fuel oil market was not a priority. Oil was never that interested in competing with coal in what they saw as a low value business, basically a dumping ground for the bottom of the barrel in a few places such as New England where coal was particularly expensive. Oil was focused on the far more lucrative transportation fuels and chemical markets.

So when nuclear power came along with all its promise, oil decided to jump on the train. W. R Grace, (chemicals, oil drilling, etc) built a fuel reprocessing plant at West Valley about 1963. Grace sold West Valley to Getty Oil in 1969. Getty gave up on West Valley in 1972 due to rapidly escalating regulation, taking a big hit in the process.

Pure Oil Company made a big investment in graphite to supply moderator to nuclear reactors. Pure Oil is gone, swallowed up by Union and then Chevron. But the graphite operation lives on with the name shortened to Poco.

Tidewater, Kerr-McGee, Skelly, and Getty, all oil companies, formed the Petrotomics partnership to develop the uranium reserves of the Shirley Basin in Wyoming. The silly name tells you all you need to know about Big Oil's embrace of nuclear.

Gulf Oil bought General Atomics in 1967 and renamed it Gulf General Atomic. In 1973, Shell through their nuclear subsidiary, Scallop Nuclear, became a 50-50 partner. Later Gulf Oil was swallowed up by Chevron. Chevron and Shell bailed out of General Atomics in 1986. Gulf and Shell also worked on a high temperature gas reactor, a project to which Shell contributed 200 million dollars. Gulf also had a fuel fabrication facility at Elmsford , New York. Shell also invested in a fuel reprocessing plant at Barnwell, South Carolina that never went into operation. Shell was also involved in a Dutch attempt to develop centrifuge enrichment.

The biggest push into nuclear was by Exxon. Exxon intended to be the fuel supplier to the burgeoning nuclear power industry. They set up Jersey Nuclear (later Exxon Nuclear) in 1969, built fuel fabrication plants at Hanford and in Germany, and took a big stake in uranium reserves, as did Scallop Nuclear, and Gulf. Exxon became an early promoter of global warming, even instrumenting one of their largest tankers, the Esso Atlantic, to measure ocean water temperatures. Exxon finally bailed out of nuclear in 1986 after taking an enormous hit. Exxon's concern over global warming disappeared at the same time.

Gas Until the first decade of the 21st century, Big Oil wasn't that interested in gas. It was more of a nuisance than a commodity, often flared. Gas was more expensive than coal. It's only real market was heating, and specialized firms developed to produce and distribute natural gas. But as coal and nuclear were regulated into oblivion, gas for electricity became a big time business. Gas prices rose, and the big oil companies jumped into gas in a big way in the late 1990's.

Their timing was terrible. Fracking exceeded everybody's projections, and gas prices plummeted. But now they were in the gas business, and the gas business was now electricity generation. The oil companies found themselves in the same position as the coal companies 50 years earlier, and responded in a similar manner, fighting nuclear subsidies and promoting wind/solar, knowing that their intermittency would lock in gas as the dispatchable source.

But this is a recent development, which has nothing to do with nuclear's demise in the 1970's. I worked in the Oil Patch from the late 70's to around 2000. I cannot recall a single instance when the word “nuclear" came up in a conversation. Nuclear power simply was not on our radar.

The Rockefeller Foundation The fossil fuel conspiracists often point to the Rockefeller Foundation's machinations against nuclear as evidence of Big Oil's guilt in destroying nuclear power. After all the Foundation was funded by the most successful oil man of all time. These people believe:

1. Big Oil was worried about nuclear power in the 1950's.
2. Big Oil hatched a radiophobia based plan to undermine nuclear power.
3. The Rockefeller Foundation people would do the bidding of Big Oil.

This dog does not hunt.

John D. Rockefeller was born in 1839. He retired around the turn of the century. And when he did so he really left the business, perhaps partly because his baby, Standard Oil, had been broken up into a dozen pieces. The family immediately began distancing itself from oil and the Old Man's business practices, preferring real estate, politics, and philanthropy. The current generation is openly critical of oil. And so is the Rockefeller Foundation which has divested itself of all oil stocks.

More to the point, we know why the Rockefeller Foundation set out to undermine nuclear weapons. The history is clear, Section 5.3. It had nothing to do with Big Oil. Thanks to the nuclear establishment's inept handling of the situation that the Foundation created, nuclear power was collateral damage.

And we know that the key decision by BEAR1 to accept LNT was made in February, 1956. At the time, there was no such thing as commercial nuclear power. The tiny, experimental Shippingport plant would not go on-line until late 1957. To assume Big Oil was worried about competition from nuclear power in 1956 and earlier in a market they had little interest in is a preposterous stretch. And the fact that a few years later, the Foundation was undermining nuclear power at the same time Big Oil was investing in nuclear proves that Big Oil had no control over the Rockefeller Foundation.

Big Oil is now fighting nuclear power using renewables as green cover; but blaming Big Oil for the demise of nuclear power in the 1970's is counter-productive nonsense. The idea that singularly successful people, holding some of the most prestigious and secure jobs in America, could be bribed by Big Oil is patent nonsense. And it wasnt just the Rockefeller Foundation. It was Linus Paulling. It was Ed Lewis's boss, George Beadle, a department chair at CalTech and Nobel Laureate. It was a hundred other smart, well meaning scientists. It was even Lewis, by all accounts a fine human. Were they all bribed by Big Oil?

Of course not. No, like Lewis, they were prepared to put aside scientific integrity for a more worthy purpose: stopping World War III. It was only the creepy Mullers of the world that were bribed. This motivation is important to understanding the whole LNT history. It goes a long way toward explaining why there was so little push back, from the scientific community, many of whom knew LNT was nonsense. They thought they were serving a still greater good.

9.12 Nuclear is too slow

One plausible argument against nuclear power is that it is too slow. The evidence offered is recent interminable builds in the US and Europe, Table 9.6. But is this inherent in the technology?

Table 9.6: Recent US and European NPP Costs and Build Times

	Initial		Latest	
	$/kW	Years	$/kW	Years
Vogtle 3/4	4500	5	9000+	10+
Flamanville 3	2000	5	8000+	15+
Olkioluto 3	2000	5	8000	16

The American Disaster In the USA, Figure 9.16, prior to 1966, the build times were 4 years or less, with two exceptions.

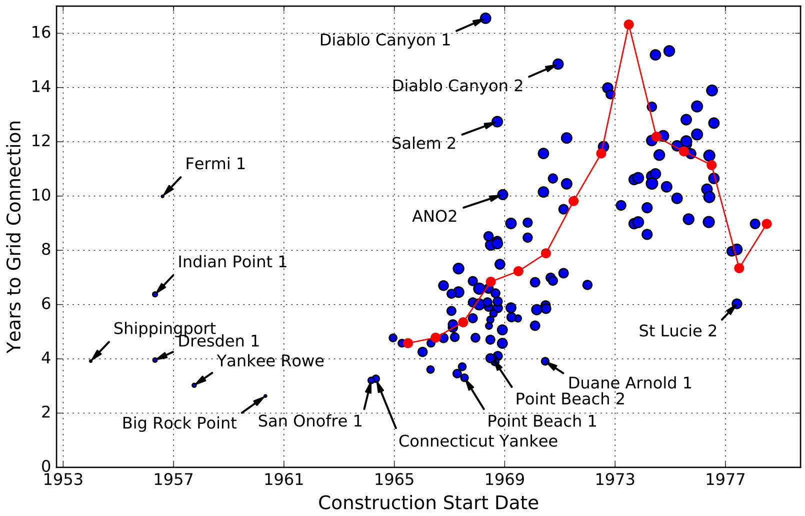


Figure 9.16: USA Build Times. Red dots are average for that start year. Area of blue dots is proportional to plant capacity. 17 years and more not shown. Data from IAEA PRIS database.

Fermi 1 was a one off, a sodium cooled, fast breeder, basically an experimental reactor.[27] I do not know what went wrong at Indian Point 1. Connecticut Yankee which was featured in Section 3.1 was built in 3.3 years.

But after 1966, build times deteriorated rapidly. Plants started in 1968 had an average time to grid connection of about 7 years. By 1970, this was up to 8 years. By 1972, it was close to 12 years. Time to grid connection peaked for plants started in 1973 at about 16 years. After 1973, there was some recovery, but build times remained over 8 years for almost all the late 1970's plants, The scatter for functionally equivalent plants is preposterous. In any given year, the low to high range is better than a factor of two. Since the 1970's were a period of very high interest rates, this escalation in build times was a major contributor to plant costs.

Some of the worst cases involve site specific issues including court ordered delays, engendered by anti-nuclear groups. But this was a post-1978 phenomenon, and not the case for the bulk of the plants, and certainly not the better performers in each start year. For these plants any learning was wiped out by escalating regulation compounded by backfitting.

---

[27] Zirconium sheets covering the core spreader were a last minute safety add to handle an event that was later determined to be impossible. In the start up testing, the zirconium pulled off the spreader, balled up, and clogged some of the coolant channels, which overheated portions of the core. The plant was shut down for four years to correct this.

The French Decarbonization The French were able to hold their build times below 6 years up to about 1985, Figure 9.17, with very little scatter. In the 1980's, France was adding 35 TWh's of new nuclear power production each year, Figure 9.18. France's annual electricity demand at that time was about 350 TWh. France was decarbonizing her grid at the rate of 10% per year.

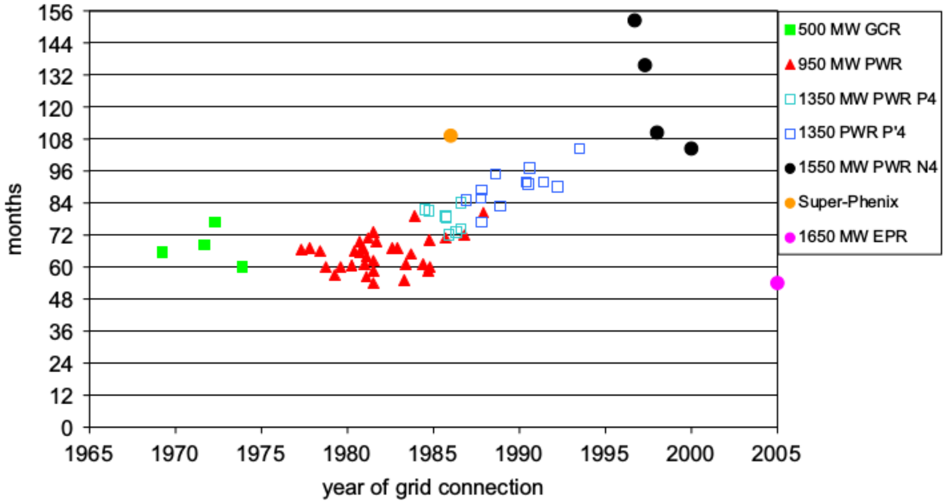


Figure 9.17: French Build Times.[99][Fig 3] Data from IAEA PRIS database.

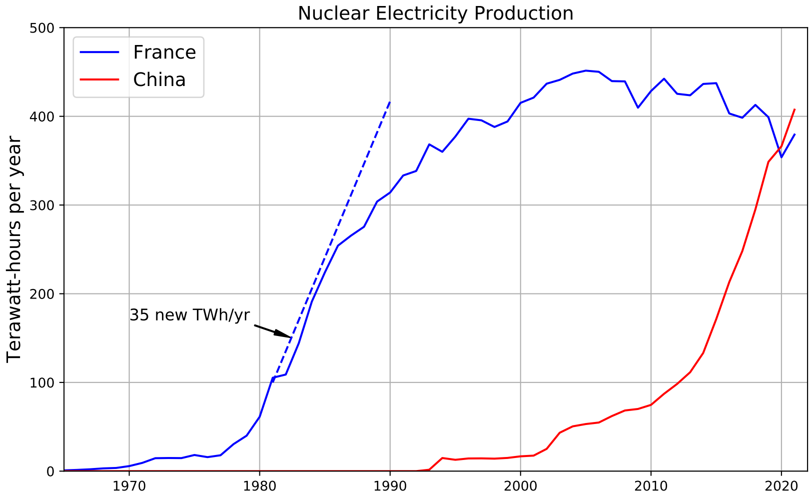


Figure 9.18: French and Chinese nuclear power production. Source: BP Review.

After 1985, things began to deteriorate. According to the learning curve, build times should be dropping with added experience. We cannot blame blame escalating regulation for this fall off. EDF, the state owned utility, was given complete control of the project.[99][Box 1] It was essentially a form of self-regulation. But EDF is a monopoly, beset by strong unions. As the initial momentum wore off, all the standard monopolistic inefficiencies set in. The reduction in the build rate after 1985, which in a competitive market would have reduced costs, instead required build periods to be stretched out to keep everybody "busy'. After 1995 with no competitive pressures, things completely fell apart.

Japanese Discipline It is the Japanese that really put the lie to the claim that nuclear has to be slow. They built 60 plants between 1970 and 2009, Figure 9.19. The median build time was 3.8 years, which is about the time it takes to build a big coal plant. There is no sign of a learning curve in Figure 9.19. But there is also no sign of a fall off.

The Japanese system involves shipyard-like competition. The two big players have been Mitsubishi and GE-Hitachi. Mitsubishi offers a PWR and Hitachi a BWR. Other entrants such as Toshiba are always prowling around. While we might expect some form of cartelization in both shipbuilding and power plant construction, effective competition has been maintained in both cases. And in the Japanese case, the regulators have not played an American style dominant role, at least not until after Fukushima.[28]

Conclusion There is nothing inherent in the technology that says a nuclear plant should require any more time than a coal plant to build. In both cases, the critical path is dominated by the turbogenerator. The reactor pressure vessel, steam generators, and pressurizer are all far more compact than a coal plant boiler, and can be manufactured in less time than the turbine. In the right environment, nuclear power can be deployed as quickly as coal, as the French proved. Sweden also completely decarbonized her grid between 1970 and 1986.

On the other hand, the whole learning curve concept for power plants appears to be overrated. Coal plants show little sign of a learning curve. Rather we see slow, incremental, technological improvements, that over time add up. The French did not see much of a learning curve during the period in which EDF was in total control. Nor did the Japanese ever. If there is a learning curve in on site construction projects, it is largely exhausted in unit or two. Those who are betting on the learning curve to markedly reduce current exorbitant nuclear costs and interminable build times, are very likely to be disappointed. What's required is regulatory stability and competition.

---

[28] Until Fukushima, Japanese nuclear was regulated by the Nuclear and Industrial Safety Agency, which was under the Ministry of Economy Trade and Industry (METI). METI was also responsible for promoting nuclear power. After Fukushima, the government set up the Nuclear Regulation Authority (NRA) and placed it under the Ministry of the Environment. The NRA has taken a very NRC-like stance on nuclear power, focusing narrowly on nuclear hazards and ignoring nuclear benefits. That's precisely what they have been told to do. If Japan starts building nuclear plants again, we can confidently expect build times two or three times as large as those in Figure 9.19.

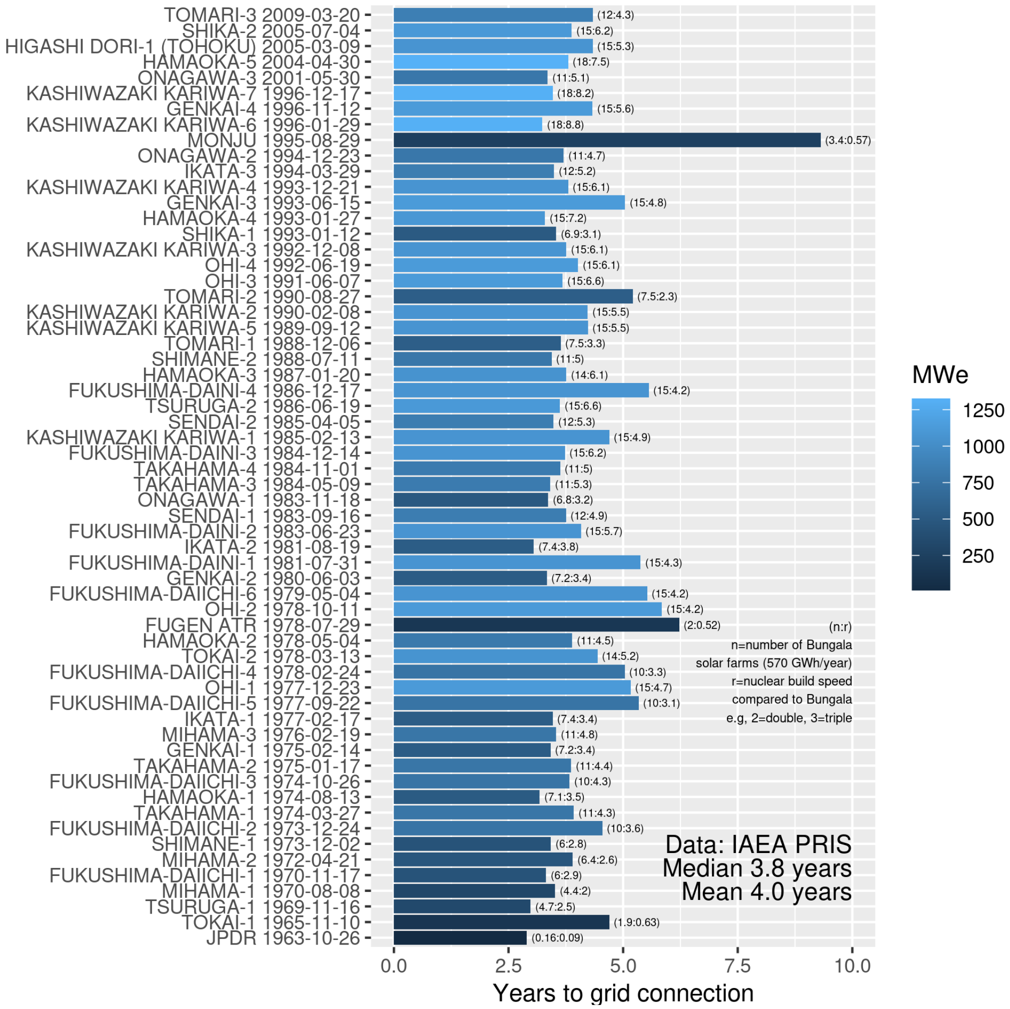


Figure 9.19: Japanese NPP Build Times. Monju was an experimental breeder. Fugen ATR also experimental. Graph courtesy Geoff Russell. Data from IAEA PRIS database.

Chapter 10

Real Quality Enforcement or Formal Quality Assurance?

Most people find it hard to believe that inefficient regulation can increase the cost of anything by a factor of three or more. 25% sure. 50% maybe. But 200% no way.

This chapter argues that inefficient regulation can easily increase the cost of just about anything by a factor of ten or more. And here's the worst part: quality and reliability often, if not usually, suffer as well. How can this be?

To answer this question, I unfortunately have to bring me into the story. In the 1960's, I trained as a Naval Architect at M.I.T. At the time, being an American naval architect meant you worked for the U.S. Navy, either directly or at a naval shipyard or some other Navy funded activity. This I did for about 10 years. I worked for three yards, Newport News, Electric Boat, and Litton Industries. I became a junior faculty member at my old department at M.I.T. which was largely supported by the Navy. I saw the Navy way, up close and personal. I saw time and time again how expensive, how wasteful, and how counter-productive the system could be. The ships were hugely over-priced. They were never delivered on time. And they almost never worked well, and often performed horribly.

I finally got fed up and decided to seek my fortune in the tanker market. One thing led to another and around 2000 I found myself in Korea managing the building of eight super-tankers for a company called Hellespont. The Korean shipyards physically did not look all that different from the US Navy yards. But they were on different planets. The ships were almost always delivered on time and almost always performed as designed. By any reasonable metric, they were at least ten times cheaper than the naval ships that did not work.

Late in life I became concerned about electricity poverty and global warming. Although I had almost no contact with nuclear power up to that time, it did not take long to figure out it was the only realistic solution to the Gordian knot. But when I got into nuclear power, I found myself suddenly transported back to my Navy days. We were building nuclear power plants the way the Navy builds ships, and not the way the Koreans build ships. This chapter explores the differences.

10.1 A Tale of Two Ships

There are two approaches to costing:

1. One is to ask: what should the cost be?
2. The other is to ask: what did it cost?

In a reasonably competitive market: multiple providers, nil price power, no big secrets, no major barriers to entry, there is usually little difference between these two questions. An example might be large oil tankers.

In situations where these conditions do not apply, there can be an enormous difference between what the cost should be and what it is. Consider Table 10.1 which compares a 360,000 ton displacement Very Large Crude Carrier(VLCC) with the US Navy LPD class. The VLCC can carry 320,000 tons of crude oil. The LPD is a 25,000 ton ship designed to carry 700 marines and their landing craft (two air cushion vehicles) and aircraft (4 helicopters or 2 Ospreys). The LPD has one 30 mm gun, four 50-cal machine guns, and two compact RAM close-in missile launchers for armament.[1]

	VLCC	LPD
Length Overall(m)	333.0	208.5
Beam(m)	60.0	31.9
Full Load Draft(m)	22.0	7.0
Displacement(mt)	360,000	25,300
Accommodations	40	1002
Power	1 x 35MW	2 x 15MW
Speed	16kt	(flank) 22kt
Cargo capacity	350,000m3	2229m2+2190m3
Ballast capacity	150,000m3	abt 5000m3
Construction time	1yr	3 to 8 yrs
Cost	$80,000,000	$1,700,000,000

Table 10.1: Comparison of VLCC and LPD

The VLCC is 14 times larger and 20 times cheaper.[2] VLCC contracts are fixed price usually with stiff penalties if the ship is not delivered within a few weeks of the target date.

Of course, the VLCC was not built with the same stringent quality control backed up by extensive paperwork as the naval ship. As a result, on average a VLCC will experience involuntary offhire time of about 15 days per year. This includes a two week dry docking every 5 years. Most

---

[1] Each RAM launcher weighs about 6000 kg and costs $440,000 exclusive of pre-launch target detection.

[2] The price of a VLCC varies with the market. During a tanker market boom, the price can rise to 120 million or more. During a slump, it will drop to about 60 million which is about the yard's marginal cost of building the ship. A good yard can very profitably build a VLCC for 80 million dollars.

ships do better than 15 days, but some VLCC's don't live up to this standard. A VLCC that has more than 30 days offhire per year in the first 15 years of her life is regarded to be a lemon. She will probably cost the yard a customer.

In contrast, LPD availability reflects the kind of standards that can be expected when enormous amounts of taxpayer money are applied to the problem. Nothing's too good for our sailors. Here's a bit of the history of the lead ship, the San Antonio, LPD-17:

1996-12 Contract awarded. Navy says "The LPD 17 program is the Navy's best case of capitalizing on acquisition reform" and goes on to list the reasons why this will be an unusually successful program. The budgetted cost of the ship is $617 million.

2000-08 Construction started. Supposed to be commissioned 2002-07. Navy admits cost is now up to $861 million. CBO estimates cost at 1.3 billion.

2003-07 San Antonio launched.

2004-12 Towed from Avondale to Pascagoula. Could not move under own power despite being christened in 2003.

2005-?? Attempted sea trials. Navy came up with 15,000 deficiencies. Some of these were major enough to compromise watertight integrity.

2006-01 Inexplicably Navy accepts ship waiving the unresolved issues. She is commissioned, but still can't deploy. Northrop-Grumman gets extra money "for post-shakedown availability". Having accepted the ship, Navy's legal options are non-existent.

2007-03 Failed to finish sea trials, complete failure of one steering system, major defects found in 3 of 17 sub-systems. Ship is now 840 million dollars over budget.

2007-06 SecNav Winter writes builder "23 months after commissioning of LPD 17, the Navy still does not have a mission capable ship".

2008-08 After a further series of problems and legal wrangling between Navy and builder, San Antonio finally deployed on first mission in late August, 2008. Most sources put the total taxpayer cost at 1.5 billion or higher. Some say 1.7 billion, one says 1.8 billion. Navy itself says cost may go to 1.85 billion. Stern gate failure delays departure 2 days.

2008-10 Got as far as Bahrain in October. Extensive oil leaks. 30 welders and fitters flown out from USA for at least two weeks of repairs.[3]

2008-11 All four main engines out of commission.

2009-02 During transit of Suez, one screw suddenly went into reverse, sending the ship out of control and aground.

2009-?? Ship's XO Sean Kearns refuses Captain's mast, is court-martialed, and then acquitted after testifying that ship officers had been pressured to declare the ship was ready to deploy when she wasn't. Defense provided copious evidence supporting claim.

2009-07 Inspections reveal that 300 m of piping must be replaced. Reduction gear shavings found in main engines.

2010-03 San Antonio to Norfolk for 4-5 month overhaul costing 5 million. But inspectors finds bolts in the main engine foundation improperly installed, extensive bearing damage. Problems include bent crankshaft. Repairs now expected to take about 11 months and cost at least $30 million. Northrop Grumman releases a statement saying

---

[3] There are plenty of high quality welders and ship fitters in the Persian Gulf repair yards.

> The report's findings support many of the findings from the industry/Navy technical team investigation into the bearing damage on the LPD main propulsion diesel engines [other ships in class were having similar problems] this spring, resulting in a corrective action plan with recommended actions which are already in process. Northrop Grumman has aggressively prosecuted the issues and we are focused on corrective action and moving forward.

2011-04 San Antonio still in repair. Navy starts an investigation into "issues with the San Antonio". Maintenance firm Earl Industries fired. Earl had won the 75 million dollar contract despite not being low bidder on the basis of "exceptional" performance on past contracts. Earl still has USN carrier maintenance contracts.

2011-05 San Antonio leaves yard, and after trials declared ready for duty.

2011-07 Unable to maintain full power. Returns to yard for repairs.

2012-03 San Antonio given the Navy's Battle Effectiveness Award, beating out four of her sisterships. Gets to paint a big E on super-structure.

The performance of the eight sister ships has not been much better. They were all delivered late and have experienced essentially the same set of problems. Availability, generously defined, has been in the 50's and 60's. The initial cost per ship has remained at over 1.5 billion (Navy numbers), despite the fact that multi-ship contracts were supposed to reap economics of scale.

If the job of building a 22 knot, 25,000 ton ship capable of carrying 700 marines a couple of helicopters and a couple of air cushion vehicles were put out for competitive bid to the world's shipyards, I am quite confident the price would come in under 50 million dollars, quite possibly well-under. And the ships would perform per spec.

In some situations, ***the difference between should-cost and did-cost can be a factor of 30.*** Does this apply to nuclear power? Lochbaum claims that about 1990, the Susquehanna plant installed a fifth 4000 kW emergency diesel generator at a cost of 100 million (1990) dollars.[149] This generator was a backup to a backup. In 2000 in Korea, the cost of a marine diesel generator of this size was about 1.2 million dollars.

It gets worse. In January, 2023, final testing of Unit 3 at Vogtle revealed a bit too much vibration in one of the depressurization system lines. The fix was an addtional pipe brace. On a normal job, this fix would have been implemented in a day or less. But this is nuclear. The additional pipe brace requires a license amendment. Southern hopes their request will be expedited; and the start up of Unit 3 will only be delayed by a month.

The cost of the delay will be at least a million dollars per day. That will be a 30 million dollar pipe brace. A system is which this is "just the way things are" is suicidal insanity.

10.2 Shipyard Production of Nuclear Power Plants

Speaking of shipyards, there had been an immense amount of hype, and considerable nonsense written about Small Modular Reactors. When you are trying to solve a problem as big as the Gordian knot, small is not beautiful. There are strong economies of scale in nuclear power generation. Any solution that does not recognize this will be hopelessly wasteful. But it is also true that we must take advantage of the order of magnitude improvement in productivity and quality associated with assembly line manufacture, as compared to conventional on site construction. ***What we need is Big Modular Reactors, the biggest reactors we can build on an assembly line.***

The masters of building big on an assembly line are the shipyards. World class commercial shipyards, exposed to a brutally competitive market, have developed truly remarkable productivity. I have watched this magic. Flat plate comes in at one end of the property and an immense, complex ship goes out the other end. A good yard needs only 400,000 man-hours to build a ship weighing 30,000 tons, a little more than 10 man-hours per ton. This includes everything: coating, piping, wiring, machinery, and testing. The contract is fixed price, which will be about $3000 per ton. The ship will be built in less than a year. The ship must perform per contract and there are substantial penalties for late delivery.

The shipyards achieve their remarkable productivity by a combination of automation, Figure 10.1 and block construction. Sub-assemblies are produced on a automated panel line, combined into assemblies, and then into fully coated blocks with HVAC, piping, wiring (and scaffolding if required) pre-installed. In the last step, the blocks, weighing as much as 3000 tons, are dropped into place in a building dock.

Figure 10.1: One man controlling 48 welding machines

Block construction, Figure 10.2, not only creates order of magnitude improvements in productivity; but it also produces striking improvements in quality. Very tight dimensional control is automatically enforced.[4] Extensive inspection and testing at the sub-assembly, assembly, and block levels is an essential part of the yard's productivity. Inspection at these levels is easy. Defects and faults are caught early and can be corrected far more easily than after erection.

Figure 10.2: Two super blocks in building dock

For this to work, detailed design and production scheduling must be tightly integrated. All the world class yards do their own engineering. The process is divided into basic design and detailed design. Basic design takes a potential project far enough to do accurate costing, allow the yard to bid the job, and be confident that it has a good handle on the resources required. After they sign a contract, detailed design takes over. Detailed design not only does the working drawings, but just as important the production scheduling down to per shift detail. This includes scheduling each sub-block and block lift by crane. The weight and center of gravity of each lift is calculated and the lifting lugs are part of the design. Even any scaffolding which will be required in final erection is part of each block design, and installed at the block level. ***Detailed design and production scheduling cannot be separated.***

The production process is so tightly scheduled that any delay cascades throughout the yard. A problem on one project is a problem for every project in the yard. To prevent these delays, the yards have a well developed Test and Inspection System. The yards' Quality Standards are 200 page books covering just about every imaginable defect. A steel sample is taken of every ladle. Plates are marked by date and ladle. Tests are much easier to do and to automate at the sub-assembly and block level then after erection. Every fillet weld is pressure tested at the block

---

[4] Super-blocks are 30 m cubes with an overall tolerance of ±5 mm. Westinghouse targeted ±15mm on their far tinier AP-1000 modules, and did not maintain this.

stage. Critical welds are either xrayed or tested ultrasonically.

The process is overseen by an independent inspection and certification outfit, known as a Classification Society. The Classification Society approves every drawing, and Classification Society inspectors witness and sign off on every scheduled test. The cost of this service is about 2% of the ship's price. Classification Society approval is required for the shipowner to purchase insurance.

A third layer is the buyer's own inspectors. The shipowner will have a team of his own people in the yard, witnessing and signing off on every test, constantly patrolling and ensuring the contract standards are upheld. The overall result is the ships are almost always delivered on time and perform as designed.

A key to the efficiency of this process is that all the players understand and agree to the rules of the game. Once the contract is signed, all the quality standards, all the test protocols, everything is known and fixed. Nobody, not yard, not owner, not inspector can change the requirements.

Contrast that with an NRC license. The Atomic Energy Act, Section 187, makes it abundantly clear that the NRC can change the rules whenever it feels like it.

> SEC. 187. MODIFICATION OF LICENSE. The terms and conditions of all licenses shall be subject to amendment, revision, or modification, by reason of amendments of this Act or by reason of rules and regulations issued in accordance with the terms of this Act.

The whole shipyard system is based on functional tests. ***How the yard produces the product is the yard's business.*** The only thing that counts is the result.[5]

We must build nuclear power plants like the world class shipyards build ships. But the good shipyards are petrified of nuclear. They know, if they allow nuclear style regulation into the yard, their finally tuned production process will be thrown into complete disarray. The last thing the yards need is NRC-like bureaucrats telling them how to do things.

The nuclear regulatory system grew out of the way the US Navy builds ships. The shipyards that build Navy ships have access to exactly the same production technology as the Korean and Japanese yards. In fact, if you go into the US Naval yards, you will see the same equipment.

But as we have seen, the results are completely different. Even a very lightly armed, non-combatant Navy ship like the LPD will cost the taxpayers well in excess of $60,000 per ton.[6] Moreover, Navy ships are almost never delivered on time or anywhere close. Cost overruns of a factor of two or more are commonplace. And “despite" elaborate quality assurance requirements

---

[5] Tests are scheduled when the yard wants to do the test. The Classification Society and the owner's inspectors need only be given proper notification. If they don't show up for the test, the test is deemed approved.

[6] A 600 MWe super-critical steam turbine and generator weighs about 1200 tons. It costs about 100 million or $80,000 per ton and it is ALL high precision machinery. A ship — Navy or otherwise — like a nuclear plant is mostly simple steel.

and procedures, they almost never perform per original spec. In many cases, their performance is a tragic joke.

I have seen both sides of this coin. I spent the first 15 years of my career working for the U.S. Navy and the next 30 years in foreign flag tankers. So when I come to nuclear power plants, the question is not: can we build them in a shipyard? The answer is obviously yes. But the real question is: what manner of shipyard?

- Will we build nuclear power plants the way the Koreans build ships?
- Or will we build nuclear power plants the way the US Navy builds ships?

Will it be the certificate shuffling, ass covering, talent stifling, paperwork obsessed operation that Naval ship construction is, or will it be competitive market enforced efficiency and quality? In America, even the most casual observer of US nuclear knows the answer to this question. Unless this changes completely, building a nuclear power plant in a shipyard will be no better than building it stick by stick in a swamp.

10.3 Real Quality Enforcement

Here's what I learned in Korea about quality. Real Quality Enforcement is based on the following rules.

1. Quality starts with a rock solid set of product requirements. In shipbuilding, this is called the *owner's specification* or *spec*. The spec is the foundation.
2. Bid everybody, trust nobody.
3. Don't show me your certificates; show me your guarantee.
4. Test the weld, not the welder.
5. Strict, hands on test enforcement.
6. Admit and fix mistakes.

10.3.1 The Spec

Everything depends on a strong spec. Unless the spec is rock solid, all the enforcement in the world will not result in a solid product. To the extent possible, the spec should be functional rather than prescriptive. This maximizes the vendor's responsibility while giving him freedom to innovate and come up with better or cheaper ways of providing the required functionality.

The spec must require stringent physical tests of all critical components. Those tests must be delineated in an unambiguous fashion, no wiggle room. The spec should say as little as possible about how the vendor produces the component. For example, standards that specify how welds shall be tested are essential. Standards that specify who can do the welds are anathema.

One person who understood the importance of the spec was Rickover. During World War II, he was head of the electrical section at BuShips. His main innovation was insisting that the Navy write the spec for the stuff he was buying.[236][p 23] Up to that point, the vendors wrote their own spec! This change required that the Navy have the technical competence in house, to produce a proper spec.

10.3.2 Bid everybody, trust nobody

In procurement, the most important weapon is competition. We must do everything possible to maximize competition among vendors.[7] There is always somebody who will do it cheaper and better. Our job is to find that guy; and all the vendors must know we are searching for him. Often that somebody is the new guy on the block. Sometimes he has discovered a better way of providing the function. He tends to have low overhead. And he's always the hungriest.

There is no greater motivation than survival. If the vendors know that in order to survive, they must come up with the cheapest product that will meet the spec, that's what they will do.

---

[7] The antithesis is *pre-qualification*, a procedure which constrains “competition" to a small, well-established handful, who know each other well. Hard to imagine a more counter-productive policy. Much the same thing can be accomplished by requiring burdensome certificates.

10.3.3 Don't show me your certificates. Show me your guarantee

So if we are going to base everything on price, what's to prevent the vendors from producing a shoddy product? Fear. Fear of production delays. Fear of rejected products. Fear of penalties. Fear of warranty claims.

When asked about quality, vendors will offer a long list of references and extol all their QA certificates.[8] The proper response is "Wow! That's really impressive. With such great quality, you should have no problem giving us a ten year guarantee with substantial penalties if the product fails." It is amazing how many vendors offer wonderful quality which they won't guarantee, especially if they know the competition is limited.[9]

A good model here is the commercial aircraft industry. Here are the typical guarantee terms for a commercial aircraft purchase.

1. Full warranty for five years.
2. Rewarranty of two years.
3. Service Life Policy. Primary structure including landing gear and movable surfaces are guaranteed for 12 years in the sense that cost of replacement is shared between builder and buyer with the builder proportion decreasing linearly from the end of the full warranty period to zero at 12 years.
4. Similar terms are provided by the engine manufacturers.

Such guarantees generate another benefit. Since the aircraft and engine builders are on the hook, they take a real interest in how the airplanes are maintained. For example, the airplane engine builder is involved in every major inspection and overhaul of his engines. He has a strong pecuniary interest in calling out poor maintenance and operating policies in a way that a regulator does not. If he can prove that the maintenance/operation is not per manual, he is off the hook. This in turn puts real pressure on the aircraft owner to do his maintenance correctly. The system is self-policing.[10]

The required guarantee must be written into each spec. This is one place where the new guy is at a disadvantage. He will have to offer the same guarantee as everybody else but he may not have the financial resources to back it up. In that case he will have to post a bond. If he does, he's just like anybody else.

Buyers tend to treat guarantees as an add-on. Maybe we can get another six months with no change in price. The guarantee is a fundamental part of the specification, just as important

---

[8] Test certificates can be forged, bribing an inspector if necessary. See Korea, Section 9.5. A forged guarantee is almost an oxymoron. Who is going to do the forging? Won't be the vendor. The customer could try; but he would have to suborn most of the guarantor's top management to have a chance at pulling it off. Won't happen.

[9] References are pretty much useless. No one wants to admit that his ship or whatever is sub-standard. He has to claim that he has bought a wonderful product. And even if the quality is so lousy, he's prepared to say something uncomplimentary, his lawyers will tell him to keep his mouth shut, for fear of being embroiled in a legal dispute. Usually the only way to get the real story is to get the reference drunk.

[10] The engine builders have taken this sort of monitoring to the point where on-line sensors are transmitting in-flight operating data back to the vendor continuously.

as the capacity or any other requirement. A strong spec and a strong guarantee may not come cheaply; but, if that's the case, then that is the real cost of obtaining a quality product.

10.3.4 Test the Weld, not the Welder.

Real quality enforcement focuses on the results, not procedure. This is summed up in the mantra "test the weld, not the welder". All shipyard welders are trained and duly certified. But that does not mean they are equally competent, or even competent. Our newbuilding specs had weld specifications that were considerably more stringent than normal shipbuilding practice. It did not take long for the yards to figure out that it was in their best interest to put their best welders on our ships. But even the best welders have bad days. All we care about is the weld itself.

10.3.5 Test Enforcement

It is not enough to spec a thorough, rigorous set of tests. The actual tests must be closely monitored. All acceptance tests must be witnessed by our guys. Accept no vendor paperwork. But our inspectors must be aware that acceptance tests are carefully choreographed, as much stagecraft as test. The spec must allow them to force a repeat test if anything is questionable. Most importantly, the inspector must know that we want him to reject the test if he's the least bit unhappy, regardless of the effect on the production schedule.

At the Midland, Michigan, two reactor plant, the contractor, Bechtel, failed to compact the fill per spec. This was a major screw up that could not have gone unnoticed. But utility employees were discouraged from complaining about Bechtel's work, because it would slow the job down. Buildings erected on this soil began sinking almost immediately. The cost of rectifying the problem was a major reason the plant was never completed, and at least four billion dollars went down the drain.[236][p 113]

Finally, our inspectors must spend most of their time randomly patrolling, getting to know the real workers, explaining our standards and why, appreciating a job well done, and politely but firmly calling out defects and bad practice. This avoids the stagecraft, and properly done motivates the work force. Most people would rather do good work than bad work. Patrolling is at least as important as witnessing tests in enforcing quality. We caught far more problems patrolling than we did during acceptance tests, in part because if the patrols had revealed no problem, the component was unlikely to fail the test.

All this implies a large, expensive inspection force. Most shipowners assign a half dozen inspectors to a large newbuilding project. For our newbuilding project, we had 24. This too is part of the cost of real quality.

10.3.6 Admit Mistakes and Correct.

No spec is perfect. It is inevitable that as the job proceeds, we will uncover mistakes on our part, and design features that can and should be improved. There will be screws up in the implementation. This means Change Orders. In negotiating a Change Order, we are at a big disadvantage since the vendor will have a monopoly on us. The tendency is to cover up the mistake and avoid pointing out the improvement.

Our team must know that if you go down that route you will be fired. We must catch our mistakes as early as possible. The owner welcomes ideas for improvement and is willing to pay for them. If you made a mistake and admit it, you are likely to get a fatherly lecture, and a mental note that this guy is the real thing. If you made a mistake and attempt to cover it up, you are gone. The goal is to build a web of trust within which each level can be completely honest with the next level up, and expect the next level up to react in a way that is consistent with getting the job done right.

10.3.7 Quality is hard work

Quality enforcement is a lot of hard work. It starts with drafting an iron clad spec. It forces buyers to turn over every stone. It means a lot of on-site inspectors, working 60 hour weeks, almost none of which is sitting at a desk. It means managers must spend most of their time patrolling with the inspectors. It is the only way they can know which of our guys are doing their job and which are not. There is no easy way to quality.

10.4 Formal Quality Assurance

Formal quality assurance (QA) take a quite different approach to the problem. QA programs focus on procedure. Quality Assurance relies on the proposition that by mandating detailed reporting procedures and checklists, sign offs, mistakes will be prevented. The product of the system is detailed documentation. The assumption is that, if the paperwork is clean, quality is assured. Entities that institute such procedures to the satisfaction of an accredited auditor are awarded fancy certificates attesting to that fact. The program must undergo periodic audits by the auditor.

When people hear the term nuclear quality, they tend to think there is something different about the production line itself. In fact, when a vendor makes similar equipment for a nuclear plant and a non-nuclear application, he will almost always use the same production process.[11] Sometimes it's just a different bin. Manufacturers will periodically test assembly line components, perhaps one in every hundred. The tested units are thrown in a separate bin. Since nuclear quality components must be individually tested, a unit pulled out of that bin is nuclear quality. The difference is the paperwork.

Some documentation is just common sense. The pre-takeoff checklist that a cockpit crew goes through is obviously a good idea. And indeed most formal QA programs start out innocently enough. But however well-intentioned, they often become counter-productive monsters. The problem is human nature.

Despite the paperwork burden, formal quality assurance programs are rarely resisted and often welcomed. The reasons are revealing.

1. Top management welcomes the barriers to entry that a costly QA program represents. In fact, they often participate in their creation.
2. Marketing loves to wave meant-to-impress QA certificates in front of customers.
3. The purchasers' job becomes much easier if there are only a few qualified suppliers. A few calls and his job is done. And if a close working relationship with a few favored vendors gets him a nice meal once in a while, why complain? And if the stuff that he bought turns out to be lousy, he can point to the vendor's certificates. It is not his fault.
4. Field management's job becomes more comfortable. It is far easier to review paperwork in a office that go out in the cold and heat and find out what is really happening. As long as the paperwork is clean, it's not his fault.
5. Formal QA is rarely welcomed by the guys actually doing the work, but they have little say in the matter.

It is little wonder that incumbents rarely resist formal QA even though it represents a reviled nuisance. When formal QA was pushed on the tanker owners by their customers, the oil companies, the universal reaction was "it's a pain in the butt, but at least it will get rid of the

---

[11] The nuclear equipment may or may not be built to tighter specifications. But the goal of QA is to ensure *as-built* meets *as-designed*. The spec choice is not part of formal QA.

ma-and-pa's."

But what's good for entrenched suppliers is almost never good for society. The first effect is an increase in price “to pay for the enhanced quality". But the longer term effects are more insidious and far more important. They include:

1. Shoddy product.
2. Suppression of technical progress.
3. Suppression of competition.
4. Suppression of problems.
5. The best suppressors get promoted.

Shoddy Product Scrutinizing paperwork is no substitute for patrolling and inspection; but it's a lot easier. The assumption is, if the QA process is followed, the product will be satisfactory. So all the buyer has to do is check the paperwork.

A crucially important element in Westinghouse's Vogtle and V. Summer AP1000 projects was the construction of steel submodules on an assembly line basis. The outfit chosen to do this work was Shaw Industries in Lake Charles, LA. Shaw was the holder of three of the prized ASME Nuclear Quality Certificates: NA (field installation), NPT (piping), and NS (supports).[81] These are known as N-stamps, since they give the holder the right to stamp his product as nuclear quality. Here's how ASME puts it:

> N-type Certificates of Authorization issued by ASME signifies that a Certificate Holder has been through a rigorous survey to verify the adequacy and effective implementation of the quality assurance program. The N-type Certificates of Authorization allow Certificate Holders to certify and stamp newly constructed components, parts and appurtenances used at a nuclear facility with the Certification Mark in accordance with Section III of the ASME BPVC.

In the nuclear system, certificates and paperwork are what counts. Therefore ***Westinghouse had nobody at the Lake Charles plant to check the submodules.***[134] Since Shaw was an N-stamp holder, Westinghouse could check Shaw's QA reports from a desk in Pittsburgh. When the submodules reached the plant sites, they were not to spec, did not fit, and had to be scrapped or undergo extensive rework. at a giant facility that Westinghouse hastily erected. This was a critical factor in the failure of these projects.

A real quality enforcement effort would have had at least a 4 or 5 man team at Lake Charles crawling all over every submodule, witnessing the weld tests, making their own measurements. If a submodule is not to spec, it does not ship. Under formal quality assurance, such a team was deemed unnecessary. Instead we trust the paperwork.

In October, 2022, after operating at power for at most a month or two, “centimeter" long cracks were found in the impellers of all four Okioluto 3 feedwater pumps. The kneejerk reaction by the nuclear establishment was that this was a teething problem associated with a first-of-a-kind scale up of an unusually large pump.

Okioluto 3 is a French pressurized water reactor called an EPR. There is nothing nuclear about a PWR feedwater pump, or at least there should not be. The steam mass flow in the EPR is 2552 kg/s. The EPR has four feedwater pumps, each designed to handle one-third the flow, allowing one pump to be offline at full power. The volume flow rate per pump is 3100 m3/h. The hot standby pressure is 9.0 MPa. Using 9.0 MPa as the pump discharge pressure, and assuming a probably low 0.8 pump efficiency, the power per pump would be 9.6 MW. We don’t know what margins, the EPR designers used; but it seems unlikely that the nameplate pump power is more than 12 MW.

Meanwhile, in the real world, feedwater pumps are so reliable that, despite the extremely high cost of power plant downtime, coal plants often go with a 1x100% design. For example, the 800 MW units at Eemshaven, use a single feedwater pump. The pump outlet pressure is 35 MPa. The rated flow is 2500 m3/h. At a pump efficiency of 0.8 (probably low), the required power is 30.4 MW. The designers actually installed pump turbines rated at 38.3 MW. The Shenhua Wanzhou 2 x 1000 GW plant also uses a 1x100% pump. It’s volumetric flow rate has to be about 3100 m3/h. A Sulzer flyer claims the pump efficiency is 87%, but the power rating is still over 40 MW.

In short, the EPR pumps are no larger than coal plant feedwater pumps on a volume flow basis. They operate at a far lower discharge pressure and a corresponding lower power. The size of the pumps is not the problem. For that we must look elsewhere.

Technological Stagnation Competition spurs progress. Lack of competition, especially from new entrants, means there is no need to improve or innovate. Technical innovation happens in two ways:

1. Incremental improvements.
2. A new and strikingly better way of doing something.

Incremental improvements occur almost naturally. Once a product is in the field, any number of changes will be suggested by weaknesses that are revealed by operating experience, or people coming up with a slightly better way of doing something. In a competitive market, vendors quickly move to correct such weaknesses and implement such improvements. Formal QA stifles this process by both eliminating the motive for such changes and increasing their cost. The more highly developed the QA program is the more expensive any change is.[12] This creates enormous pressure to "gloss over" problems. If fixing a simple defect will shut down the whole job, the rational response is to accept the defect and fix the paperwork. This inferior quality becomes the new standard from which the next step downward is made. Lather and repeat.

Nuclear has taken quality assurance to such high levels that, even if the approved drawing is obviously and easily improvable, in other words, stupid, the change will not be made because of the re-analyses, checks, and sign offs that will be required, and the corresponding delays. The guy who is actually doing the job often is the guy who knows how to do the job best. QA relieves him of any responsibility to use that knowledge. Requiring people to do something stupid is an excellent way to destroy both worker morale and standards.

I'm confident a dozen or so engineers looked at the plans for Fukushima Daichi and said to themselves: how much would it cost us to move one of the emergency generators up on the hill behind the plant and make it air cooled? If one of them had the temerity to make this suggestion, he would have been told the design has been approved. End of story. Once the plans were approved making this obvious, ridiculously cheap change becomes unthinkable because of the costs and delays associated with getting the change through the QA process. Formal QA programs effectively assume that what is put through the process is unimprovable. That is never the case.

Really big improvements rarely come from incumbents. Such changes usually emanate from an outsider. But the QA barriers to entry impose at best an expensive paperwork hurdle between the new idea and it implementation. And in some highly developed QA programs, there is a rule that you must buy from a QA certified vendor, but experience is a requirement for QA certification. The ultimate barrier to entry.

---

[12] An example is FAA GPS certification. All commercial airlines navigation system must be certified by the FAA, a time consuming, largely paperwork process taking close to a decade and increasing the cost of the component to the airlines by more than an order of magnitude. But GPS-like technologies develop on time-scales of a year or so. As a result, private aircraft have GPS systems costing less than a $1000 which are more capable than those on commercial aircraft costing $20,000.

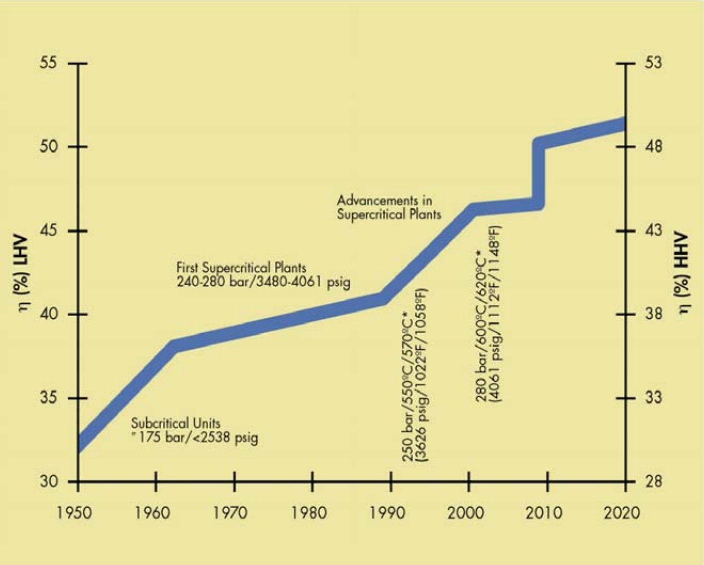


Figure 10.3: Coal plant thermal efficiency, 1950 to 2017

Lack Of Competition Competition is constant stress. Is our product at least as reliable as the best of our competitors? If not, our customers will go elsewhere. Are we making our product as efficiently as possible? If not, we will be eliminated. Is there a new guy out there with a new and better idea? If so, she will bury us. Everybody knows that sooner or latter that new guy will show up, unless we come up with the improvement first.

Figure 10.3 shows that over the last 70 years, coal plant thermal efficiency has gone from 30% to 48%. Under the pressure of competition, the same incompetents, who cannot build a nuclear power plant on time or on on budget, pushed coal plant efficiency up 60%. During the same period, nuclear power plant efficiency has stagnated in the 30 to 33% range.

Lack of competition breeds complacency and then arrogance. Why obsess about reliability and efficiency if the customer has no where to turn? What becomes important is not the product itself but keeping the paperwork clean. Maintaining your certification, not producing quality product, becomes the goal.

Suppression of problems Formal QA programs are based on the idea that all non-conformances must be reported. This is a good idea in theory.

Problems happens all the time. There are tiny mistakes that are best handled by the guys doing the job. There are bigger screw ups that need to be dealt with by a foreman or crew boss. And there are dangerous problem areas and design faults that need to be reported up the chain. Formal QA programs have great difficulty distinguishing which problems fit in which category. It is not long before everybody realizes that reporting even the tiniest problem will generate a blizzard of paper work, delay the job, and make everybody up the line unhappy. Formal QA effectively punishes people for reporting near misses, minor screw ups, or even nagging concerns. So people do the rational thing. They clam up.

The Wrong People get Promoted To make matters much worse, many QA programs evolve *metrics*. These metrics are based on the number of problems reported. A good metric — few problems — gets you promoted. A bad metric gets you fired. This not only means that problem areas are allowed to fester, but can actually generate dangerous responses in a casualty. Section 12.2.5 describes how the Byron Station power plant suffered a serious casualty and then operated with a blind control room for seven minutes because the shift supervisor did not want an unplanned shutdown on his record.

In such an environment, people who are adept at covering up problems move up the chain. Troublesome types who refuse to do this or worse point out incipient problem areas are bypassed and eventually leave or are pushed out or mend their ways. In short, the wrong people get promoted.

The Downward Spiral As an industry protected by formal QA becomes more inefficient and more expensive, the need to maintain and increase the barriers to competition become more critical. Whole departments are engaged in producing and reviewing QA paperwork. The goal of the QA department head becomes defending and extending his turf. I ran into an example of this in my first job, an example which cost the taxpayer millions of 1960 dollars, and could easily have killed people. I responded very poorly.[13]

---

[13] My very first job in 1961 was at Newport News, probably the world's largest naval shipyard. As a temporary hire, I was assigned to the Weight Control Group. The problem was that the center of gravity estimates produced by the recently installed computerized system were seriously wrong. The actual center of gravities (CG) were higher and farther forward than computed. The ships had less stability and too much trim by the bow. A submarine on initial trials with Rickover onboard buried its bow in the bottom of the Chesapeake Bay scaring the hell out of the crew and embarrassing everybody. The Navy response was to set up a 15 man Weight Control Group which went over each drawing in detail, produced hundreds of thousands of lines of data, individual weights and CG's. These were punched onto cards and then fed into the computer. The purpose was unclear since the ships were already being built. Worse, the Weight Control Group numbers matched the earlier, wrong numbers.

I did a simple calculation showing that, even if we were making individual errors far larger than we could possibly be making, as long as those errors were unbiased, the probability that we could be as far off as we were was negligible. There was no reason to expect the WCG guys were biasing their estimates downward or aft. If anything, the reverse was true.

The errors had an interesting pattern. The transverse CG's were spot on, and there was no problem with the longitudinal CG's of the aircraft carriers. The transverse CG were taken from the ship centerline, positive to port and negative to starboard. Half the numbers were positive and half were negative. Normally, the longitudinal CG's were based on the rudder position, positive forward. So almost all the numbers were positive. The vertical CG was based on the hull bottom; all the numbers were positive. But the aircraft carriers were over 1000 feet long. Given the limited precision of the computer, they moved the base for longitudinal calculations to midships. Now we had as many negative numbers as positive and the problem disappeared.

It seemed obvious to me that there was something wrong with the computer's round off algorithm. I found that, if the limited precision computer were simply truncating rather than rounding, then we would get very close

The incumbents make sure they are well-represented on industry standards committees and regulatory advisory boards. They are strongly supported by the auditors whose motivation for pushing for ever more detailed even more burdensome procedures is obvious. And when the inevitable casualty happens, it's nobody's fault. The problem is that the quality assurance program wasn't strict enough.

Stifling competition kills quality A competitive market works in a Darwinian fashion. Mistakes are allowed but they are punished. QA attempts to eliminate the mistakes. But in so doing it creates perverse incentives. Humans respond to the incentives, not the good intentions. The end result is that most QA programs result not only in products that consume far more of the planet's resources than they should, but products that perform poorly. And technology stagnates.

No industry has adopted Formal Quality Assurance more enthusiastically or more thoroughly than nuclear. So we have fancy NQA certificates and lousy guarantees. However, the NRC did not actually require a formal quality assurance program until June, 1972 with the issuance of Regulatory Guide 1.28.[14] The great bulk of the existing American plants were designed and constructed without the benefit of an NRC mandated QA program. Three Mile Island, Unit 2, which operated for all of 3 months before having a meltdown, was the beneficiary of such a program. The Olkioluto 3 feedwater pumps also benefited from nuclear QA.

The nuclear establishment has bought into the idea that the way to quality is expensive certificates. What drives quality is buyer standards and vendor competition. And without robust vendor competition, buyers cannot impose standards. Nuclear QA drives up costs and drives down competition. The result is outrageously expensive components that do not work.

---

to the pattern we were seeing.I prepared a little report and took it to my boss, the head of the Weight Control Group. His initial reaction was incredulity. This was IBM's top of the line mainframe computer. There was no way it could make that kind of mistake. After I had gone over the argument a couple more times, and pointed out it could be a software error, he suddenly went silent, and said he would take care of it. Which he did, by throwing the report in a shredder.

To my eternal shame, I did not go around him. I was scheduled to go back to school in a few weeks, which I quietly did. Perhaps I sensed that, if I did go further up the chain, I would get the same response, which is no excuse. But the pressures to go with the flow are very strong. A year or two later, Newport News upgraded to the next generation IBM mainframe and the problem went away.

[14] In fact, since a Regulatory Guide is not a regulation, RG 1.28 “endorsed the requirements" of an American National Standards Institute set of QA program requirements. The NRC helpfully explains: “Regulatory Guides do not constitute requirements. Thus the term ‘requirement’ is taken from its use, in context of the referenced standards.”[193][Page A-1] I have no idea what this means.

Chapter 11

The Nuclear Power Establishment

> It would be poetic justice, if we were saved from the consequences of having cheap, abundant power, not by the general understanding of its manifold dangers, but by the continued fumbling and bumbling of the nuclear power establishment.[Paul Ehrlich, 1975]

The American nuclear power establishment consists of

1. A few large vendors that have developed the expertise to maneuver through the regulation and formal quality assurance procedures.
2. A few large utilities most of whom operate as regulated monopolies.
3. The Department of Energy and the national labs. This is a sprawling enterprise that was created during World War II to make the bomb and was never shut down after its reason for existence disappeared. It requires feeding to the tune of $20 billion dollars per year.
4. The university nuclear engineering departments which largely subsist on funding from the DOE.
5. The Nuclear Regulatory Commission.

The key players in the establishment move easily back and forth between the complex's components. See Section 11.8.

Nuclear power emerged out of a gargantuan military project. This chapter discusses the implications of that birth and the fundamental changes that are required, not just to make nuclear power marginally economic, but to create an environment in which nuclear's real costs are driven ever lower by harsh competition and technological progress.

11.1 With Friends like these ...

The national labs are an important component of the nuclear power establishment. They have enthusiastically embraced ALARA. One the biggest labs is Argonne outside Chicago. At Argonne, they monitor people going in and out of some of the buildings for radiation contamination. The alarms are set so low that, if it's raining, in coming people must wipe off their shoes after they walk across the wet parking lot. And you can still set off the alarm, which means everything comes to the halt while you wait for the Health Physics monitor to show up, wand you down, and pronounce you OK to come in. What has happened is that the rain has washed some of the naturally occurring radon daughters out of the air, and a few of these mostly alpha articles have stuck to your shoes. In other words, Argonne is monitoring rain water.[1]

Why would a bunch of highly trained nuclear scientists and engineers be concerned about rainwater levels of radiation? The answer is money. More specifically, your money. Table 11.1 shows the big labs are billion dollar a year businesses. And the business they are in is extracting money from the taxpayer.

Table 11.1: Fiscal year 2019 Budget Enacted

	Million USD
Argonne/Fermi	1,347
Bettis	687
Brookhaven	579
Idaho	1,708
Knolls	740
Lawrence Livermore	2,420
Los Alamos	2,484
Oak Ridge	1,978
Pacific Northwest	1,554
Sandia	2,320
Total	15,817

To be fair, a sizable proportion of the DOE budget goes to weapons development and production.[2] But a large proportion goes to *clean-up*. The DOE budget includes around 7 billion dollars per year devoted to clean-up of radioactive material.

The problem is that almost all this material is already in a state where the dose rates are at natural background levels or below. One of the dirtiest sites is Hanford, Washington where

---

[1] For another example, see Toomer's Creek, Section **??**.

[2] In Table 11.1, I've excluded the DOE facilities that are devoted almost entirely to weapons development and manufacture. Overall about 42% of the DOE budget is listed as "defense". The one place where the anti-nuke conflation of nuclear weapons and nuclear electricity is factual is at the DOE. Unfortunately, in 1946 Congress gave control of these two entirely different functions to the same bureaucracy. This makes about as much sense as giving responsibility for conventional bombs and fossil fuel power generation to the same bureaucrats on the grounds that both activities are based on the same underlying chemistry. The intent of the Atomic Energy Act of 1946 was to take control of nuclear weapons away from the military.[165] In practice, it guaranteed that military thinking would strongly influence nuclear electricity.

weapons grade plutonium was produced from 1944 to 1986. Hanford is located on almost 40 miles of the Columbia River from which it drew the water needed to cool the plutonium production reactors and the purification processes. Early on, little attention was paid to avoiding spills and leaks. Contaminated water was disposed of in trenches or cribs and allowed to percolate into the soil or routinely released back to the river. A wide area was contaminated with "deadly" radiation. As a result, 8000 people are employed in cleaning up Hanford. The program is costing the taxpayer about 2.5 billion dollars per year.

But how deadly is the contamination? In 2003, the State of Washington and DOE did a joint survey of the radiation levels on the Hanford shoreline.[264] They determined that the average background radiation along the river was 0.7 mSv/year. This is on the low end world wide. The geology is glacial till that was deposited in a series of massive floods. This soil is low in both uranium and thorium. The team took thousands of measurements, concentrating on known hot spots. Most of the measurements were at or near background; but they did find a few spots where the numbers skyrocketed to 1.2 mSv/y. In other words, the worst case dose rates along the Hanford river front are about average background worldwide, and well below natural background in areas like Finland and Kerala.

Inland it's the same story. Hanford is fitted with about 120 permanent radiation monitors clustered around the old processing and storage facilities. Table 11.2 shows the measured dose rates for 2011 and 2012.[191][Table 4.1] Most of the measurements are at or near background in a low background environment. There are a few measurements in the 2 to 3 mSv/y range and one at about 6 mSv/y. All the measurements are below the average background dose rate in Finland.

Table 11.2: Hanford Dose Rates

Location	No. of Dosi-meters	2011 Max mSv/y	2011 Ave mSv/y	2012 max mSv/y	2012 Ave mSv/y
100-K	14	2.07	2.02	1.07	0.82
100-N	5	2.03	1.16	3.11	1.40
200-East	42	3.85	1.00	1.76	1.02
200-West	24	1.78	0.96	1.51	1.00
200-North	1	5.70	2.51	0.88	0.83
300-area	8	1.14	0.86	1.11	0.86
300-TEDF	6	0.81	0.79	0.86	0.83
400-area	7	0.89	0.79	0.91	0.82
618-10	4	0.75	0.74	0.80	0.77
CVDF	4	0.78	0.74	0.76	0.75
ERDF	3	0.89	0.81	1.01	0.76
IDF	1	0.88	0.83	0.98	0.89

So why is the taxpayer paying 2.5 billion dollars per year to try and push these dose rates still lower?[3] The answer of course is ALARA. To keep this money flowing, the nuclear establishment

---

[3] Trying and failing. The 2012 numbers in Table 11.2 on average are 7% higher than 2011. Overall the numbers

must embrace ALARA. They must claim that dose rates that are a millisievert or two per year above background in a low background environment are so harmful that we should spend billions of dollars per year to ineffectively try and reduce them further.[4] Once you, the country's leading nuclear scientists and engineers, make that false claim, then you must consistently apply it everywhere. That includes wiping rain off wet shoes.[5] Far more importantly, once you tell that lie, any sizable release of radioactive material from a nuclear power plant becomes unthinkable. You must claim or at least imply it won't happen.

11.2 When does clean up become corruption?

It is hard to avoid the conclusion that the Hanford program has morphed from unnecessary cleanup to a deliberate, monumental ripoff of the taxpayer. In their 2019 "Life Cycle Report", the 8th official clean up plan since 1989, Hanford's management estimates that it will take $323 to $677 billion to complete the job.[232] To come up with these numbers, they assume that the waste must be separated into *high* level and *low* level. *High level waste* is defined to be the waste from the initial separation of the fission products from the uranium and transuranics. *Low level waste* is everything else.

Fission products tend to decay fairly rapidly. Due to decay over the last 60 years, there is now little difference in the dose rates. By the NRC's own numbers, the *high level waste* at Hanford now easily meets the radioactivity requirements for NRC Class C Low Level Waste, which is routinely dumped into NRC licensed landfills.[232][page 766] But the assumption is that the *high level waste* must be separated from the *low level waste*, so that the *high* level material can be shipped elsewhere. But there is no elsewhere; and Hanford, a government reservation 200 feet above the water table in a dry desert, is a pretty good place to keep the stuff.

Assuming we need to do anything at all, the unseparated waste could fairly easily be vitrified in phosphate glass. The phosphate glass would be in the form of pebbles which would be the aggregate in a concrete-like grout. Hanford has 177 very large stainless steel tanks. If all the waste were turned into concrete in this manner, poured into these tanks, and allowed to cure, the tanks would only be 30% full. Job done for a few score millions of dollars, even at government rates.

---

at Hanfold have tracked the half life of ^{137}Cs, the main remaining radioactive isotope. Most of the work just moves radioactive material from one place to another. Unless you put the material in a reactor and transmute it, you can change neither the amount nor the type of radiation you are dealing with.

[4] The actual EPA legal limit is 0.15 mSv/y, for the most exposed person drinking from the worst case well. When Hanford did the required EIS on the tank clean up, by law they had to include a Do Nothing option. The worst case dose rate for this well user for the walk-away option was 0.59 mSv/y in 4313.[190][Table S.10] 0.59 mSv/y exceeds 0.15 mSv/y. Ergo, spends billions of dollars. I suppose if the limit had been 0.6 mSv/y, we could have saved all that money.

[5] There is a paradox here. Just about all the national lab people I've met are unusually decent, intelligent, hard-working humans who are truly out to help mankind. But they do spend a lot of time thinking about funding. And as far as I can tell, they have completely bought into the Gold Standard.

When this plan was proposed to Hanford management in 2013, it was rejected. Since then nothing much has happened, other than the disappearance of another $15 billion of taxpayers' money while we wait for the government to spend $300 billion or more to do what? This is not incompetence; it is corruption, feeding on bogus fears that the nuclear establishment itself has created.

The clean up efforts at the Idaho National Lab (INL) show a similar pattern: a series of decisions that can only be explained if the goal is to spend as much taxpayer money as possible for as long as possible.[232] In May, 2021, DOE announced that a Jacobs led team had beaten out Fluor and four others in a contest to manage clean up at INL. The "indefinite delivery, indefinite quantity" contract will cost the taxpayers at least 6.4 billion over ten years.[184]

This does not mean that the establishment is filled with evil people. My experience is that this is clearly not the case. It's the system that is corrupt. Reinhold Niebuhr said "The problem of the age is not imposing morality on the individual, but imposing morality on the organization."[185] Niebuhr wasn't talking about the nuclear establishment. But he could have been.

11.3 Carlsbad Environmental Monitoring and Research Center.

What is the most extreme example of using LNT and ALARA to rip off the US taxpayer? Consider the Waste Isolation Pilot Plant (WIPP). WIPP is a deep geologic repository for defense department radioactive waste. Most of the waste is alpha emitting transuranics that can be *contact handled*, meaning moved around with no special shielding. WIPP is located in a salt formation 655 meters below the desert about 30 miles from Carlsbad, New Mexico. Life cycle cost: 11 billion dollars.

To reassure the public about WIPP's safety, DOE set up the Carlsbad Environmental Monitoring and Research Center (CEMRC). The goal of CEMRC is not to measure dose rates in milli-sieverts or even micro-sieverts. The goal is to push detection limits down to levels never before achieved, far below background. CEMRC has a Whole Body Counter capable of detecting whole body counts by isotope down to a few decays per second. Of course, to do this you have to exclude the background, which is at least 10,000 decays per second. So the Whole Body Counter is a cube 8 feet on a side, whose walls are made of 10 inch thick pre-WW II cast iron. Volunteers in the *Lie Down and Be Counted* program lie on a bed in the cube for 30 minutes to find out how radioactive they are.

Over 500 locals participated in the widely publicized program. Idea is to compare the pre-WIPP levels with post-WIPP to convince everybody that nothing bad is happening. And indeed so far there have been no significant changes in whole body or lung counts. But the numbers CEMRC is looking for are so small that the measurements had to be corrected for miniscule amounts of ^{60}Co in the cube walls and thorium in some of the detectors. Of course, the program also sensitized people to extremely low levels of radioactivity, levels 100's of times below background. If these levels are worrisome enough to be measured at great cost, what happens when we have a real release?

We found out in February, 2014. One of the stored barrels caught fire, burst the lid, and released some plutonium and americium.[6] The leak was quickly detected by the monitoring system which automatically switched the exhaust to filtration mode, pushing the exhaust through HEPA filters. As a result, the release into the environment was measured in micro-becquerels per cubic meter, million times less than EPA levels requiring action.

But this non-event generated nation wide publicity, shut WIPP down for three years, and resulted in 500 million dollars of expenditures, plus a 74 million dollar settlement to New Mexico. The settlement is a clear admission that the community has somehow been harmed. And the plant is now operating in full filtration mode hampering ventilation of the facility, despite the fact the unfiltered air would put out the same amount of ^{241}Am per year as is in a single household smoke detector.

11.4 The Used Fuel Ripoff

Another area where the nuclear power establishment has ripped off the taxpayer; and at the same time convinced him low dose rates are perilous is used fuel disposal.

West Valley was a fuel reprocessing facility about 30 miles south of Buffalo, NY. It was the keystone of what was to be an atomic center, much sought after by the local politicians. The initial cost was $32,000,000. It operated from 1966 to 1972. In 1972 it was shutdown for a 15 million dollar enlargement; but by that time the Gold Standard was taking over, and the cost ballooned to $600,000,000, mainly due to new earthquake protection requirements. Buffalo is not an earthquake prone area. The owner, Getty Oil, decided to close the plant.

During its operation the plant had collected 2,500 m3 of high level liquid waste. This was stored in two tanks. Each tank was a stainless steel tank within a tank within a concrete silo, surrounded by gravel, surrounded by a highly impervious clay. There were similar back up tanks. If the inner tank leaked, the liquid would be pumped to the back up tanks. The gravel was fitted with pipes so if the liquid somehow leaked through both tanks undetected, and then through the concrete, the liquid could be sucked from the gravel. Much of the radioactive material had precipitated out and was sludge at the bottom of the tanks. But the most troublesome isotope, ^{137}Cs, was in solution in the water. Every 30 years, half of the remaining Cesium-137 would decay away.

Despite the four barriers, by 1978 some locals has turned against the project. The DOE proposed pouring cement into the tanks, which would immobilize the material, turning it into blocks of concrete. DOE figured this would cost $20 million. But the locals wanted the material removed from the region.

DOE quickly caved and agreed to vitrify the material to a glass which could be transported

---

[6] The contents of this barrel contained both nitrate salts (strong oxidizers) and some metal, an unstable mixture that can react, produce heat, and generate gas. Usually this material is diluted with inorganic kitty litter to keep the reaction under control. But for some reason wheat based litter was used instead which just added fuel to the fire. Wonder what the PRA probability of this screw up was.

to deep geological disposal. This would cost \$1 billion dollars which DOE asked for and received from Congress. But one regulatory or political hurdle after another ensued. To date, over 4 billion taxpayer dollars has been spent; and, since no deep repository exists, the stuff is still at West Valley. Cohen estimates that the extra worker exposure due to the vitrification process was larger than a very conservative estimate of the possible exposure if DOE had gone the concrete route.[50][p 217] Both numbers are far below background rates.

I'm not going to spend any time on the 12 billion dollar Yucca Mountain debacle, nor the half billion dollars a year that the taxpayer is paying the nuclear power industry in order not to take the used fuel. It would be repetitive. The basic strategy is familiar. Claim that even extremely low dose rates are unacceptably dangerous and then get paid for proposing or studying or rarely providing a solution to a problem you have created. These people have no interest in seeing the used fuel problem disappear even if it means convincing the public that nuclear power is perilous.

A less selfish group are the breeder reactor proponents. Only about 0.7% of natural uranium is fissionable ^{235}U. Almost all the rest is ^{238}U. Uranium-238 won't fission; but, in a properly designed reactor, enough of the ^{238}U can be turned into Plutonium-239 which will fission, so that you end up with more fissionable material than you started with. Such reactors are called *breeders*. Breeders would cut our requirement for mined uranium by something like a factor of 50. And they can burn recycled fuel from an ordinary reactor. In short, another solution to the used fuel problem.

Here is a highly excerpted PBS interview with Dr. Charles Till, former director of the Integral Fast Reactor breeder project. Till is a superlative engineer, a fine writer, and one heck of a nice guy. But watch how he pivots from plutonium is no more toxic than lead, to solving the waste problem in this interview with PBS.

> Q: What is the key product created from uranium?
>
> A: The main useful isotope, and the one that has become controversial for reasons I'm not sure I totally understand, is plutonium.
>
> ....
>
> Q: What is plutonium? Is it a metal like uranium?
>
> A: Plutonium is, in fact, a metal very like uranium. If you hold it [in] your hand (and I've held tons of it my hand, a pound or two at a time), it's heavy, like lead. It's toxic, like lead or arsenic, but not much more so.[7]
>
> Q: How can plutonium harm you?
>
> A: You have to eat it in order to harm yourself with it. It is radioactive, naturally. Radioactive, but much less so than radium, for example, which is scattered all over the earth's crust. So it's not a very frightening material.

---

[7] Till is completely wrong here. Lead is far more toxic that plutonoium. Lead has a remarkably high uptake for a heavy metal. Roughly 50% of any ingested lead will end up in our organs. Less than 0.03% of ingested plutonium will be absorbed.

> Q: So you say you hold it in your hand. What about the radiation that is emitted by plutonium?
>
> A: The radiation from plutonium tends to be very easily stopped by any kind of shielding around the plutonium. A pair of gloves, paper.
>
> Q: Is the skin on your hand enough to shield yourself from plutonium's radiation?
>
> A: The skin on your hand is probably sufficient to stop most of it.
>
> Q: We've all heard that it's the most toxic substance in the world. Isn't it?
>
> A: Well, I think it's absurd. As I say, it's no more toxic than any other heavy metal, and its radioactivity is very considerably less than many other things that are on the earth's surface. It's an absurd statement.

At this point, Dr. Till has told us the same thing Galen Winsor told us in Chapter 2, plutonium is an easily handled material. The interview then moves into a discussion of plutonium as a reactor fuel and the ability of breeders to burn recycled fuel.

> Q: How significant was the decision by this country to not go the recycling route?
>
> A: Well, I think that the importance of that decision cannot be underestimated. ...
>
> When all of those factors were there, and when the decision was made not to recycle, so many implications followed. So all of a sudden we had a nuclear waste problem. Volumes of nuclear waste from our present reactors, but [no] good way to deal with it. By recycling, you deal with it very adequately. Without recycle, you don't.
>
> Q: Why does not recycling or reprocessing make the waste issue worse?
>
> A: If you look at nuclear waste from the point of view of the long-lasting nature of the nuclear waste, or any of the things that the general public would be encouraged to worry about, always it's the plutonium and other isotopes in the nuclear waste that is of concern. And in a sense, they should be, because they are the long-lasting isotopes that, if they get into the drinking water or into the air, could cause real concern.
>
> Q: And they last a long time?
>
> A: They are cancer-causing chemicals.
>
> Q: What is a half-life of plutonium?
>
> A: Well, Plutonium-239 has, for example, a roughly 25,000-year half-life. ... And that's a good long time. And the other isotopes that are similar to that, some have longer half-lives, some of them shorter. The point is that they are the most toxic elements in the waste. ... But if they are there in the waste, they represent a long-term hazard that people can legitimately be concerned about. You know, I think

> again it's a handle-able problem, but it's a problem that needn't be there, for if you recycle, you separate out exactly those elements and use them in your reactor.

My guess is that Till's private position is we don't have a real nuclear waste problem, we have a perceived nuclear waste problem, and recycling is the solution to the latter. But if that's the case, he certainly does not make himself clear. Towards the end of the interview, there is this exchange.

> Q: Why haven't experts been able to demonstrate to people that radiation is a natural phenomenon from which there's no escaping?
>
> A: Well, I'm not sure. I'm not sure that we are always able to convince people of our views, even though they may be correct. I think it requires a little bit of scientific background, probably, to be able to assess whether a statement that's made (you'll forgive me) on television is to frighten you for some political or other purpose, or whether it's there to provide you with information.
>
> Q: Do you think most people trust the DOE nuclear physicists, the utilities?
>
> A: No. Of course they don't. And that, I think, is somewhat understandable. But why the anti-nuclear folks, who say such extreme things that on the face of it one would question, even one who knew nothing about the subject, why they would have credibility, that does puzzle me.

Me too. But an open minded listener who trusts Charles Till more than Ralph Nader can be forgiven for coming away from this interview convinced we do have a perilous nuclear waste problem, despite the fact a few minutes earlier Till had told him plutonium is about as toxic as lead.

Others are not so charitable. Here's a quote from a highly respected nuclear engineer:

> As uranium prices remained persistently low, breeder reactors switched to become waste burning reactors and developers started fear-mongering campaigns to scare people that nuclear wastes are uniquely dangerous and that geologic disposal of nuclear waste is also dangerous. They linked arms with anti-nuclear activists, protesting the development of geologic disposal, in the same way that anti-nuclear activists and fossil fuel interests are working together now to prevent development of consolidated storage.

The sad fact is that nobody in the nuclear establishment has stood up and said “No, we don't have a difficult waste problem. The amounts are tiny, and the material is easily shielded." Instead they have proposed extremely expensive and difficult solutions to a problem that has a cheap and easy solution. And in the process these experts have told the public in unmistakable terms that near-background dose rates are very dangerous.

11.5 How crazy can ALARA get?

ALARA implies that any level of radiation is scarily dangerous. Once the nuclear estblishment promulgated and promoted ALARA, they had to expect the public to take them at their word. And they have. Here are a few examples.

11.5.1 Burying Beach Sand

Theo Richel did an instructive video on low dose radiation, https://youtu.be/JpcUCo0ebNA. In the course of filming that video, he visited the high background dose rate beaches in Guarapari, Brazil, Section 5.8. Theo brought two kilograms of beach sand back to his home in Holland, to demonstrate natural radioactivity in his presentations. When the Dutch government discovered he had Brazilian beach sand in his possession, they confiscated it. They intend to bury it at a depth of 500 m in a yet to be developed repository to protect future generations from beach sand.

11.5.2 Panic in New Jersey

The parents of a South Jersey high schooler gave him a dosimeter for Christmas 2020. To demonstrate it, they took him to an antique store and bought a 1950's Fiestaware plate. At the time, Fiestaware was a popular, upscale dishware brand, prized for its deep, glowing colors. To create these colors, the glaze contained uranium oxide. The dosimeter duly registered the change in dose rate as the young man moved the meter towards and away from the plate, demonstrating the square law.[8] A good learning experience. Well done, parents and son.

Entranced, the kid took the dosimeter and the plate to school to show to his science teacher. When it was discovered that radioactive material was on the premises, the alarm was sounded, the school evacuated, and a phalanx of local police, firemen and the county Hazmat team rushed in to thwart the menace. The school was searched room by room, and the dangerous plate was found. I don't know how it was disposed of.

If you stood 1 foot away from the plate for a full year, you would receive a photon dose of about 0.06 mSv.[228][Table 3.11.2] Your SNT LLE would be 0.03 seconds. Science teachers should know a little bit about science. Apparently this one did not.

I can't blame this one directly on the nuclear power establishment, but it is a consequence of adopting ALARA.

---

[8] If he doubles the distance from the plate, the dose rate will drop by about a factor of 4.

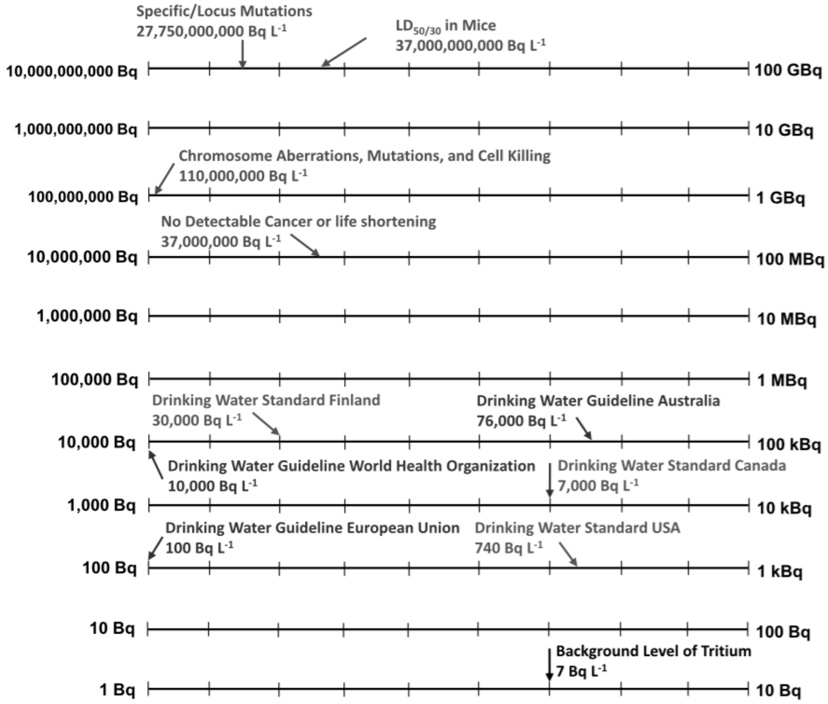


Figure 11.1: Tritium Exposure Chart

11.5.3 The Fukushima Tritium

Perhaps the most extreme example of the unnecessary problems the nuclear establishment has created for itself — and humanity and the planet — is hydrogen-3 or *tritium*. It is hard to imagine a less dangerous radioactive isotope than tritium. Tritium has half-life of 12.3 years and emits an extremely weak electron, so weak it is stopped by a half-inch of air. Tritium radiation is so weak it cannot be measured by a normal Geiger counter. The electron is too weak to make it through the wall of the thinnest gas tight detector tube.[158][p 110] A tritium electron cannot penetrate the dead outer layer of your skin. Each electron in a cathode-ray tube television has more energy. Tritium is used in luminous watches, rifle sights, and road and runway signs.

Tritium, ^{3}H, is just hydrogen with two extra neutrons. Like ordinary hydrogen, it combines with oxygen to form water. In humans, water has a biological half life of 10 days. The only way tritium can possibly hurt you is if you drink such enormous quantities of tritium containing water that the water itself will be the health problem. Tritium is everywhere. Cosmic rays produce 150,000,000,000,000,000 Bq per year in the upper atmosphere, much of which rains out into the surface waters we end up drinking.[255]

Tritated water is extremely difficult to separate from ordinary water. After Fukushima, the Japanese amassed about a million tons of contaminated water in the process of cooling the damaged reactors. At great expense, they have removed almost all the radioactive isotopes from this water. But about 6 grams of tritium remain. The tritium content of this water is about 13 times above the Australian drinking water limit (76,000 Bq/liter) and about 1350 times the US legal limit (740 Bq/L).

The World Health Organization limit is 10,000 Bq/L. The WHO level is based on limiting the cumulative dose to someone who drank 2 liters of this water per day for 365 days to 0.1 mSv. The EPA limit is supposedly based on an allowable annual dose of 0.04 under the same rules. If EPA has done the calculations the same way WHO did, the EPA limit is really 0.008 mSv/y. In 1991, EPA did a study which concluded that by its own rules the tritium concentration limit in drinking water should be 2500 Bq/L.[188] However, the limit was not changed. Regulatory changes can only go one way. If 740 Bq/L was the safe limit, then 2500 Bq/L must be unsafe. Or if you don't buy that argument, the old level was obviously achievable, so it would be a clear violation of ALARA to raise it.

Since no harm has ever been observed from people drinking tritated water, nobody knows what the real health limit is. To get any response from mice, they had to be fed 37,000,000 Bq/L water, Figure 11.1.[71] The limits are really ALARA based. They are there because they are reasonably achievable for a Light Water Reactor.

The obvious solution is to dump the 6 grams of tritium in the Pacific Ocean. Once this water was diluted by a factor of 15, it would be legal to drink in Australia. A factor of 1000 would make it legal just about everywhere. There are 660,000,000,000,000,000 m3 of seawater in the Pacific Ocean.[76] Average seawater has a natural activity of about 12 Bq per liter, mostly from Potassium-40 which emits a penetrating photon, which is 250 times more powerful than the anemic tritium electron.[155][Table 1] However, spots with high salinity such as the Persian Gulf can be as high as 22 Bq/L. Dumping the 6 grams of tritium would increase the radioactivity of the Pacific Ocean by little more than two-ten-millionths.[9]

Of course, the activity would be more localized initially. Irrational public response could cause a problem for the local fishermen. But three large tankers could dump the million tons of water over an area of 1000 square miles in a week. The initial dilution would be better than a factor of 10,000; and, by taking more time, we can make it whatever we like.

Saltwater fish normally have a natural radioactivity of about 250 Bq/kg, mostly from Potassium-40.[155][Table 1] The biological half-life of tritium in fish and wildlife is about 2 days. Tritium does not concentrate up the food chain. Forget about harmful. No one would receive a measurable dose of tritium from this disposal. The solution is obvious. But the nuclear establishment's embrace of LNT and promulgation of ALARA has paralyzed us.

---

[9] The activity of a gram of tritium is 3.57e14 Bq. The ratio of the activity of 6 grams of tritium to that of the Pacific Ocean is 6 * 3.56e14 / (660e18 * 12) = 2.4e-7.

Other Tritium Silliness

An innocuous tritium leak in 1997 at the Brookhaven National Lab combined with a panicked reaction by the DOE ended up shutting down a valuable medical and research reactor.[58] A similar leak at the Vermont Yankee plant was critical in its premature decommissioning, but mainly because it revealed the plant owner to be untrustworthy.[273]

All nuclear reactors generate liquid tritium. The 670 MW Monticello reactor on the Mississippi produces about 2.5 GBq/y or about 7 micrograms of ^{3}H annually.[113] Per license, the plant is allowed to release that ^{3}H at a rate of up to 37,000 Bq/L into the river, although normally the effluent concentration was less than 1600 Bq/L.

However, under local pressure, the plant “voluntarily” went to a closed cycle system in which the ^{3}H continually built up. In November, 2022, that system leaked. At the time, the tritium concentration in the system was reported to be 74,000 to 185,000 Bq/L. Still innocuous. An attempt to patch the leak was unsuccessful, and the plant was forced to shut down amid all sorts of unfavorable publicity. The volume of the leak was estimated at 1.5 million liters. The leak contained at most 0.8 milligrams of tritium.

In an attempt to appease totally irrational fears, the plant turned a harmless release into a media circus and an expensive shutdown.

11.5.4 Tritium and Nuclear Power

It is easy to make fun of the Japanese handling of the Fukushima tritium; but our fear of tritium is an important, pervasive problem for nuclear electricity. Tritium is about as difficult to contain as it is innocuous. Tritium is hydrogen. At elevated temperatures, hydrogen can worm its way through just about anything, even thick pipes. In practice, the nuclear power plant tritium limits are set by what is “reasonably achievable" by a Light Water Reactor (LWR) operating normally. In other words, not by health considerations, but by what a Light Water Reactor can afford.

Non-LWR technologies operating at higher temperatures and with other materials produce 60 or more times as much tritium as a LWR of the same capacity. These same technologies promise totally passive safety and significant improvements in cost. But for them, achieving the LWR ALARA based levels can be as expensive as it is unnecessary. One of the new technologies is molten salt. Some molten salt designs include an additional loop in order to capture tritium. This adds cost, complexity, inefficiency, and a whole new set of failure modes. And since tritium is so hard to contain, releases are inevitable.

Nuclear electricity has two choices:

1. Continue to accept unreasonable regulation and die.
2. Somehow convince the body politic to regulate nuclear power intelligently.

Tritium regulation is as unreasonable as it gets. So it's a good starting place, a good test. My advice to the developers of the non-LWR technologies is make your case to the regulators for reasonable limits on tritium, being prepared to walk. When he balks, take your case to the regulators' bosses, who presumably represent society as a whole, letting them know that if the regulator continues to be unreasonable, you will have to take your technology elsewhere. If you can't win this one, you are going nowhere.

11.6 The nuclear establishment is nuclear power's worst enemy

Anti-nuclear groups like to take full credit for making nuclear power uneconomic. But we have seen (Section 9.8), they were very late to the party. In all fairness, they should at least acknowledge the help they have had from the nuclear power establishment itself. Consider:

1. It was the nuclear power establishment that embraced LNT which overstates the hazard associated with low dose rates by orders of magnitude when they knew or should have known that the hypothesis was egregiously incorrect.
2. It was the nuclear power establishment that attempted to suppress its own ten million dollar study of shipyard workers which contradicted LNT, Section 5.6.9.
3. It was the nuclear power establishment that squashed the Low Dose Radiation Research Program (LDRRP) which was producing results which invalidated LNT.
4. Table 11.3 shows how consistently and stubbornly the establishment has defended LNT. In five of these examples, highlighted in yellow, the AEC/DOE ignored and sometimes attempted to suppress results from programs it had funded.

Table 11.3: The Nuclear Establishment's Defense of LNT

Low Dose Bomb Survivors	Ignored	fruit fly data	Ignored
Dial Painters	Outlawed	Shipyard workers	Suppressed
Berkeley, LDRRP	Squashed	Taipei Apartments	Ignored
Beagle, Mice studies	Ignored	Yangiang Results	Ignored
Nuclear worker studies	Outlawed	Kerala Results	Ignored

5. It was the nuclear power establishment that invented ALARA, a philosophy that explicitly mandates that any nuclear technology shall be at least as costly as other sources of electricity no matter how inherently cheap or safe the technology is.
6. It was the nuclear power establishment that embraced LNT and invented ALARA at a time when there was nearly universal public support for nuclear power. The combination of LNT and ALARA resulted in people being scared to death of near background dose rates — literally in the case of Fukushima.
7. It is the nuclear power establishment that routinely fails to contest claims of harm from near-background or lower exposures in a release. Instead they compensate the alleged

victims generously, a clear admission that such dose rates are dangerous.

8. It was the nuclear power establishment that solicited tens of billions of taxpayer dollars to move undangerously radiated material from one place to another, confirming the anti-nuke claim that near background dose rates are hazardous.
9. It was the nuclear power establishment that bought expensive newspaper ads claiming dry cask storage was unacceptably dangerous, creating the nuclear waste problem in the public mind.
10. It was the nuclear power that killed subseabed disposal and directed the money to Yucca Mountain when the entire scientific community, including the Union of Concerned Scientists, was telling the DOE that subseabed disposal was far better and far cheaper.
11. It was the nuclear power establishment that solicited tens of billions of taxpayer dollars to provide used fuel storage in as expensive a manner as possible, telling the public that any radioactivity is very dangerous and convincing the public that nuclear power has a prohibitively expensive used fuel problem.
12. It was the nuclear power establishment that accepted the idea that any sizable release of radioactive material was unthinkably catastrophic and then demanded the public accept a portion of those consequences.
13. It was the nuclear power establishment that fraudulently and stupidly implied that the probability of such a release was so low we can assume it will never happen.
14. It was the nuclear power establishment that adopted a military quality assurance regime that shelters a few chosen vendors from competition resulting in ruinously expensive products that don't work. And then stifles any attempt at improvement.
15. It was the nuclear power establishment which was so proud of this regulatory regime that they named it the *Gold Standard*, in effect bragging about how expensive it is.

Somehow the people who should be nuclear power's strongest supporters have become its destroyers.

11.7 Feeding at the public trough

Why would an industry be so hell bent on its own destruction? A lot has to do with a set of organizations, a complex, that depends on feeding at the public trough.

Until 1954, nuclear power was a government monopoly. All the early greats of nuclear power, were government employees or military personnel, most importantly Rickover himself. Almost none of these people had any background in private business. They emerged in a war time environment where cost was at most a secondary consideration. And the vendors they hired were companies that had thrived in this environment.

The rules for defense vendors are quite different from competitive market rules. The golden rule for defense vendors is extract as much gold as you can from the taxpayer. These vendors operate in a cost-plus world in which more cost is better. They are quite uncomfortable in a competitive market.[10] The mind set, the tactics, the skills are entirely different. Regulation is welcomed because it is such an effective barrier to entry. If hyped up fears of radiation result in more regulation, it means we get to hire more people.

Problems are a good thing. No problems, no funding. After World War II, the immense enterprise spawned by the Manhattan Project had become too big to shut down. With billion dollar per year budgets, the major laboratories were often the single largest employer in their congressional district. Whole towns had built up supporting and depending on the local lab. They had to find reasons to be funded. If creating or grossly exaggerating a problem got you funded, that's what you did. For the labs, the nuclear waste problem was a godsend.

And it is essential that the problem NOT be solved. Once a problem is solved the funding stops. So first we study the problem very carefully. This study reveals that the problem is more worrisome and more complex than we originally thought, and requires a more detailed study, which goes into next year's funding request. Lather and repeat.

This is exacerbated by a political process in which every congressman strives to maximize the taxpayer money directed to his district. Once again the higher the cost the better. There is no more effective and open ended way of increasing costs than ALARA.

The problem is, while there is no real limit on how far weapons costs can be driven up, nuclear power has to compete with the alternatives. This competition can to a certain extent be avoided in a regulated monopoly environment, asking the rate payers to play the same role as the taxpayers. Regulated utilities have much the same rules as defense spending. Get as much cost into the rate base as you can and thereby increase shareholder profits.

But the limit to rate payer patience is a lot lower than taxpayer. The defense vendor mentality quickly pushes costs up to and past that limit. When the rate payers balk, the response is not to try and compete. The response is to call for subsidies. Which is where we find ourselves now.

11.8 A Recent Example: The USEC/Centrus Fiasco

Under the Gold Standard, nuclear power technology has stagnated for 50 years. The light water reactor plants being build in Georgia today look and are very similar to the plants that were built in the 1970's. The light water reactor is a klunky, brute force technology. There are a number of concepts that have been proposed that promise to provide nuclear electricity more cheaply and efficiently. Many of these designs work best on nuclear fuel that has been enriched in ^{235}U to just below the legal limit of 20%. This fuel is known as *LEU19.* For starters, at least

---

[10] This mentality reflexibly equates expense with quality. Cheap is bad. Yankee Rowe was a 185 MW plant in western Massachusetts. In 1958, the utility budgeted a cost of $57 million. When Rickover heard this number, he was aghast. He called up the utility and told them that cost "is impossible to achieve" and they would ruin their reputation. The plant was completed in less than two years at a cost of $45 million. It ran for 32 years, generated 34 billion kWh, and had a life time capacity factor of 74%.

20 tons per year of LEU19 is required. But no USA enrichment facility is licensed to produce more than 5% ^{235}U, the preferred fuel of the light water reactor.

In 2019, DOE awarded a $115 million dollar contract to Centrus Energy to produce “up to 600 kg" of 19.75% enriched fuel. Centrus is supposed to produce this fuel with a 16 machine cascade using AC-100M centrifuges. These experimental centrifuges, whose development was funded by the US taxpayer, have never worked to spec and have never produced a commercial ounce of enriched fuel of any percentage.

The President of Centrus is Daniel Poneman, who took that job in 2015. Prior to that, Poneman had been the Deputy Secretary of Energy at DOE. Under his tenure in 2012, DOE transferred 300 million dollars of uranium from the US stockpile to Centrus, then known as USEC, to be enriched in a failed attempt to prop up the enterprise. The Government Accountability Office found that DOE had no authority to do this and these transfers violated federal law. In 2013 USEC declared bankruptcy.

USEC was the old DOE gas diffusion enrichment facilities at Paducah, Kentucky and Piketon, Ohio which had been privatized in 1998. Gas diffusion enrichment is an energy hog and in the 1990’s and early 2000’s was replaced by centrifuging which requires 50 times less energy. USEC was not able to make that transition, despite or perhaps because it was continually being propped up by the DOE with taxpayer money, much of it doled out by Poneman. When USEC came out of bankruptcy in 2014, the clouded name was changed to Centrus.

The DOE could have awarded the LEU19 contract to an outfit called Urenco. Or better allowed Urenco to bid on the job. Urenco has a large, successful commercial enrichment facility in Eunice, New Mexico.[11] Urenco was prepared to quote a fixed price for whatever amount of LEU19 DOE wanted to buy with delivery starting in 2021. The reason given by DOE for selecting Centrus is that it was the only US owned entity that is capable of producing LEU19. Leaving aside the fact that Centrus’s capability has not been demonstrated — quite the contrary — Urenco is majority owned by the UK, Dutch and French governments, America’s close allies. Moreover, the Urenco plant is in New Mexico licensed by and under the total control of the US government. It is staffed almost entirely by Americans.

Centrus will produce little or no LEU19. It is not in the business of producing enriched fuel and has not been for a long time. It is in the business of funneling taxpayer money to a particular congressional district, some lobbyists, and some politically connected executives. Poneman went from making $178,000 per year at DOE to 1.5 million at Centrus. Much worse, Urenco is now prohibited from producing LEU19. DOE policy ensures that there will be no affordable LEU19 produced in the US in the foreseeable future. This is the kind of nuclear “subsidy" that has killed nuclear in the USA and is now stomping on its grave. This is how the nuclear power establishment self destructs.

---

[11] To produce LEU19 from an existing cascade of centrifuges only requires that the cascade be operated in a different configuration. The Russians design their cascades with the proper piping and valving, so that they can produce a range of enrichments with the same cascade.

11.9 The Need for Competition

I spent the first 10 years of my career working for the US Navy in one form or another. I saw the focus on process rather than substance. I saw the waste. I saw inexplicable decisions. I saw strange promotions. I saw the enormous price overruns. I saw schedules busted by months and then by years. I saw ships that did not work.

In my thirties, I left a government funded job in academia for the tanker market. Eventually, I ended up in Korea building very large tankers. I was blown away. Technically, the Korean shipyards did not look all that different from the US naval shipyards. But I was on a different planet. The productivity was orders of magnitude higher. I sort of expected that but still I was astounded by the numbers. What I did not expect was the quality was night and day superior to what I had seen in the naval yards. The attitude was completely different. Everyone was focused on building a ship as cheaply as possible while meeting the owner's specification and passing the trials. And get it done on schedule. Delivering a ship a week late was unacceptable; two weeks late unthinkable. Testing was done at every stage in the production process. Failure to meet the spec meant delays and rework that would cascade down a very tight production schedule. It was cheaper to make sure the quality was right the first time.

Compared to the naval yards, things ran like clockwork. And when there was a hiccup, the issue was resolved quickly with little or no finger pointing or paperwork. Often it took no more than a conversation between an owner's inspector and a yard foreman. Fixing the problem quickly was a lot cheaper than slowing down the production line.

Management was completely different. In the Navy yards, the higher up you went the less impressive the people. In the Korean yards, the quality of people in middle and upper management was something I had never seen before.

The Korean yards compete with each other tooth and nail. One result is that the real cost of a 300,000 ton tanker decreased by a factor of three between the mid-1970's and early 2000's, despite increasing regulation.[12] There was no spectacular technical breakthrough. Just incremental improvement on top of incremental improvement. Yards unable to make these improvements did not survive.[13]

The shipyards never made much money on these improvements. Over time, they passed the savings on to the ship owners in the form of lower real prices. The owners overall never made much money on these improvements. They were passed on to the oil companies in the form of lower shipping rates. The oil companies in turn passed most of these savings onto the consumer. That's how it's supposed to work.

When late in life, I became interested in nuclear electricity, to my dismay I found myself back in the Navy system. All the same problems. All the same horrible results. The same belief in

---

[12] And increasing real wages. Currently, the fully built up, average hourly wage of a Korean shipyard worker is over $30. When Samsung investigated resurrecting the defunct Avondale shipyard near New Orleans, they were surprised to find that the prevailing wages rates on the Gulf Coast were less than what they were paying at home.

[13] For another example of the power of competition, check out solar panel prices over the last 30 years.

and adherence to the system that produced those results. The nuclear power establishment will not, can not change itself. It invented and believes in ALARA. It exults in the Gold Standard. The only thing that can change this industry is to impose competition on it. We must find a way to do that.

11.10 The NRC Strongest Man Contest

Imagine a contest in which the goal is to to carry a heavy weight from a starting line to a finish line. If you are successful, you get a nice reward. So naturally you need to pay a substantial entry fee to get into the game.

You are a big, strong guy so you ante up. But after you have taken a couple of steps, you notice that one of the referees is moving the finish line farther away. Another referee comes along and piles more weight on your load. The head referee shows up and says you are taking too much time. You need to pay some more money to stay in the contest. Since you can't get your entry fee back, you reluctantly agree.

You take another couple of steps. And the whole process is repeated. Now you are getting fed up. You complain bitterly. But the head referee points out that everything they are doing is within the rules, because the rules say the referees not only make the rules, but can change the rules whenever they want to. He pulls out his rule book, the Atomic Energy Act, and points to Section 187 which says

> SEC. 187. MODIFICATION OF LICENSE. The terms and conditions of all licenses shall be subject to amendment, revision, or modification, by reason of amendments of this Act or by reason of rules and regulations issued in accordance with the terms of this Act.

You say yeah I knew that, but you said you would be reasonable. The head referee responds we are being reasonable. Is it not reasonable for us to get paid for standing out here in the hot sun watching you stagger around? Pony up or quit. You're in too deep. You pony up.

Now some other potential contestants are standing around considering whether to enter the contest. The referees don't want to scare them away. So their tone changes a bit. They start being encouraging. Keep it up, you're getting there, we won't move the finish line much anymore, we promise. Just need a little more money. You finally collapse across the finish line. Unfortunately, you find collecting your reward requires going through much the same process again. But that problem is out of sight of the other contestants.

The referees have already forgotten about you. They have gone over to the other potential contestants telling them, we've learned our lesson; this time it will be different; just give us a try. Finally, another big guy steps forward. Guess what happens next.

This little parable is seriously incomplete. It begs the question: why would a smart, rich investor enter such a contest? It's because the reward depends on the cost. The calculus is: if I am one of the very few that can get through this ridiculous process, then I don't have to worry about any competition.[14] Now I can soak the public as much as I want and get my money back and then some. It is not the contestant that pays. It is the rate paying public.

But sometimes the rate payer gets no electricity for her money. On February 24 2002, the NRC Commission rescinded the license extensions for the Turkey Point and Peach Bottom plants. The extensions had been granted by the Commission in 2020, after an 18 month review process costing millions of dollars. For nearly two years, the utilities had been operating under the assumption that they could count on the extensions. The 2 to 1 decision overturning their earlier ruling violated the clear wording of the NRC's own regulations. The two commissioners decided that the word *initial* in the regs should not have been there, and therefore can be ignored.

---

[14] For this to work, the successful applicant needs to do everything he can to ensure that everybody who comes after him faces at least as onerous a process. He become a strong supporter of the system. The system is self-perpetuating.

Chapter 12

Four Essential Requirements for Regulating Nuclear Power

> So the question is, given the NRC's history, the incredibly costly and time consuming process of applying for and receiving licenses, and the new policy that the NRC can just change its mind after a stakeholder spends years and millions of dollars on an application, why would anyone invest in anything nuclear power related? [Josh Payne]

It's time to stop bashing the nuclear establishment, and outline out what we must do if nuclear power is to be allowed to solve the Gordian knot. I will take this in two steps:

1. In this chapter, I will lay out four fundamental principles that will be required of any successful replacement system for regulating nuclear electricity. These are sine qua nons. Unless the regulatory system abides by these essentials, nuclear power is doomed. In my view they are not disputable.
2. In the next chapter, I will propose a specific regulatory regime which abides by these four essentials, a regime which attempts to align the incentives of all the players with societal well-being. It is not the only possible system that complies with the four principles; but in my opinion it is the one that has the best chance of being successful.

The four essential requirements are:

1. Renounce the two lies that are killing nuclear power.
2. ALARA must go.
3. Mandate full scale, rigorous physical testing.
4. Competition must be enforced on all the actors.

12.1 Renounce the Two Lies that are Killing Nuclear Power

I've collected an informal database of commercial airplane casualties. It purports to include all 1960 and later non-terrorist crashes involving 50 or more fatalities. It includes an incomplete scattering of casualties involving as few as 10 fatalities. Military related and private aviation casualties are excluded. Hijackings, bombs, and shoot downs are also excluded. The database contains 488 casualties with a total of 45,812 deaths. Including the terrorist related deaths would pump this figure up by about 5000. We are averaging about 8 major crashes per year. Each crash receives a great deal of publicity. In the country where it occurred, it dominates TV and the news for at least a day or two. In just about every case, the crash reveals flaws in design — occasionally serious — or poor judgement, or lousy management. Crashes just don't happen. People are imperfect. ***Yet flying commercial is regarded as "safe".***

Over the same 60 year period, we have had three highly publicized nuclear power casualties. In one of these, nobody was hurt, let alone killed. In another, two people were killed; and, if there will be any eventual harm due to radiation, it will not be reliably observable. In the third, the Lost Life Expectancy due to radiation was roughly equivalent to around 210 sure deaths.[1] ***Yet nuclear power is regarded as "dangerous".***

In both cases, the individual risk is extremely small. Your chance of being involved in a fatal commercial airplane crash is about 0.2 per million per flight.[205] If the planet went entirely nuclear for all its electricity, your chance of having your life shortened by nuclear power would be about 1 in five million per year.[2]

So what's the difference? I believe it's honesty. Commercial airlines are out front about the risk. They put a plastic placard in front of every seat with instructions on what to do in a crash. They make us sit through a safety demonstration before every take off. They say "We are so certain there will be more deadly casualties that it's worth installing two expensive orange boxes on every commercial aircraft. These boxes are designed to survive a crash that kills everybody on board. The only purpose of these boxes is to help us figure out what caused the horrific casualty so we can make intelligent fixes." The public applauds this attitude, and accepts the industry's risk numbers.

The losses associated with an occasional aircraft crash are tolerated in return for the benefits of air travel. The benefits of cheap, reliable, pollution free, CO2-free electricity are incomparably greater than the benefits of air travel, the losses are less, but nuclear power is too dangerous.

---

[1] This estimate is based on SNT, Section 6.6. But even if we accept the inflated UCS LNT based estimate, the number of people who may have their lives shortened by a radiation induced cancer is 26,000, roughly half the number of people who have been killed outright by commercial aircraft crashes.

[2] This is based on the Markandya and Wilkinson estimate of 0.07 statistical deaths per TWh, the 2019 consumption of 22,300 TWh, and a world population of 7 billion.[159] Sovacool et al put the nuclear power fatality rate at 0.01 statistical deaths per TWh.[239] Of course, the shift to nuclear power would materially increase your life expectancy relative to any other dispatchable source of electricity.

Here's the problem. The nuclear power establishment has told us two lies, two tragic whoppers:

- ***The Intolerable Harm Lie***: Any sizable release of radioactive material would be a catastrophe.
- ***The Negligible Probability Lie***: But don't worry. The probability of such a release is so low that we can just assume it won't happen.[3] In nuke jargon, it is not a *credible* event. In fact, sizable releases are guaranteed to happen.

The Negligible Probability Lie is preposterously stupid for three reasons.

Obviously false It was proven false at Three Mile Island, again at Chernobyl, and again at Fukushima. We've had at least five reactor-releases in about 20,000 reactor years. Per Section 1.2, a healthy, decarbonized, all nuclear planet will requires at least 20,000 gigawatts per year. Twenty thousand large power plants.

Based on the performance to date, on such a planet we will have five releases of radioactive material each year. Even if we can reduce the release rate by a factor or 10 or 20, which we have no right to assume until we prove it, we would still have a release every few years.

Prohibitively expensive Preventing any and all releases is impossible. There is no limit to the amount of money you can spend attempting the impossible. More precisely, the limit is when you price nuclear power out of the market. We reached that limit pretty quickly.

Tragically Unnecessary The Negligible Probability Lie is a product of the Intolerable Harm Lie. This lie was first promulgated by the Rockefeller Foundation and its allies as part of their campaign against nuclear weapons, Section 5.3. Tragically, it has been embraced by the nuclear power establishment, in part because it justifies their expenditure of scores of billions of dollars of taxpayer dollars per year on problems that either don't exist or have simple, cheap solutions. But we have seen that even a very large release, sensibly handled, has a Lost Life Expectancy similar to a bad airplane crash. The Intolerable Harm Lie is as false as the Negligible Probability Lie. ***An occasional release is not only tolerable; it is societally optimal.***

Don't get me wrong. I'm not in favor of nuclear power plant releases anymore than I'm in favor of aircraft crashes. But the planet will be a far better place with abundant, cheap, reliable, pollution-free, CO2-free electricity and an occasional release than without both. But such a planet will not happen, unless the nuclear establishment renounces both these lies.

---

[3] The Japanese even have a word for this lie. They call it *anzen shinwa*, the safety myth. In telling this lie, the complex has tied itself into linguistic knots. We can't say such a release is impossible. So it's "not credible" or "exceedingly small"[WASH740,1957] or "virtually inconceivable"[272][p241] or "so small as to be almost negligible".[Hans Blix, 1986] or "vanishingly slim".[Nuclear News Wire, 2022-08-25] In fact, the probability of the next release is 1.000. It is only a matter of when. Whatever the wording, when a release occurs, public trust is lost for decades.

The Two Lies and the War in Ukraine

The war in Ukraine has created a dilemma for the nuclear establishment and the Two Lies. Recent attempts to resurrect the Negligible Probability Lie have focused on claimed improvements in safety due to technical progress: natural circulation, passive cooling, etc.

The argument was never very compelling. We may be able to reduce their frequency, but releases are going to happen. But the war in Ukraine makes it crystal clear that no technical improvement can withstand man's destructive capabilities. Does anybody believe that the probability of a release from one of the Ukrainian plants caught in the middle of the war — for practical purposes, all of them — is so low we don't have to worry about it?

The Russians are using the 6 unit Zapo plant as a human shield. The Ukrainians are hitting targets within the plant anyway. The Ukrainians, abetted by the IAEA, are cleverly and aggressively using the Intolerable Harm Lie to put pressure on their allies for more help. But the Russian counter move is to threaten or even create a release to end the war on their terms. This is not beyond Putin. A strike on a plant, intentional or inadvertent, will occur if the war lasts long enough.

The plume will depend on the weapon. There are bunker busters that can easily penetrate the containment. A standard cruise missile can probably breach the containment. A hole in containment combined with loss of cooling or rupture of the primary loop will produce a Fukushima-like release. A bunker buster will make a big hole and then create a secondary explosion after penetration. This would produce a Chernobyl-like plume.[a]

Provided you accept a roughly realistic radiation harm model such as Sigmoid No Threshold, the resulting casualties become just another part of the horrors of war. According to SNT, Section 6.7, the radiation from a Fukushima style release will detectably harm nobody more than a kilometer or two outside the plant boundaries. A Chernobyl-like plume could result in eventual radiation induced Lost Life Expectancy equivalent to several hundred immediate fatalities, Section 6.6. This is equivalent to a few days of the fighting in the war.

But if you are promulgating the Intolerable Harm Lie as the IAEA and others are doing, either plume becomes terrifying. The combatants are handed a Damocletian Sword which they can dangle over the head of Europe. And the revival of public support for nuclear hangs by the same thread.

---

[a] In the Ukrainian case, employing a bunker buster against a plant seems very unlikely:

1. A bunker buster would expose malice aforethought on the part of the Russians.
2. It is unnecessary. It's the fear of radiation that is the weapon, not the actual number of casualties.

But a bunker buster-like plume from a combination of more conventional weapons is not inconceivable. The claim that there will never be another Chernobyl is not necessarily true.

12.2 Replace ALARA with Firm, Balanced Radiation Limits

12.2.1 ALARA must go.

We must replace ALARA with firm dose rate limits.

- No engineer can design to ALARA.
- No rational investor can allow himself to be exposed to ALARA.
- ALARA guarantees that the cost of any technology, no matter how inherently cheap or safe will be pushed up to the point where it is barely competitive.[4]

If after a contract is signed, a political body decides to change the limits, the cost of that change must be borne by that political body or existing plants must be grandfathered.

In practice, As Low As Reasonably Achievable is interpreted by the regulators to mandate any regulation that allows nuclear to remain competitive with alternate sources of power. This is a perfectly reasonable interpretation of reasonably achievable. Any requirement that still leaves a design or a plant competitive with other sources of power is manifestly reasonably achievable. Almost no nuclear regulators are anti nuclear power.[5] The reason they got into nuclear power is that they believe in nuclear power. But under ALARA, unless nuclear power is at least as expensive as the alternatives, they are not doing their job.

But driving the cost of all nuclear power up to say the cost of coal has four effects:

1. Technology stagnates. There is no point in developing cheaper, safer designs if all that means is still more expensive regulation. If investors cannot benefit from taking a risk on a new technology, they will not invest. Even incremental improvements are pointless. The winners are the incumbents. They don't have to worry about some cheaper provider of nuclear power coming in and undercutting them. They become both comfortable and sloppy. Then they embrace the system because it protects them.
2. Under ALARA, nuclear power can never be cheaper than coal. If the providers of nuclear power were forced to operate in a truly competitive market, competing with each other, the inherent cheapness of fission power combined with technological advances would push the real cost of nuclear power lower and lower. The real losers here are the poor and the planet.

   But it's the longer term implications of ALARA that are the most tragic. Imagine a world

---

[4] Automatic creep is inherent in ALARA. All nuclear regulatory bodies monitor the exposure of each plant's workers. Under ALARA, if a plant is in the bottom half, it gets a bad rating; and takes measures to decrease the exposure further, regardless of how low the exposure is. But half the plants are always in the bottom half. This process continues at least until the plants cannot afford any further reduction.

[5] Political appointees such as the NRC commissioners can be an exception. Gregory Jaczko was appointed by President Obama precisely because he was anti-nuclear. In February 2022, the NRC by a 2 to 1 vote rescinded previously approved license extensions for the Turkey Point and Peach Bottom plants. The extensions had been approved after an 18 month long process costing the applicants tens of millions of dollars. To justify the reversal, the two commissioners claimed the word "initial" in the NRC regulations did not mean "initial". There is no appeal from such arbitrary, inconsistent behavior.

in which nuclear power costs less than three cents real a kilowatt-hour as it did not long ago. Not only would the poor be immensely richer, but the planet would be far better off. Electrification of transportation and industry would explode. Desal would take off. Synthetic fuels become viable. Skies would be clean. All this electricity would require little land and produce almost no CO2.

3. But under ALARA we will never even get started. One problem with driving the cost of nuclear power up to the cost of other sources is the cost of other sources changes. In the 1970's, the cost of fossil fuel skyrocketed. Under ALARA, the cost of nuclear rose in lock step with the cost of coal. Then from 1980 on the real cost of coal power started declining and is now as low as it has ever been. But the regulatory ratchet only works one way. Nuclear was left high and dry. New plant construction abruptly halted.
   ALARA was not through. Nuclear power is an inherently low marginal cost source. For ALARA that's just means here's an opportunity, nay, a requirement, for more regulation. ALARA now went after nuclear power's operating costs, driving them up toward the operating costs of coal.[6]
   Then fracking came along and the real cost of gas dropped by a factor of three. We now have the nonsensical situation where a fully depreciated nuclear plant which should have a marginal cost of well below a penny a kWh cannot compete with natural gas, a high marginal cost source of electricity. That's the power of ALARA.
4. ALARA starts a vicious circle. The more money that is spent on radiation protection, the more concerned the public becomes about radiation. The more concerned the public becomes, the greater the pressure to spend still more money.

ALARA is often defended by emphasizing the adverb “reasonably". The assumption is that the regulator will be *reasonable.* But what is perfectly reasonable to a bureaucrat covering his rear can seem nonsensical to the rest of us. But it is the bureaucrat's opinion that counts.

Here's an example from Rockwell:

> A forklift at the Idaho National Engineering Laboratory moved a small spent fuel cask from the storage pool to the hot cell. The cask had not been properly drained and some pool water was dribbled onto the blacktop along the way. Despite the fact that some characters had taken a midnight swim in such a pool in the days when I used to visit there and were none the worse for it, storage pool water is defined as a hazardous contaminant. It was deemed necessary therefore to dig up the entire path of the forklift, creating a trench two feet wide by a half mile long that was dubbed

---

[6] In the US a typical 1 gigawatt nuclear plant will have a staff of 700 people or more. But such a plant can easily be operated by fewer than 20 people per shift. This was recently demonstrated in Spain. Spain has three 1 GW nuclear plants on two sites near Barcelona. Normally the three plants employ 850 people, far less than USA practice. When COVID-19 came along, the plants were instructed to keep all non-essential employees home. Turns out only 120 people were needed to operate the three plants.[225] Not surprising. The 450 MW Riverbend coal plant in North Carolina operated with a total of 14 people per shift.[57][p 195]. Coal plants are far more maintenance intensive than nuclear plants.

> Toomer's Creek, after the unfortunate worker whose job it was to ensure that the cask was fully drained.
>
> The Bannock Paving Company was hired to repave the entire road. Bannock used slag from the local phosphate plants as aggregate in the blacktop, which had proved to be highly satisfactory in many of the roads in the Pocatello, Idaho area. After the job was complete, it was learned that the aggregate was naturally high in thorium, and was more radioactive that the material that had been dug up, marked with the dreaded radiation symbol, and hauled away for expensive, long-term burial.[217]

The bureaucrat is playing with other people's money. For him, the Toomer's Creek expenditure was quite reasonable. It cost him nothing while completely rectifying the mistake. And as we have seen in Chapter 11, Toomer's Creek is just a particularly silly example of a pervasive and totally debilitating doctrine. Unless ALARA is dispensed with, nuclear power is doomed.

12.2.2 Balanced Limits

Regulation should attempt to balance risk versus benefit. The benefits of reliable electricity are manifold. Countries which are poor in electricity are poor in health, poor in quality of life, and poor in opportunities. Countries are far better off with coal powered electricity than with no electricity. Myers et al estimate that each 100 watts of per capita electricity consumption in a less developed economy increases life expectancy by 22 days.[175] But they are still better off with a power source that emits no sulphur, no NOx, and no particulate matter. The benefits of CO2 free electricity are currently incalculable. But they could be crucial in determining the fate of the species. These are the benefits that must be balanced against the losses associated with a release of radioactive material.

The easiest way to do this balancing is to compare nuclear with its non-intermittent alternatives. In North America the alternative is gas. In most of the rest of the world the alternative is coal. Theoretically, we should set the regulations so the Lost Life Expectancy (LLE) per marginal dollar spent on safety would be the same for all alternatives. Otherwise we can shift a dollar from where it is having less effect on LLE to where it would have more with an increase in life expectancy. But as a rough proxy, we can target the same LLE per kWh.

Comparing alternative sources of power on the basis of their risk per electricity generated would seem obvious. But apparently not to the nuclear community. The Advisory Committee on Reactor Safeguards, an independent group of highly knowledgeable scientists and engineers, agonized for decades over the number of deaths in hypothetical nuclear plant casualties. Okrent describes this process in great detail for the 1960 to 1980 period.[197] But nowhere in his 300 pages of fine print is such an inter-fuel comparison even mentioned.

From a comparative perspective, the current regulatory regime is highly biased toward fossil fuels. According to Kharecha and Hansen, coal is 387 times as hazardous in terms of reduced life expectancy per unit output as nuclear.[129]. Gas is 38 times as hazardous. Other authors come up with roughly similar numbers. Nuclear regs could be relaxed by an order of magnitude where gas is the alternative and by two orders of magnitude where coal is the alternative and we would shorten the lives of one-third as many people while ending power plant CO2. Win, win, and win. Legislation should explicitly instruct the regulators to factor in the health hazards of alternative sources of power in setting limits.

As soon as you base the regulations on comparing power alternatives, ALARA disappears and common sense reappears. In the case of the NRC, this will require new instructions from Congress. The NRC has been told by law "to protect the health and safety of the public" which it has interpreted to mean to protect the health and safety of the public from the risks associated with nuclear power. This was almost certainly Congressional intent, but the result is that NRC legally MUST ignore the non-nuclear health and safety implications of overly restrictive legislation. And there is no guidance on where to stop.

This suggests having a single body regulating all sources of electricity. When we tried to make the argument for balanced limits to a group of Indonesian nuclear regulators, one member of the group had the honesty to stand up and say "I don't care what the problems with coal are. I'm a nuclear regulator. My job is to make nuclear as safe as possible." And under the instructions and incentives that he has been given, he's right. Unless these instructions and incentives are changed, horribly unbalanced regulation will continue to be the norm. The losers will be the human race and the planet.

12.2.3 Focus on Dose Profile, not Cumulative Dose

Table 12.1 shows the evolution of allowable dose rates since the 1930's.

	mSv/y	Comment
1924	730	really 2 mSv/day
1934	365	really 1 mSv/day
1951	156	really 3 mSv/week
1957	5	but 50 for nuke workers
1991	1	100 mSv/5 yr for nuke worker, 50 in 1 year ok

Table 12.1: Evolution of General Public Radiation Limits. See also Figure 9.14

Remember when NCRP called for the factor of 30 reduction in the Maximum Permissible Dose in 1957, they admitted, Section 9.8,

> The changes in the accumulated Maximum Permissible Dose are not the result of positive evidence of damage due to use of earlier permissible dose levels[179, page 1]

But what they really did is lower the annual dose limit while relaxing the daily limit. This is dangerous. As we found out in Section 5.9, what counts is the dose received within the repair period. The repair period is roughly a day. We need to go back to daily limits; and, as Table 5.19 shows, Lauriston Taylor's statement that "No one has been identifiably injured while working within the first numerical standards first set by the NCRP and then the ICRP in 1934." is still true. ***The nuclear establishment must widely promulgate and defend the fact that dose rates of 1 mSv/day or less will result in no detectable decrease in life expectancy.***[7] In the process, they must abandon regulatory periods such as a year, which have no relationship to the repair period.

---

[7] The DOE accepts this fact. The DOE requirement for *contact handled* material, meaning no shielding required, is a surface dose rate of no more than 2 mSv/h. This is based on assuming that a worker will be in close contact with the material for no more than a half-hour, and thus will receive no more than 1 mSv per day.[199][page 9]

Nuclear power plants routinely issue Radiation Work Permits (RWP's) that set limits of 1 mSv for a day.[29][p 142] At least in the past actual daily doses in an outage could be as high as 20 mSv for jumpers.

So does NASA. "The typical daily dose rate inside the International Space Station ranges from 0.5 mSv to 1 mSv depending on solar activity."[131] The ISS is in Low Earth Orbit. Trips to the moon and beyond will face more hostile conditions. The plan is to provide enough shielding to hold the average dose rates to ISS levels. The NASA annual limit is 500 mSv, with career limits of 1000 to 4000 mSv depending on age and gender.[212]

12.2.4 Limits are Triggers

A limit without defined consequences for violating that limit is no limit at all. We actually need a hierarchy of limits and consequences. As an example, consider the Table 12.2 hypothetical set of plant boundary rules.

Table 12.2: Example set of plant boundary triggers

Trigger for corrective action	0.5 μSv/h	Violation of this level for more than an hour triggers an independent Accident Review Board investigation. Failure to correct the exceedence within 10 days triggers an ongoing fine. The fine shall be paid out of deferred executive compensation (see Section **??**), until that is exhausted. Has no health implications. Just an indication something is not operating properly.
Trigger for Plant Shutdown	5 μSv/h	Violation of this level for more than a day triggers a plant shutdown. Nil health implications. But something is seriously wrong and must be fixed. Top management forfeit any deferred compensation, are fired, and barred from employment in nuclear electricity.
Trigger to warn public to shelter in place	20 μSv/h	If the tolerance dose rate is 1 mSv/day (42 μSv/h), this is not an unreasonable number. Concern early on is it could go higher. By the way, 15 microsieverts per hour is the IAEA recommended Operational Intervention Level (OIL) for shelter in place.
Trigger to recommend evacuation	80 μSv/h	This is about twice a 1 mSv per day tolerance dose rate. Evacuation should be considered. 150 microsieverts per hour is the IAEA recommended Operational Intervention Level (OIL) for evacuation. This is a local, not plant boundary number.
Trigger to lift evacuation order	40 μSv/h	Based on a 1 mSv/day tolerance dose rate. This is a local, not plant boundary number. ICRP level of 2.3 μSv/h way too low. and inconsistent with the other OIL's.

Table 12.2 is not meant to be an argument for this particular set of numbers. Rather the purpose of the table is to make two points:

1. Regulatory limits are best regarded as a set of triggers whose violation indicates something has gone wrong and corrective action, penalties, and/or other intervention is required.
2. These trigger levels need not, and usually are not, harmful dose rates. In most cases, they are and should be set well below the dose rates at which any radiation health effects have been reliably observed, which is at least 10 mSv/day.

Regulatory bodies understand this critically important distinction; but to my knowledge they have never made it clear to the public. Here's the Canadian Nuclear Safety Commission's attempt.

> Dose limits have mistakenly been regarded as the line between what is safe and what is not safe. The dose limit of 1 mSv/y is a regulatory limit, not a health limit. It considers the scientific evidence on the health effects of radiation, as well as societal and value judgments regarding both the risks of exposure and benefits of licensed activities.[47]

This paragraph starts out OK but quickly descends into circular bureaucratese, which will leave the most intelligent member of the public scratching her head. Here's what I think they are trying to say.

> The 1 mSv/y normal operating requirement is a trigger. Exceedence of this level means that something is not operating properly and corrective action must be undertaken. This alert level has been set far below — more than a factor of 3000 below — the dose rate at which any radiation harm has been observed.

A corollary to the define-the-consequences is: make clear what the meaning of each regulatory level is to the public.

At least the CNSC tried. The opposite is the lowering of limits after a release. This happened both in Japan after Fukushima and in Europe after Chernobyl. One area was the radioactive activity in meat. In both cases, the pre-release limits were such that the dose that would be received would be a small fraction of background even if one ate impossible amounts of meat.[9][pages 104-105] The idea was by lowering the limits by factors of 5 and 10 the public will feel protected. We politicians will demonstrate how responsive we are to our voters' concerns, and maybe they won't throw us out at the next election. In fact, the voters drew the obvious lessons:

1. The old limits must have been dangerously high.
2. The new limits are marginally safe, only if you are willing to trust the same bastards that set the old bogus limits.

The response should have been: The max legal level is precautionary. It has been set far below the levels which could cause any harm. Eat as much as you want of the meat that passes our inspection.

12.2.5 Enforce Only the Limits

The regulator's job is not to dictate how a plant complies with the dose rate limits. Monitoring and reporting requirements should be limited to that required to detect any violation of the limits. The system should be similar to that for monitoring fossil fuel plant emissions, except that radiation monitoring tends to be much cheaper and easier than stack gas monitors.

The current enforcement system is a triumph of process over substance. It involves hundreds of people at each plant whose only function is to produce paperwork documenting that all the prescribed procedures have been followed and investigating in detail any non-conformance, however trivial.

Such systems pretty quickly develop metrics. These metrics are based on the number of problems reported. A good metric — few problems — gets you promoted. A bad metric gets you fired. This not only means that problem areas are allowed to fester, but can generate dangerous responses in a casualty. In January 2012, the Byron Station nuclear power plant suffered a failure in which power to the instrumentation was lost. The initial failure was a broken insulator on one of the incoming power phases, grounding that phase. This open phase condition was not properly recognized by the QA certified software. The cross-tie breakers to plant power did not close. The on-site emergency diesels were not started. The control room was blind. The operator correctly began to initiate a shutdown, but was over-ruled by the shift supervisor who did not want this blackmark on his record.[211] The plant operated in the dark for seven minutes at which point a fire was reported in a transformer and the operator initiated a scram without the supervisor's approval. This is the nuclear safety culture.

Once the limits are set, the regulator's job is to catch any violations of those limits. The system must be simple Pass/Fail. The temptation is to reward those plants that reduce exposure below the limits more than their brethren. This can take various forms: a bad rating or more frequent, more stringent inspections for plants that are in the bottom half. But half the plants are always in the bottom half. Pressuring plants to do better than the limits is just ALARA in another form.

The NRC requires all USA plants to report the collective exposure in person-sieverts at each plant annually. Not only does this induce each plant to go to expensive measures to further reduce exposures that are already below background, in its acceptance of LNT it could be counter-productive. It is easy to imagine scenarios in which collective exposure is reduced by having a few people do a job and take all the dose rather than changing out people to distribute the dose. If NRC really were concerned with worker health, they would focus on the most exposed individuals.

The regulator's job must be to enforce the dose rate limits and the corresponding penalties, not dictate how the plant should be operated.

12.3 Mandate Rigorous, Fullscale Testing

12.3.1 The Fermi Debacle

In 1956, Detroit Edison proposed building a 100 MWe sodium cooled fast breeder at the western end of Lake Erie between Detroit and Toledo, at a place called Lagoona Beach. At that time the only US fast breeder was the 1.7 MW EBR-1 which had just suffered an unexpected excursion and partial meltdown. The problem was traced to unanticipated bowing in the core elements. Yet the AEC was pushing ahead with Lagoona Beach.

The ACRS wanted a much bigger prototype tested at a remote location. The AEC argued that was unnecessary. Any problems could be handled by modelling and sub-system tests. The head of the ACRS sub-committee looking into Lagoona Beach was a guy named Harvey Brooks.

In a letter to the AEC, Brooks wrote:

> In any technology as new and untested as that of the sodium cooled reactors, there are likely to be serious surprises which were not anticipated by the designers. Experience indicates that such surprises always occur in connection with any new development, even when the technology is much more thoroughly tested than in the case of the fast reactor. Many of these surprises can be matters of apparently trivial detail which may nevertheless seriously influence the safety or operation of the reactor. ***The purpose of a prototype is primarily to minimize the possibility of such surprises rather than to find the answer to specific technical questions which are anticipated now, and which presumably can be answered on a piecemeal basis by experiment and theory.*** [Emphasis mine.]

The AEC went ahead and licensed the reactor anyway. The plant, called the Enrico Fermi Nuclear Generating Station, encountered a long series of problems including a coolant blockage which shut down the plant for four years. The safety systems operated properly and there was no radiation release. But the accident created a great deal of publicity and a strongly anti-nuclear book with the catchy title of “We Almost Lost Detroit". The plant never operated at full power and was a commercial disaster.

12.3.2 Build It and then Try to Break It.

It is imprudent to license any new nuke (or any nuclear design) without full scale, rigorous, stress testing, including physically simulating major failures and proving that the backup safety systems actually work. Only after such testing is successfully completed can we consider certifying the design for commercial operation. This is simple common sense, followed everywhere in engineering except nuclear. ***It was the process followed by nuclear prior to the Gold Standard.***

Between 1954 and 1964, there were at least five power excursions at the Nuclear Reactor Test Site in Idaho, in which the reactor core was trashed. At least one of these, BORAX-1, was intentional. The original Light Water Reactor design, the Pressurized Water Reactor, works very hard to keep the water from boiling, despite the fact that boiling automatically reduces power in a water cooled reactor. A Boiling Water Reactor in theory could be simpler and more easily load follow than a Pressurized Water Reactor. But the feeling was that the chaotic boiling process would be too difficult to control. There was only one way to find out. Build it and try and break it. The first of these experiments was called BORAX-1.

In 1953/54, an Argonne team under Walter Zinn tortured a boiling water reactor for 14 months. They put it through every screw up and failure that they could think of. Every time the reactor shut itself down with no harm to the machinery. On July 24, 1954, having nothing left to do, they decided to blow out the control rods, an impossible casualty in normal operation, just to see what would happen. They predicted the reactivity excursion would release 80 megajoules (MJ) of energy. Boom. The actual release was about 135 MJ.[101] Time to correct the models. But these guys had manufactured the worst possible casualty, and it turned out to not only be tolerable, but kind of anticlimactic. Without BORAX-1 and the four succeeding experiments, we would not know how to do a boiling water reactor.

Such testing is essential for the underwriters and the public to be assured that a new design is adequately safe. The situation is a bit like that facing commercial aircraft. Few would board a commercial aircraft without such testing. And with good reason. The Boeing 777 was not that different from earlier Boeing aircraft. The design had undergone extensive computer analyses and wind tunnel tests. However, flight testing revealed that the stall recovery software rolled the airplane and put it into a steep dive. The test crew recovered and problem was quickly corrected.

The GE Boiling Water Reactor Mark 1 containment was duly approved and licensed by the AEC. But when the Germans decided to do a full scale test at Wurgassen in 1972 by opening up all eight steam relief valves at the same time, as was supposed to happen in a real casualty, the suppression torus started oscillating, banging back and forth, and badly damaging the reactor.[268] The AEC deemed such a test was unnecessary.

The Super-Phenix was one of the most thoroughly analyzed nuclear systems ever constructed. But during start-up, it became evident that the control rod *worth*, the ability of the control rods to stop the chain reaction, had been greatly over-estimated.

A promising nuclear technology is the molten salt reactor (MSR). MSR's combine low pressure, high temperature, with a liquid fuel which can be moved around with a pump and passively drained in an upset. One of the uncertainties with this concept is the amount and location of plate out from the fission products, which could build up in heat exchangers. The computer cannot help us much here. The only way to find out is long term, full scale testing.

12.3.3 Can't test without a license. Can't license without tests.

Most of the new designs are modular in nature, in an attempt to take advantage of assembly line production. But by far the most important advantage of modular reactors is that they can be feasibly tested at full scale in pretty much the same manner we test commercial airplanes. Unfortunately, under the current regulatory process, there is no feasible way of taking advantage of this godsend.

The NRC and others have made it clear that it is not willing to treat prototypes much differently than a standard commercial reactor. This puts new nuclear in an impossible quandary. ***We need fullscale prototype tests in order to prudently license these new technologies. But we can't do the tests without a license.*** Unless this Catch 22 is eliminated, the potential bonanza of new nuclear will pass the USA by. The country that is in the best position to prudently solve the Gordian knot of electricity poverty and global warming will have kicked away the opportunity.

12.4 Enforce Competition

Section 11.9 makes the argument that, unless we use competition to root out the incompetents and drive technological innovation, nuclear power is going nowhere. We must ruthlessly eliminate barriers to entry. We must find a way to align the regulator's motives with society's best interest. We must find a way to impose competition on this industry.

Chapter 13

Underwriter Certification

> It is not from the benevolence of the butcher, the brewer, or the baker that we expect our dinner, but from their regard to their own self-interest. [Adam Smith]

13.1 Introduction

If the Gold Standard effectively precludes nuclear power and prevents mankind from solving the twin problems of energy poverty and global warming, with what should we replace it?

We need a system that fairly and efficiently compensates anyone harmed by nuclear power. We need a system in which all the players, including the regulators, are motivated in a way that is consistent with societal well-being.

Underwriter Certification is a market based regulatory system. It harnesses human nature, rather than pretending bureaucrats are self-sacrificing saints. It depends on competition to balance economics and harm, competition among vendors, competition among underwriters, and competition among Certification Societies. But it is not a free market system. Federal and local governments play critical roles in making the system work.

Underwriter Certification assigns the following roles to four major actors.

1. National Government
2. Underwriters
3. Certification Societies
4. Local Government

13.2 National Government

Impose an incrementally increasing CO2 tax. Mankind's use of the atmosphere as a dumping ground for CO2 exhausted from the combustion of fossil fuels is a prototypical case of an *externality*, using something without paying for the costs of that use. The atmosphere is a *public good*. It's not owned by anyone, and anyone can use it for free. As a result, CO2 concentrations in the atmosphere are 40% higher than the highest the planet has experienced in at least the last 650,000 years. If we do nothing, these already unprecedented CO2 levels will probably double by the end of the century. The costs are unknown but could be cataclysmicly large. This is the mother of all market imperfections.

Economists have known for at least 100 years that the efficient way to handle externalities is a tax, in this case a tax on CO2 emissions. A tax on a public good re-establishes market forces. It is *efficient* in that, whatever level of emissions reduction is achieved by a properly administered tax, it will be achieved at least cost to society, that is, with a minimum wastage of the planet's precious resources.

We have not spent any time on taxing pollution including CO2 in this book, in part because it is not specific to nuclear power. And in part because it is well treated elsewhere. I particularly recommend reference [166]. But an incrementally increasing CO2 tax is essential to a smooth, efficient transition to a low carbon society.

Dump all subsidies and mandates. Technology specific subsidies and mandates are the opposite of a pollution tax. They introduce market imperfections and inefficiencies. In their most pernicious form, the tax credit, they are a blatant, in-your-face transfer of wealth from the poor to the rich.[1] They are the worst of all possible approaches to the problem.

Set plant boundary dose rate limits. These limits are triggers whose violation indicates something is not working right, and corrective action, penalties,and/or other intervention is required. These trigger levels need not, and usually are not, harmful dose rates. In most cases, they are and should be set far below the dose rates at which any radiation health effects have been reliably observed. The government must make this distinction clear.

If a government decides to change any of the trigger levels, any existing or under construction plants must either be grandfathered or compensated for any additional costs imposed on the plant by the change.

Promulgate and enforce a firm, fixed table of compensation payments. The unique hazard associated with nuclear power is the potential for a large release of radioactive material. Anyone who suffers true harm from such a release must be compensated. This is not just

---

[1] And create absurdities like negative electricity prices.

a matter of equity. Such compensation internalizes this harm, ensuring that the potential harm is part of the developers' design and operating calculus.

The compensation must be based on the Lost Life Expectancy from the dose rate profile each individual incurred, according to a reasonably realistic dose-response model, and nothing else. That model must recognize our bodies' ability to repair radiation damage. Once an individual's dose rate profile is established, the payment would be both automatic and not subject to dispute. The tort system must be eschewed.

In the American system, all sorts of indirect effects are claimable. After the Deepwater Horizon blowout in the Gulf of Mexico, one bar in Key West was awarded $600,000 for lost business. The oil spill never came within 700 miles of Key West. If the bar actually lost business, it was not the fault of the spill; but rather the lurid, grossly exaggerated media coverage of the casualty. A system in which such tenuous impacts are compensatable is uninsurable and will stifle even the most beneficial project.

If negligence is subsequently proven, the proceeds from any fines or penalties go to the local and state government, not individuals and their ambulance chasers.

Require iron clad insurance for this liability. This amount of insurance required should be based on a generous estimate of the cost of a reasonable worst case release under the compensation scheme. This cost will be site dependent. It depends on the local population distribution, weather patterns, buffer zones, and other site dependent variables. So Congress must specify how the worst case cost shall be estimated. This could be done using the existing MACCS2 software, but with LNT being replaced by SNT. That methodology would then be applied to each site's population distribution, etc. This must be done transparently by elected officials, not bureaucrats. The insurance requirement can have well-defined inflators, but once set these rules cannot be changed for existing plants.[2]

If a plant's insurer cancels the insurance and the plant is unable to come up with a replacement, government shuts the plant down. If necessary, it can commandeer the plant and take over the operation.

In the very unlikely case that the compensation exceeds the amount of insurance in a casualty, then the compensation payments above that amount shall be paid out of public funds, spreading the uninsured harm across all taxpayers.

The liability insurance requirement is a keystone of the system. It provides money to compensate victims of a release. Just as importantly, no underwriter will insure a plant that he does not have real confidence in; and he will stop providing insurance as soon as he loses confidence in its operation. He will undertake regular, probing inspections to assure himself that the plant is being operated properly. Operators of American nuclear power plants fear underwriter inspections much more than they fear NRC inspections.

---

[2] The inflators can include a local population adjustment, say every 5 years.

Set food and land contamination limits. Set the legal contamination limits above which produce must be taken off the market. Set the contamination limits above which the land cannot be farmed or grazed until the contamination falls below the limit. These limits should be set by elected officials, not unelected bureaucrats. Once set they cannot be changed for existing plants, unless the plant is compensated for any additional cost.

Set Business Shutdown Dose Rate As long as the dose rate at a business' location is above this level, a business can shut down and be compensated for the loss of profits. Similarly, employees of the business can refuse to show up for work and be compensated for the loss of wages. The Shut Down Level cannot be changed for existing plants, unless the plant is compensated for any additional cost.

Require any property insurance to have large deductibles. Radiation aside, the property cost of a major nuclear power casualty tends to be extremely large. In the Sovacool data base of electricity casualties, the average property cost of a nuclear mishap is 1.4 billion dollars.[239][Table 3] That's 30 times that of the average gas plant casualty and about 500 times that of the average solar/wind casualty. The reasons are:

1. The large scale and high capital cost of nuclear power plants.
2. Repairs are difficult to impossible to implement because of residual radioactivity.

This massive potential loss represents a very strong incentive for robust, conservative design for nuclear power investors; ***but only if it is internalized***. If for example the cost of a damaged reactor can be pushed on to rate payers, the investors have no such incentive. Or worse if it can be incorporated in the rate base, then the investors have a perverse incentive. Ideally nuclear (and all) power plants would operate in properly functioning competitive markets. But if we are dealing with a regulated market, the regulation must ensure that the costs of any casualty are born by the investors, and not the rate payers.

While we must impose sufficient property damage insurance to cover the costs of clean up and decommissioning, this insurance should be subject to the following conditions:

1. Extremely large deductibles and copays. The utility shareholders must bear a large proportion of the costs of a casualty.
2. The utility must go bankrupt and the shareholders wiped out, before any of the casualty's costs are borne by the rate payers.

Under these rules, the investor community will carefully scrutinize the design and management of any plant before plunking down the money to build the plant.

Require portion of top management compensation to be deferred. In the US, corporate governance is as screwed up as the tort system. In 2020 Excelon, the largest American operator of nuclear plants, paid a fine of $200 million for bribing Illinois lawmakers. Excelon's rate payers and shareholder paid the fine. In 2020, Excelon's CEO Christopher Crane took home $15.2 million in cash, stocks, and benefits.[29][p 347]

In a large utility, the investors are almost always passive shareholders who have little or no say in the actual investment decisions and operating policies. The real decision makers are the plant company's top management. We need to hold these people accountable for any screw ups. They must be motivated by the carrot and the stick.

1. A substantial portion of executive compensation must be performance based.
2. Any such bonuses, stock options, and the like shall be deferred for a substantial period. These will the first funds used in the event of a release, to pay any fines or radiation harm compensation.
3. Any release that results in compensation payments above an amount set by Congress shall result in the entire top management team being fired, and barred from nuclear plant employment for life.
4. (2) and (3) require no finding of negligence. If gross negligence is proven, substantial jail terms shall be imposed.

Goal is to make sure top management suffers if a plant has a problem. In 1984, John Selby, CEO of Consumers Power, announced that work on their nearly complete, two reactor plant at Midland, Michigan was being shut down, after costs exploded from an initial estimate of 238 million in 1967 to over 4 billion. The main problem was the constantly changing NRC regulation, that all US nuclear plants faced. At one point, Consumers Power had to apologize to the work force:

> Last year we faced an unusually high number of changed NRC requirements, which caused rework in many sections of the plant, particularly in the auxiliary building. It must be frustrating for crafts to complete construction of a system or component only to find that a couple of weeks later it has to be torn out. We are building the Midland Plant during a period of changing regulatory requirements. If the NRC develops new rules, we have to modify work to meet these new rules. All too often in 1980 that meant tearing out a system, redesigning, and subsequently reconstructing it."[236][p 108]

But the proximate cause of the shut down was poor soil compaction. The Midland plant was built on a flood plain. To raise the plant above the design flood, fill was brought in, and a portion of the plant, including safety related buildings, was built on top of the fill. Bechtel, the EPC contractor, did a lousy job of compacting the fill. The utility apparently did not catch this gross violation of the design spec. Utility employees were discouraged from complaining about Bechtel's work because it would slow down the job.

The buildings began sinking almost immediately. The NRC required a complicated fix which turned into a never ending money sink. When Selby was questioned about who should pay for the mess, he said "Mistakes were honest, so our customers should pay. Electric customers should pay for soil problems, because they were the result of honest mistakes and not fraud."[236][p 158]

Prosecute alleged negligence. In the event of a conviction, levy fines and prison terms on the individuals involved. Insurance against such fines would be illegal.

Facilitate prototype testing For untested technologies, the insurers will almost certainly require intensive, full scale, stress testing of prototypes. The federal government should encourage this by providing a testing facility complete with heat sink, waste handling facilities, and security. Here's a key point. ***The park would be run on user pays basis.*** Each tenant would pay rent and other usage fees, based on how much of the park's land and services it required. Each would build its prototype entirely with its own money. Each would also be required to leave its site in an approved condition at the end of its tests. This would mean that the market and not politicians would choose which concepts would apply.[3] It would also mean that, if the park is successful, it will cost the taxpayer little or no money.

The protopark would require potential testers to post a bond which would cover a realistic estimate of the real damage caused by a credible worst case casualty.[4] This brings the market into play in a salutary way. If the tester can't get this insurance, then he should not be testing. Furthermore, the bond would require the insurer to monitor the testing and yank the bond if it becomes uncomfortable with how things are going.[5] As soon as the bond is yanked, further tests would be illegal and the prototype would have to shut down.

The size of the bond and the premium will be critically dependent on the remoteness of the test site. Under a reasonable but conservative model such as SNT, the LLE associated with a given release depends on the distance to the population raised to better than the 4th power. Doubling the distance decreases the LLE by about a factor of 20.

Government involvement in the selection of tenants would be limited to setting the value of the bond and and the terms of the insurance. The developers will have to convince potential insurers that his technology is safe enough to test, so that they will post the bond at a premium he can afford.

In many cases, the underwriters will need long term, full scale tests to have confidence in the design. Such tests will generate an enormous amount of electricity. It would be economically and environmentally stupid to not make use of this power. Test reactors should be allowed to offer their power to the grid. It is the regulatory regime that makes a test reactor a test reactor, not what happens to its power. Yet many countries follow the lead of the USA in requiring that a test reactor cannot supply power to the grid. This pretty much precludes full-scale testing.[6]

---

[3] It also avoids the ugly situation where the moocher takes taxpayer money but keeps the IP he developed with our money.

[4] There would actually need to be two bonds. One to cover a release; a second to cover the the costs of decommissioning and removal.

[5] This feature would also make the bond much more affordable. If the bond is yanked, then all or almost all of the price of the bond would be rebated. This will keep the insurer honest if the tests are going smoothly.

[6] This counter productive prohibition is the result of nuclear's politics dominated history. The Atomic Energy Act of 1954 set up several classes of reactors including commercial (Section 103) and demonstration (Section

For the successful concepts, their prototype facility will become a permanent or at least semi-permanent operation. They will be testing improvements, reacting to feedback from the commercial plants, running very long term tests, and so on. Most technological process is incremental in nature. Little of this happens under current nuclear regulation since even the smallest change involves tens of millions of dollars in licensing paperwork. By testing and demonstrating improvements in the prototype environment, the current relicensing paperwork becomes redundant.

Some of the new technologies are inherently flexible. They can operate on a wide range of fuels. They can be operated at different temperatures with different materials. They can operate with more or less on-line processing. In some cases, even the moderator can be changed. The intelligent venture will start out with a conservative version of its concept. After that is proven and in operation, all the paths forward can be explored at the protopark, leading to higher efficiencies and less waste. This is the natural and prudent progression to fuel cycles which once started require little or no enriched uranium. The protopark enables this process.

Provide protection from military attack. Providing protection against national or sub-national group attacks is the function of the nation's military. This should be true of all high value facilities, many of which such as the transmission grid are far more vulnerable than nuclear power plants. Deploying a small army at each plant is an extremely inefficient way to attempt to protect the plants, and does nothing to prevent the real threat: missile and aircraft strikes. This can only be done by the country's military.

Nuclear plants should be required to provide only normal industrial security, similar to large chemical facilities such as Bhopal or large dams such as Banqiao; both of which are more vulnerable and have at least as much potential for widespread harm as a nuclear plant.

Do not stifle competition; enforce it. Foster multiple underwriters. Foster multiple Certification Societies. Foster multiple vendors. For the system to work, there must be competition at every level. This will require aggressive application of anti-trust and price fixing legislation.

Foster coops. Final distribution is a natural monopoly. But if the rate payers own the distribution facilities and decides who runs them, then neither rate gouging nor decisions leading

---

104(b)). 104(b) plants were eligible for a range of subsidies and exemptions that 103 plants were not.

Needless to say, everybody wanted to be 104(b); and prior to 1970 all USA plants were licenced under 104(b).[15][page 205-206] Coal interests complained bitterly about this abuse of the demonstration plant clause, allowed and in fact encouraged by the AEC in its promotional role. The result of the political wrangling was Congress passed a law saying 104(b) plants could not get more than half their revenue from power sales, a back-door way of forcing the commercial plants to license under Section 103. The unintended consequence was to effectively eliminate the large scale, long run testing, essential to prudently certify new designs.

> to unnecessarily expensive or unreliable electricity will be tolerated. Coops can be fostered by providing capital in the form of loans, but those loans must come with provisions that guarantee that the shareholders/ratepayers are in control. These include frequent, democratic election of directors.
>
> This works best if the coops are small. But the coops should be allowed to form consortia to provide regional distribution.

One function the federal government does ***not*** do is approve or disapprove an individual plant. That is the role of the local government where the plant is located. There should be no federal incursions into state and local sovereignty, such as Environmental Impact Statements.

Underwriter Certification requires elected officials to do their job. They can solicit “expert" help; but they must select the radiation harm model, which will determine the Lost Life Expectancy associated with each dose rate profile. That harm model must recognize our ability to repair low dose rate radiation damage. They must set the value of a life-day. They must specify the various dose rate triggers and the corresponding penalties and interventions. They must establish the business shut down rules and the food and land contamination levels.

If they abrogate this responsibility to a bureaucracy whose primary incentive is avoiding a release rather than providing power at a tolerable risk, we will be right back in the current mess.

Legislators are not radiation experts. They can be and many are suborned by lobbyists and special interest groups. But in a democracy they are our only hope. If they cannot balance the benefits of nuclear power against the costs, then nuclear has no future in democratic societies.

Once Congress has set the compensation scheme and established the various dose rate triggers, everything become mechanical. The NRC is replaced by the Nuclear Monitoring Agency (NMA). The NMA is a system of of radiation monitors spread in and around each plant and a computer. The computer monitors the sensors, and spits out penalties, and collects and distributes compensation according to the set of rules that the Congress has enacted.

The NMA work force is a bunch of techies, who are good at keeping sensors and computers working. (One of their jobs is to ensure there is backup power for the sensors. At Fukushima, when the grid went down, the radiation sensors in the area went dead.) This is similar to the system for monitoring SO2 emissions from fossil fuel plants except radiation sensors are a lot cheaper, which is good since we will need a lot of them. I would imagine we would need at most one NMA employee per plant site, supported by maybe 20 people back at headquarters.

The plant's underwriters must provide the NMA access to their reserves, so that any compensation is automatic. In return, Congress must make clear that this system is in lieu of and precludes any other tort claims. The NMA can use the IRS and existing law enforcement agencies to enforce the fines, and other penalties.

13.3 Underwriters and Certification Societies

13.3.1 Introduction

In this system, the insurer plays the central role. He must balance the cost of a release versus his premium. It is in his interest to get it right. Too conservative, he loses profitable business. Too aggressive, he goes broke. ***If the system is set up correctly*** and no one is willing to write the insurance at a price the developer can afford, then that developer will disappear. If no developer can obtain insurance on terms he can afford, than nuclear power will not and should not happen.

It would be uneconomic for each underwriter to maintain the staff and expertise required to evaluate a design, properly specify and monitor testing, and to do the ongoing inspections of an operating plant. This is the role of the *Certification Societies*

Certification Societies are hired by a plant, in order to obtain the certification required to obtain insurance. If there is competition in the provision of these services, the Certification Societies will need to avoid the extremes of

1. Not certifying a design that would be a good risk for the underwriters.
2. Certifying a bad risk for the underwriters.

Certification Societies that cannot find this balance would soon find themselves out of business.

13.3.2 This Proposal is Not Original.

We've faced the problem of regulating hazardous, beneficial activities before. It's a question of finding the right balance between safety and economy. If the regulation is too lax, the result will be disproportionate harm. In the worst case, the technology will be rejected and the benefits foregone. If on the other hand regulation makes an activity overly costly, resources will be expended which could be better allocated elsewhere; and in the worst case, the technology will be priced out of existence.

International Trade and the Classification Societies This issue probably emerged first in ocean transportation. The activity was both highly beneficial, and at the time highly hazardous. The solution was the Classification Society system. Shipowners needed insurance. The insurers needed to understand the risk they were insuring. So they set up ship inspection services called Classification Societies. The Classification Societies not only inspect ships, they set the rules by which ships are built, and certify that a ship complies with those rules. There are roughly a half-dozen major Classification Societies. They are paid by the shipowners. The Classification Societies must compete for shipowners. This set up a balancing mechanism. If a Classification Society is too strict, it loses business. If a Classification Society is too lax, its certification becomes meaningless and won't be accepted by the insurers.

Overall the Classification Society system has done an excellent job of delivering the benefits of

Figure 13.1: The Lutine Bell at Lloyds of London. The bell was rung every time an overdue ship was reported: once if the ship was lost; twice if the ship was found. In 1799, the Lutine was lost with a large amount of gold bullion. The bell commemorates Lloyds ability to pay off even very large claims.

international trade. The real cost of transporting goods across oceans has decreased by multiple orders of magnitude. And seaman safety has improved markedly, albeit from abysmal levels.[68]

High Pressure Steam and the Boiler Inspection Services With the advent of high pressure steam in the 19th century, all sorts of formerly unimaginable things became possible. Trains, ocean liners, electricity. At the same time, a whole new danger was unleashed on the public. In the mid-19th century, fatal boiler explosions were running at better than 100 per year.[250] Between 1837 and 1878, there were at least 10 steamboat explosions that killed 20 or more people. The worst of these occurred on the Mississippi near Memphis on April 27, 1865. The steamboat Sultana was badly overloaded with Union soldiers on their way home at the end of the Civil War. At least 1700 were killed when 3 of her 4 boilers exploded.[240].

This prompted several civic leaders in Hartford, Connecticut to form the Hartford Steam Boiler Inspection and Insurance Company in 1866. The deal was pass our inspection, and we will provide reasonably priced insurance for your boiler. Boiler explosions became increasingly rare, despite a steady increase in steam pressure and temperature.

In Germany, a similar system developed, based on inspection services called TÜV's (Technischer Überwachungsverein). Like the Classification Societies, the TÜV's must compete with each other for the inspection business. Like the Classifications Societies, they must find the sweet

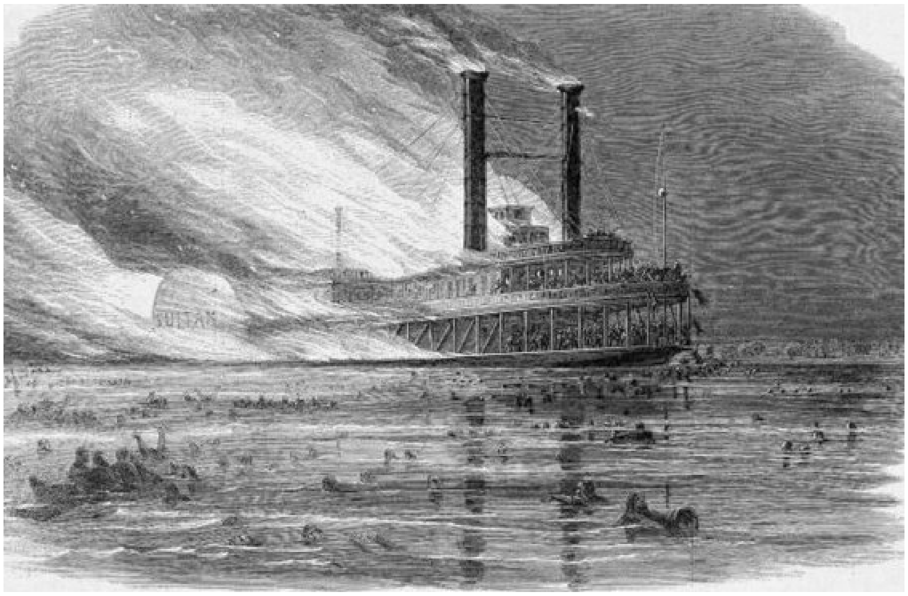


Figure 13.2: Sultana Explosion, 1700+ fatalities

spot between being overly strict and overly lax.

The system has worked well, delivering the benefits of high pressure steam, allowing technological improvement, with eventually an excellent safety record.

Both the Classification Society and TUV systems have built in balancing mechanisms. They don't always get the balance just right; but they cannot stray too far from the sweet spot. Underwriter Certification is merely a variant of the successful Classification Society and TÜV regulatory systems, both of which have already done nuclear work. In Germany, the state has delegated nuclear plant certification and inspection to the TÜV's. The American classification society is called the American Bureau of Shipping (ABS). ABS certified and inspected the Savannah, the USA's only nuclear power commercial ship. The system is already in place if we decide to use it.

13.4 Local Government

No power plant, nuclear or otherwise, or any large industrial facility should be located in a community that does not want it. Each such community should balance the benefits and costs of such a development and make its own decision. The local community will see only a tiny proportion of the benefit to society as a whole of the cheap, reliable, zero pollution, and near zero CO2 electricity that the plant will provide. But it will bear the brunt of any problem at the plant. It should require compensation for taking on this risk.

This compensation can take many forms including:

1. Hundreds of good, steady jobs.
2. Property and other tax revenues.
3. Parks and other public facilities in the plant's buffer zone, which the local government should set.
4. District heating in cold locales.
5. Here's my favorite. Shares in the plant's ownership and therefore a portion of the plant's profits. This would give the community access to everything a shareholder sees and some say in the choice of directors, and indirectly in the choice of management.

What we need is auctions. Local communities interested in hosting a plant would prepare a package, delineating what they would require in order to agree to host a plant. They could ask for anything they want. The only requirement is the agreement is irrevocable for the life of the plant. The community that offered the most attractive combination of site and compensation package would be the winning bidder.[7] This depends on nuclear being cheap enough so that it can afford to accept at least one of the offers.

Once the plant is operating, the local government would monitor the radiation sensors and enforce the plant boundary dose rate triggers, including collecting any fines. This must be on a strict pass/fail basis. There can be no judgement calls.

---

[7] In Korea, the state utility, KHNP, has a history of negotiating compensation with local communities. In 2014 KHNP agreed to pay Ulchin County $250 million in return for building two more reactors at Shin Halul.[282] KHNP also made a deal with Yeondeok County under which KHNP will build four reactors at a greenfield site in eastern Korea. In return, KHNP will pay the county 1.3 billion dollars over 60 years.

13.5 Where could Underwriter Certification actually happen?

Even I am not stupid enough to think this will happen in a place like the USA. In fact, imposing this sort of market based regulation will be next to impossible in much of the planet. Powerful special interests ranging from fossil fuel companies to counter culture activists will adamantly resist it . Well entrenched bureaucracies will fight their own demise with every parasitic tool and trick in the book. Most of the nuclear establishment will be extremely uncomfortable in a competitive environment. More to the point, they will not be the least bit happy to watch the disappearance of the regulatory morass that they labored so long and so expensively to wade through. The winners will be the rate payers, and they have no lobbyists.

But imagine a poor developing country that knows it needs large amounts of electricity, multiples of its current consumption, and it needs it now. That electricity will catapult the country from the purgatory of the poor to the paradise of the rich. This country has little or no fossil fuel resources. This country has no experience with nuclear power nor any nuclear regulatory apparat. Suppose this country has a wise and strong leader. Would she adopt a system that

1. allows her people access to cheap, reliable, pollution free electricity,
2. requires no indigenous nuclear regulatory expertise,
3. provides her country with energy independence?

And if she makes the obvious choice, who else should?

Chapter 14

Metanoeite

> If you don't pursue safety in a way that is cost effective, you are killing people.[David Okrent]

After a sparkling beginning, nuclear power has been a tragic flop. Despite having everything going for it: dispatchable, incredible energy density, tiny amount of waste, tiny amount of land, near zero pollution, near zero CO2 emissions, it never produced much more than 15% of the planet's electricity. Now that paltry percentage is declining. In much of the world, nuclear electricity, a low marginal cost source, is so expensive that fully depreciated plants cannot compete with fossil fuel on operating cost. We could have lifted billions out of electricity poverty. We could have had massive reductions in air pollution and CO2 emissions. Instead nuclear power is withering away.

What caused this epic tragedy? The standard answer is radiation, radiation, radiation. But nuclear electricity priced itself out of the market before there was wide spread concern about nuclear power safety. The real problem lies within. Nuclear power never escaped from its government sponsored and controlled birth. In the process, it developed a regulatory regime which explicitly mandates that nuclear power must be at least as expensive as the alternatives, while at the same time scaring the hell out of everybody.

But this can be turned around. Here's the good news. ***The Gordian knot of electricity poverty and global warming is solvable.*** All that is required is we free nuclear power from the comfortable but prohibitively expensive shackles of the Gold Standard.

- Renounce the Two Lies and all their works.
  - The Negligible Probability Lie must go. The nuclear power establishment has to stop thinking that the public is too stupid to evaluate risk. The nuclear power establishment must abandon and disown the preposterous lie that the probability of a radioactive release is negligibly low. Given the number of plants the planet must have, a release will occur every few years. People have a great deal of difficulty trusting a serial liar.

  - The Intolerable Harm Lie must go. The radiation protection establishment must abandon LNT for a model which is consistent with the facts. Sigmoid No Threshold is an obvious candidate. The focus must be on dose rate, not cumulative dose.
- ALARA must go.
  - No engineer can design to ALARA.
  - No rational investor can allow himself to be exposed to ALARA.
  - ALARA guarantees that the cost of any nuclear technology, no matter how inherently cheap or safe, will be pushed up to the point where it is at best barely economic.
  - ALARA says to one and all that near background dose rates are perilous.
- Regulate the regulators. Regulation must be based on fixed radiation limits. Those limits must take into account the risks associated with the alternatives to nuclear power. Nuclear power can be and is safer than the alternatives. It cannot be safer than perfection.
- It's dose rate, silly. The regulatory period should be based on the repair period. Switch from annual limits to daily limits.
- Test then license. Replace computer runs and bogus probabilities with rigorous, full scale stress testing of prototypes. If the designers claim their plant can handle a casualty, make them prove it. The step by step system for monitoring and approving this testing must be completely different from the system for regulating licensed plants.
- Foster technological progress by providing pre-licensing test sites; but make the developers pay for the use of these facilities. Do not try to pick the winners.
- Replace unbridled regulation with unfettered competition. Competition must be encouraged rather than stifled.
  - Remove the barriers to entry for new component vendors. Force the vendors to compete for the business.
  - Remove the barriers to entry for new providers. Force the providers of nuclear power to compete with everybody.
  - This will improve quality, push the cost of nuclear power down to 2 to 3 cents per kWh, and make nuclear power affordable to the people who need it most. And it sets us up to replace fossil fuel with electricity just about everywhere. The goal is not just to compete with coal or gas. The goal is keep pushing nuclear costs lower and lower.
- We all need to understand that radiation rates of 1 mSv per day or less are not a health hazard in any meaningful sense. Such dose rates will rarely be exceeded outside the plant boundary even in a Fukushima sized release.

Is this so hard? None of these changes except the last requires anything more than a few scribbles with a pen. But of course what we are really talking about is a change in attitude. One of St. Paul's favorite verbs was metanoeite. It shows up some 20 times in his epistles. In the Catholic bible, the usual translation is “repent". But that is not what the word means nor what Paul was after. The word means “change your entire way of thinking" or maybe in modern parlance “change your whole mindset". If nuclear power is going to be allowed to solve the Gordian knot of electricity poverty and global warming, then we must metanoeite.

Can such a fundamental change in our thinking happen? I'd love to be proven wrong, but I don't think it can happen in the developed economies. The rich countries have plenty of reasonably cheap, reasonably reliable electricity. They are wealthy enough that they can pretend that intermittent wind and solar will cleave the Gordian knot, while maintaining a fossil fuel based dispatchable system. Politically powerful special interests have an enormous stake in the status quo. The wealthy countries are far too fat to fit through the eye of this needle.

If metanoia is to happen, it will be in an emerging economy, a country that

- understands they need a lot more cheap, dispatchable electricity — multiples more — and they need it now,
- understands that their choice is fossil fuel or nuclear,
- has the guts to assert its sovereignty, and tell the NRC and IAEA to take a hike.

Is there such a country? I do not know. But I do know that without such a country the Gordian knot will not be solved. We will be a species that could not handle its success.

Appendix A

What about Renewables?

> Please don't get me wrong. I'm not trying to be pro-nuclear. I'm just pro-arithmetic.[David MacKay, [153][page 169]]

This book is about nuclear power. Why it has failed to live up to its remarkable promise. What needs to be done to change things. But I know what some of you are thinking. Maybe Devanney's right. Maybe nuclear is much safer than we have been told (by the nuclear power establishment among others). Maybe it could be really cheap. But why take the chance he's wrong? Wind and solar can do the job and they are way cooler.

Wind is cool. I've been a sailor all my life. It may not be the fastest or most reliable way to get from A to B, but many of us are hardwired in such a way, that once you get the sails up, turn that damned thing off, and the boat heels to the wind, everybody on board just smiles. I love the wind.

Solar is cool. In the 1990's, I helped my brother, Dave, install what at the time was one of the largest residential PV plants on a small, off grid island in the Bahamas. The motivation was not global warming or pollution. Dave wanted to avoid the logistics and mess associated with bringing in diesel in 50 gallon drums and the noise of a generator.[1] Solar was a clean, quiet alternative with no moving parts! Dave, who has sailed everything from wind surfers to maxi-boats, rejected a wind turbine because he did not want to spoil the sky line. Wind is cool. Monster wind turbines, not so much.

But you cannot solve electricity poverty with technologies that only the very rich can afford. This book is not about renewables but, since you brought it up, allow me to make three points:

1. ***Wind and solar are supplemental.*** To solve electricity poverty, we must have cheap, ***dispatchable*** electricity, the cheaper the better. At an absolute minimum, the power must be cheaper than coal. In providing dispatchable power, wind and solar cannot compete with fossil fuels. The most they can do is reduce fossil fuel usage in countries that are wealthy enough to provide both a dispatchable system and a supplemental wind and solar.
2. ***There is no such thing as a zero carbon grid.*** Nuclear can come close. But a grid that relies on installing multiples of peak load wind and solar in an attempt to be reliable will not come close to zero CO2.
3. What wind and solar, properly subsidized and mandated, can do is clobber nuclear. ***This will lock in fossil fuel as the dispatchable source of electricity.***

---

[1] Dave is not a purist. The system not only included a garage full of truck batteries, but also a diesel generator.

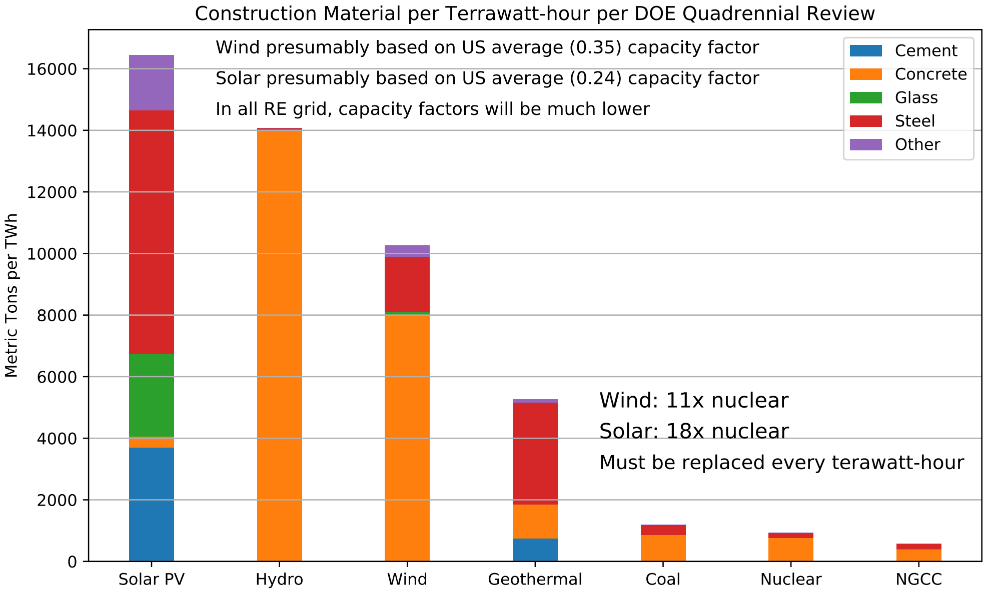


Figure A.1: DOE Estimate of Resources per Terrawatt-hour.[192][Table 10.4]

A.1 RE<C

In 2007, Google launched a project called RE<C. The goal was to show that a combination of hydro, wind and solar could provide the planet with all the power humanity needs at less than the cost of coal. The project was given essentially unlimited resources, both in money and brain power. The immediate goal was "to produce a gigawatt of renewable power more cheaply than a coal plant could."[133]

In 2011, Google shut the project down. They concluded that in their best case scenario, assuming rapid advances across the board in wind, solar, and batteries, we could only cut CO2 emissions by 55% relative to Business As Usual. We would still be putting 4 billion tons of CO2 into the air annually. CO2 in the atmosphere would continue to climb. Google concluded that the only solution was a ***dispatchable*** source of CO2-free electricity whose cost "needs to be vastly lower than that of fossil energy systems".[2] Google believes that nuclear power is inherently more costly than fossil fuel. Nuclear is not even mentioned as a possibility.

The motivated, enthusiastic, smart Google engineers ran up against two problems:

1. energy density,
2. intermittency.

---

[2] "Dispatchable" is their word, not mine. They use it four times in a short summary of the project.

Prior to the Industrial Age, the highest energy density source was falling water. Water behind a 100 m high dam has an energy density of 0.001 MJ/kg. 20 knot (10 m/s) wind has an energy density of 0.00005 MJ/kg.

Coal has an energy density of roughly 25 MJ/kg. Fossil fuels have an energy density that is 25,000 times higher than a high dam and 500,000 times higher than a strong wind. These low densities translate into massive amounts of material and land to produce the power needed to support modern life, Figure A.2.

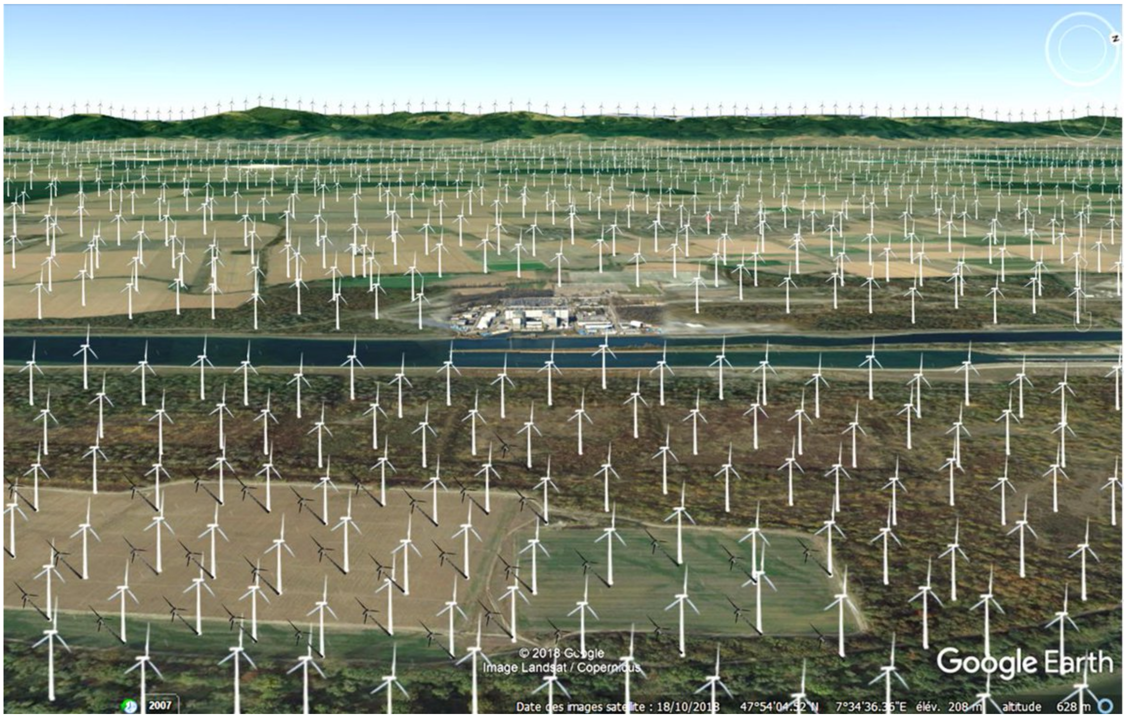


Figure A.2: The 850 3 MW nameplate wind turbines shown will produce on average about one-third the electricity of the 1.8 GW Fessenheim plant in the center of the graphic. And when the Fessenheim plant is shutdown, we will also need to replace nearly 1.8 GW's of dispatchable capacity to ensure reliability. Graphic credit: laydgeur

According to the Department of Energy, an onshore wind farm requires 11 times as much steel and concrete per terrawatt-hour as a coal plant, Figure A.1. PV solar makes wind look good. This is a continuing requirement. Every terrawatt hour these materials must be replaced. Some of the material can be recycled, although the recycling itself will require resources. If a Martian were shown Figure A.1 and asked which is the most sustainable power source, what would her answer be? Low density also translates to 100 m rotor diameters and overall turbine heights of 200 m. Local opposition to the noise, shadow flicker, and esthetics has stagnated wind expansion in many places. Wind has a socially disruptive effect. Participating landowners benefit financially from the negative effects they impose on their neighbors. This turns neighbor against neighbor.

But the real problem is intermittency. Even in a windy place such as Ireland, the actual annual wind output is about 30% the nameplate capacity. In 2018, for Europe as a whole, the average output was 22%, Figure A.3. There was only one day in the entire year, where output reached 50% of nameplate capacity. A well operated coal plant can produce 90% or more its nameplate capacity. Critically the power is dispatchable. You can call on it when you need it.

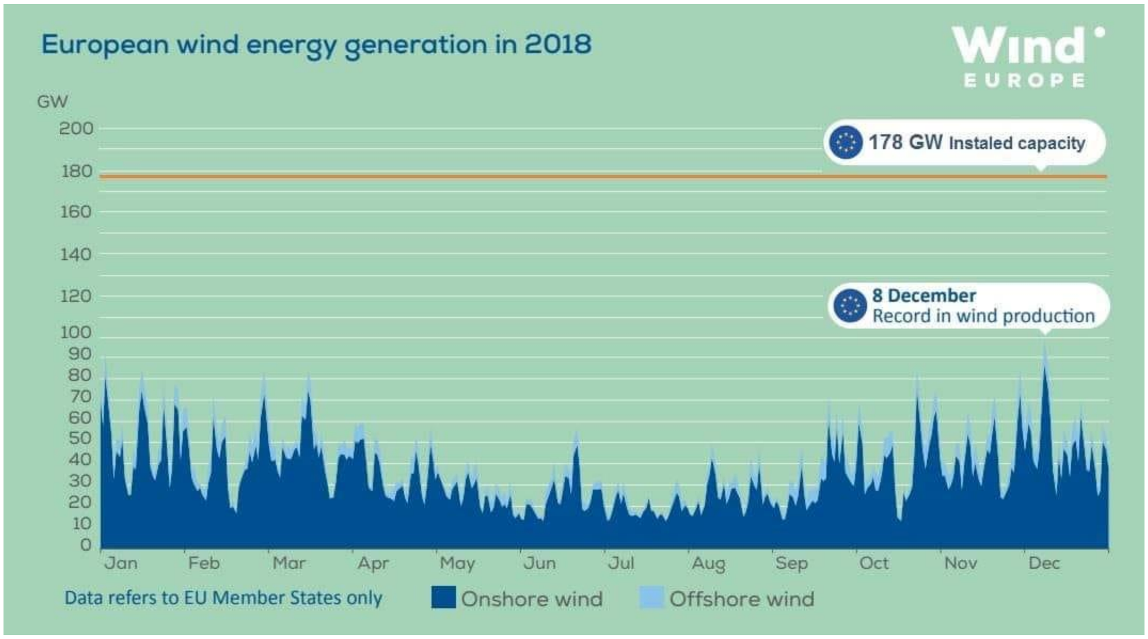


Figure A.3: European wind performance, 2018

It is not enough to say, just install four or five times as much wind. That will not get you through the multi-week long periods when the system is operating at 10% capacity. The Germans have a word for extended stretches of low wind and solar. They call them *dunkelflauten*, dark lulls. Less poetically, meteorologists know them as *anticyclonic glooms*, a combination of a large high pressure area with a temperature inversion that traps all the moisture at the bottom of the inversion, forming a low cloud layer. Solar heating of the top of the clouds just makes thing worse. Dunkelflauten usually happen in cold weather. They are characterized by low wind shear. Higher hub height gains you very little.

The UK is a windy place and has installed a great deal of offshore wind. In late winter 2021, the UK experienced a dunkelflaute, Figure A.4. Between February 26 and March 8, the UK wind farms averaged 11% of nameplate capacity for 11 days.[75] On March 3rd, the total output from 24.4 GW_i's installed was 0.88 GW. As might be expected, solar is pretty much useless in the UK in winter. On March 3rd, solar contributed 0.36 GW from 13.5 GW_i of nameplate capacity. Daily averages obscure intra-day fluctuations. For 14 hours on the 2nd and 3rd, wind and solar together averaged 0.69 GW, a combined capacity factor of 1.8%.

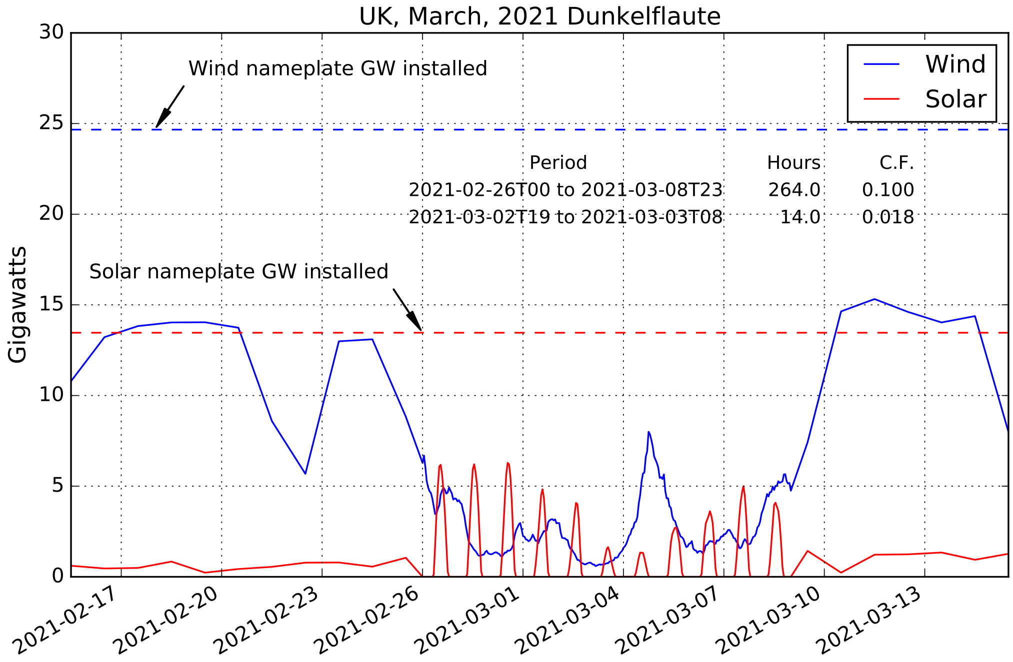


Figure A.4: UK Wind/Solar Output, 2021-02-15 to 2021-03-15. Hourly average, Feb 26 to Mar 8. Otherwise, daily average.

In order to have truly reliable electricity, the grid must have access to enough dispatchable power to meet its peak load.[3] In most parts of the planet, that dispatchable power has to be fossil fuel. Wind/solar advocates call this “back up". This is misleading. It is not back up when 50% or more of the power comes from gas or coal or hydro. Wind and solar are *supplemental* sources.

---

[3] And if you are going to add W/S to the grid, that capacity had better be able to ramp up quickly. A study of 26 OECD countries over the period 1990-2013 showed a nearly one-to-one increase in W/S capacity and fast reacting fossil (aka gas turbine) capacity.[265]

There are situations where these supplemental sources can make good sense. Maui is probably a case. Strong, relatively dependable winds and the alternative is diesel with a fuel cost of 20 cents/kWh. Wind can make economic sense in such places; but what you must do is compare the fully built up cost of the intermittent source with the fuel cost of the dispatchable source, because the only thing the grid saves is the fuel that would have been burned if the W/S capacity were not there.[4]

Germany is not Maui. The reason why Germany's electricity costs are so high, Figure A.5, is that they are bearing the cost of maintaining two systems: the intermittent, and the dispatchable.[5] Perhaps Denmark and Germany can afford a doubling in price to obtain about 40% of their electricity from wind and solar; but the developing world (and the planet) cannot.

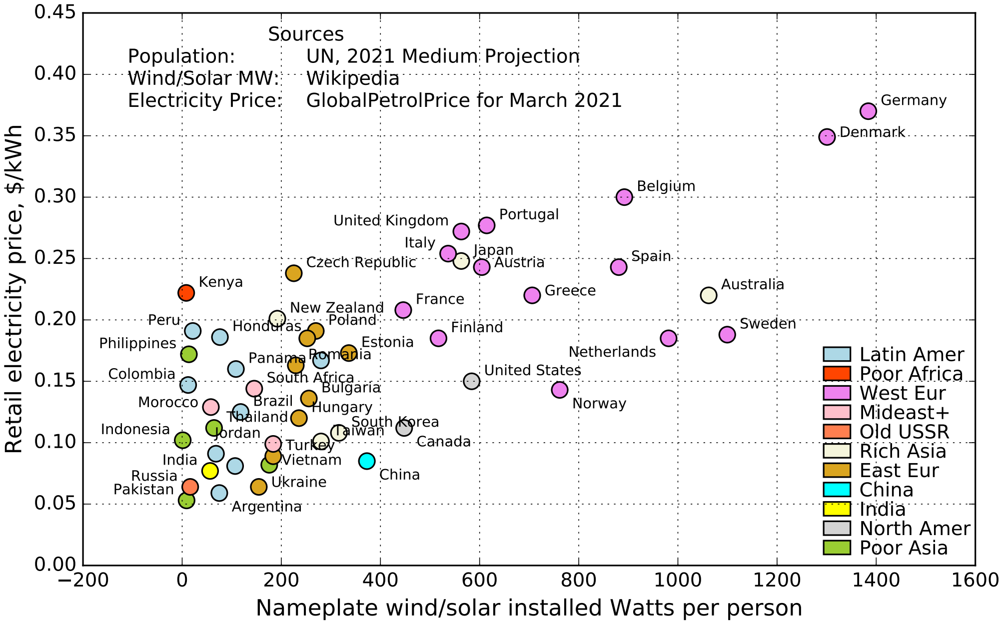


Figure A.5: Retail power price versus W/S capacity per capita. For nations which subsidize wind/solar with taxpayer money, this graph can be misleading.

---

[4] It's a little more complicated than this. Wind and solar output can fluctuate rapidly. The resulting ramping up and down of the dispatchable power imposes extra costs on the grid. It creates extra pollution such as NOx which is both a smog problem and a strong GHG. And it is usually necessary to increase the amount of spinning reserve. In practice, only a fraction of the fuel savings is achievable.

[5] Seven West European nations have already installed more than their average consumption in nameplate wind/solar capacity. Denmark and Germany have installed nearly double their average consumption.

A.2 The Jacobson Roadmap

Another situation in which a supplemental source can make economic sense is in places which are blessed with both lots of wind or sun and lots of hydro. Hydroelectric plants are usually designed to handle periods in which the river flow is high. During low flow periods, the available capacity is less than the nameplate capacity. Wind and solar can take some of the pressure off the hydro capacity allowing the reservoirs to build up and increase their effective dispatchable capacity. The Columbia River is a place where this combination can work. But few places meet this criteria and even there the impact is marginal.

In a 2015 paper, Jacobson made the astounding claim that US hydro capacity could be increased by a factor of 16 in this manner.[119] Figure A.6 shows a portion of Jacobson's simulation of his all wind/water/solar US grid. The peak demand on hydro is 1300 GW's, and we need that capacity for 12 hours. And we need about 800 GW's 12 hours later for another 12 hours. And so on. Currently, the US peak hydro capacity is 79 GW.

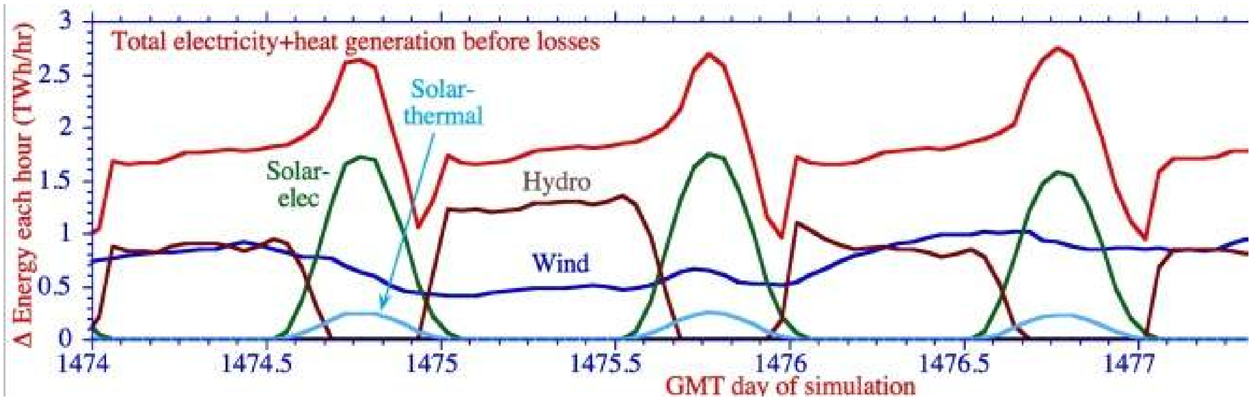


Figure A.6: Simulation of Jacobson grid, reference [45][Figure 1].

Jacobson implied that the "instantaneous" discharge capacity is far higher than the nameplate capacity. But "instantaneous" in this context is something like 12 hours. The single biggest source of hydroelectric power in the US is the Columbia River. I live on the Columbia a few miles upstream from the Bonneville Dam. The original dam finished in 1938 has a nameplate capacity of 518 MW with an overload capacity of 574 MW. The original dam was undersized for the river flow. In 1982 a "new" dam was added by extending the original dam all the way across the river. Its nameplate capacity is 532 MW; overload is 612 MW.

The current overload capacity of Bonneville is 1130 MW. When Bonneville is going all out in late summer, the river falls like a rock, at least a meter per day. And as the river drops, Bonneville puts out less power. The only way you can materially increase the 12 hour discharge capacity is to not only install a whole new set of turbines, you must build a higher dam.[6]

You also need to inundate the railroads on either side of the river, an Interstate, and a whole series of river towns. The original dams took the water level up to something like the 50 year flood level. People had responded to the floods by not building a lot of stuff including the railroads below those levels. Yet there were still severe dislocations when the current dams were built. To go higher would start a war. And that only gets you through one day.

The Columbia is pretty much maxed out. And the same thing is true of most first world hydro resources.

A.3 The Texas Blackouts

The grid operators know that wind/solar cannot be relied upon. Going into the February, 2021 cold wave, ERCOT, the operator of the Texas grid was counting on only 2.7 GW from the 33.1 GW_i of wind capacity installed in the state, and zero from the states 4.3 GW_i of solar. They actually got 0.6 GW of wind in the worst hour, so wind only under-performed expectations by about two gigawatts. Solar performed as expected.

The Texas blackouts also showed that natural gas is not a truly reliable source. Gas is expensive to store, so a natural gas grid depends on just-in-time deliveries of the fuel. In the Texas case, the production and transmission facilities were not properly winterized. Water in the gas froze, blocking valves, dropping pressure, and cascading into a loss of 22 GW's of gas, just when it was needed most. In contrast, coal and oil plants normally have about a month of fuel on site. Nuclear plants have over a year of fuel already in the reactor.

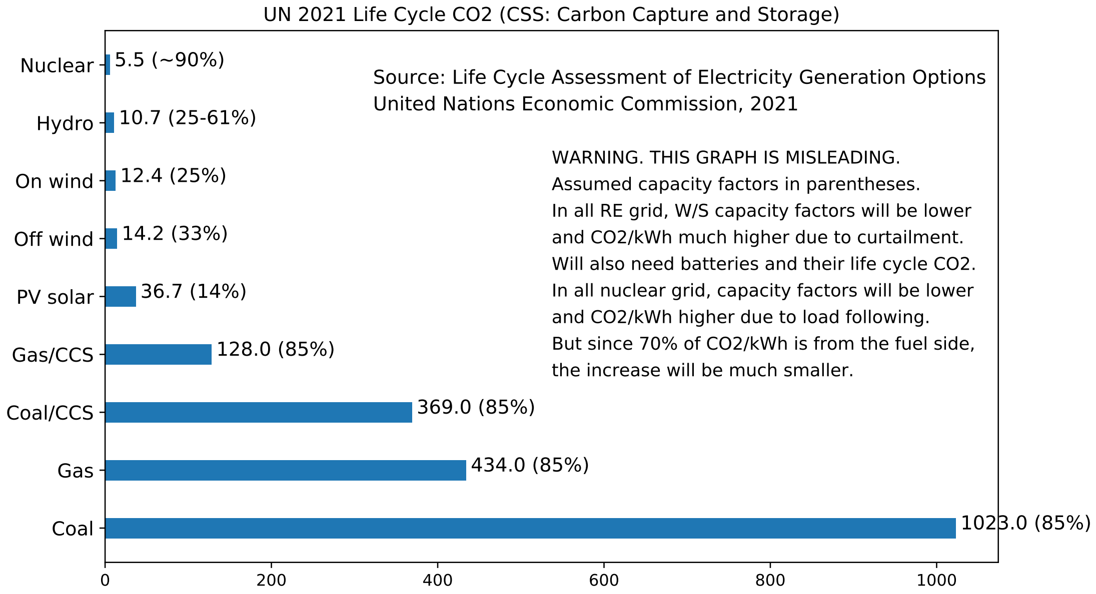
In the Texas case, the NRC regulated nuclear plants were not properly winterized either. A frozen sensor took one of the four Texas plants off line for 3 days at just the wrong time.[7] ERCOT lost 1.3 GW of nuclear that it was counting on. During the worst period, W/S had a capacity factor of 1.6%. Nuclear had a capacity factor of 74%.

The ERCOT grid, among others, needs to be made more reliable. But that means improving the dispatchable sources. More wind and solar won't help.

---

[6] This will not get you more vertical. Except for one short stretch, the Columbia is fully dammed. Increasing the height of the Bonneville Dam decreases the effective height of the next dam upriver at The Dalles, and so on.

[7] If the plant had been regulated like a coal plant, it could have been back on line in a matter of hours.



Source: Life Cycle Assessment of Electricity Generation Options
United Nations Economic Commission, 2021

WARNING. THIS GRAPH IS MISLEADING.
Assumed capacity factors in parentheses.
In all RE grid, W/S capacity factors will be lower
and CO2/kWh much higher due to curtailment.
Will also need batteries and their life cycle CO2.
In all nuclear grid, capacity factors will be lower
and CO2/kWh higher due to load following.
But since 70% of CO2/kWh is from the fuel side,
the increase will be much smaller.

Figure A.7: UN Life Cycle CO2 intensity, reference [254]

A.4 The Non-existent Zero Carbon Grid

The standard W/S solution to intermittency is install multiples of the peak demand and enough batteries to try and bridge the dunkelflauten, the lulls in wind and sun. Not only will this require a destructive amount of the planet's resources; but we simply can't get to zero CO2 by this route, even if the planet could afford it. We can't even get very close to zero.

Consider the paper by Sepulveda et al.[230] These M.I.T. authors argue that it is possible to fully decarbonize the New England power grid with a combination of wind, solar, and batteries. To do this they make a series of assumptions which strike me as unrealistic and very favorable to wind/solar. For example, they designed their system to handle the worst lull in wind and sun that was actually observed in a single year, 2015. This is far from the worst possible lull.

But by far the most basic problem with the M.I.T. paper's results is that ***the CO2 emitted during mining, manufacturing, erection, and disposal is ignored.*** Figure A.7 shows the UN Economic Commission estimates for life cycle CO2 intensity.[254] For PV solar it is 37; for wind, 12-14; for nuclear, 5.5 gCO2/kWh. As we shall see, in an all-RE grid, these numbers are misleadingly low for W/S.

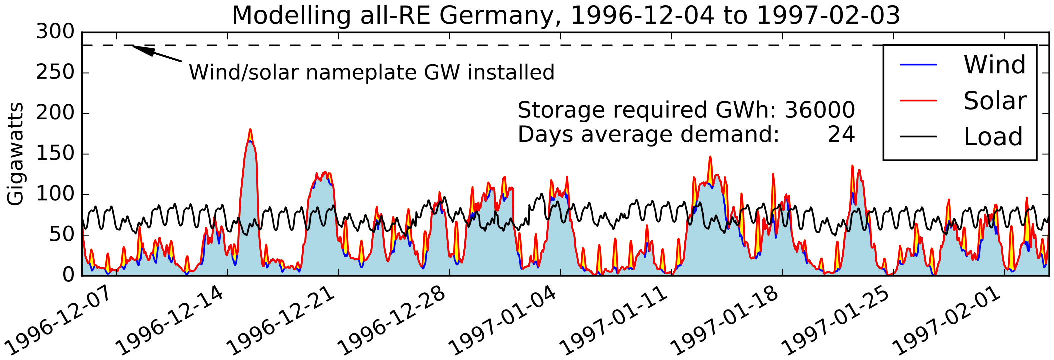


Figure A.8: German Wind/Solar Output, December 1996, January 1997

According to the M.I.T. paper, solar is cheaper than wind; so solar dominates their ‘zero’ carbon solutions. However, despite all the favorable assumptions, to get to ‘zero’ carbon in these scenarios for the New England grid requires about 5 times as much solar capacity as the ***peak*** load. They also need about 1 times as much wind capacity as the peak load. Using the UNECE numbers, life cycle this grid will produce 48 g/CO2 per kWh.[8]

They also need 350 GWh of lithium-ion battery storage which will add 60 million tons of CO2 to the mix.[221][p 24] This 3 million tons of batteries, 26 million Tesla Powerwalls costing $6500 each before installation, buys them about 14 hours of average load. The basic problem with batteries is that to first order doubling the storage time doubles the cost and doubles the life cycle CO2. At 14 hours, we are already at 170 billion dollars before installation and maintenance. In most markets a Powerwall can store less than a dollar’s worth of electricity, and you can expect to lose about 15% of that power round trip. Assuming the batteries last ten years, this adds 27 g/CO2 per kWh to the emissions, for a total of 75 gCO2/kWh.

14 hours of batteries won’t give us a reliable grid. A German study based on the actual distribution of the wind turbines in Germany indicated that Germany can expected a 5 day period in which the wind capacity factor averages less than 10% once a year.[196][Table 1] If we use the 5 day requirement for New England, then we are talking 1.5 trillion dollars worth of batteries whose life cycle CO2 intensity is 231 g/kWh.

But that won’t be enough. Ruhnau and Qvist studied 35 years of German wind/solar output, looking for extended periods of low wind/solar output.[224] Figure A.8 shows the worst interval they ran into. In December, 1996 and January, 1997, there was a 61 day period of low output, multiple dunkelflauten separated by brief periods of decent wind/solar output. For their optimized all renewable grid, they concluded they would need storage capacity equal to 24 days of average German demand.

---

[8] The actual capacity factor in all RE grid, will be much lower than the UNECE numbers due to curtailment. The combined actual capacity factor for the Sepulveda grid is just under 0.1. Adjusting for the differences in capacity factor $(5/6) \cdot (0.14/0.1) \cdot 37 + (1/6) \cdot (0.25/0.1) \cdot 12 = 48$.

A portion of the CO2 intensity of these low carbon technologies is due to the electricity required in mining, manufacturing, etc. The UNECE and Swedish battery numbers are based on the current power generation mix. In a 'zero' carbon grid, their CO2 intensity will be substantially less. Fthenakis et al estimate that PV CO2 intensity could be halved if all the electricity required to produce PV cells came from PV solar.[90][Figure 6]. Using the UNECE numbers, this drops PV solar's intensity to 18. Romare et al estimate that Li-ion batteries CO2 intensity could drop to 40% the current number in a very low carbon intensity (Sweden) grid.[221][Table 17][9]

With these adjustments, the CO2 intensity for the paper's 'zero' carbon New England grid is roughly 37 gCO2 per kWh. 118 g/kWh for a system capable of handling a 5 day lull. This is an awfully long way from zero.[10] If we are really trying to get close to zero, we need to use nuclear. Nuclear has an IPCC life cycle CO2 intensity of 5.5 g/kWh, perhaps half this in an almost all nuclear grid.

And we don't need multiples of the peak demand.

A zero CO2 electricity grid is an impossibility. A grid which attempts to be reliable by installing an enormous amount of almost always surplus wind and solar capacity will not only be a gargantuan drain on the planet's resources, ***it will produce much more CO2 than a nuclear based grid.***

An all nuclear grid would reduce nuclear's capacity factor and push the CO2/kWh up somewhat depending on the load profile. But 70% of the nuclear carbon intensity is for fuel manufacture. This portion of the carbon intensity does not depend on capacity factor. So the effect is much milder.

I personally am not a fan of an all nuclear grid. I think nuclear should be combined with some hydro if available, and with some fossil fuel peaking capacity if not. The latter would only handle demand peaks and unplanned nuclear outages. If and only if we have truly cheap nuclear electricity, then we can have very low CO2 synfuel, in which case fossil fuel peaking become synfuel peaking. We can have truly cheap nuclear electricity if and only if we have a regulatory revolution.

---

[9] These numbers assume low carbon capacity is unconstrained. Otherwise we are just switching low carbon power from one market to another. In the real world, low carbon sources will alternate between at momentary capacity and not.

[10] In fact, things are worse. If a 'zero' carbon W/S grid is really a 118 gCO2/kWh grid, then the electricity is not as clean as we have assumed. This leads to a multiplier.

The only thing worse is biofuels. I don't intend to waste any time on this BigAg scam. Suffice it to say that the target of the US Renewable Fuel Standard was a modest 20% reduction in greenhouse gas relative to gasoline. A recent University of Wisconsin study of the actual results showed a likely increase in $CO2_{eq}$/kWh relative to gasoline (417 versus 335), while increasing corn prices by 31%, which pushed up soy bean and wheat prices about 20%.[139] The study was limited to the on-site effects of increased cropland, and more intensive fertilization, most importantly nitrogen. Nitrous oxide is a powerful greenhouse gas, 298 times stronger than CO2. A classic case of special interests using global warming to enrich themselves by making the poor poorer.

A.5 Green Hydrogen

In Chapter 2, we reached the conclusion that to properly support human kind on a fully decarbonized planet would require something like 25 terrawatts of electricity. Table A.1 shows how silly it is to think about bridging these lulls with batteries. Using lithium ion technology, we would need all the known reserves of lithium and nickel to store that much power for about a half hour.

Table A.1: Lithium Battery Requirements

	Kilograms per kWh	Tons to store 25 TW for 1 hour	Planet production tons/year	Planet Reserves tons	Hours stored using all current reserves
Lithium	0.171	43,000,000	77,000	17,000,000	0.40
Nickel	0.684	171,000,000	2,900,000	94,000,000	0.55
Graphite	0.635	158,000,000	1,100,000	300,000,000	1.90

While batteries are still being pushed as a viable solution in places like California and Hawaii, the all-RE crowd has finally started to recognize this will not work. Consider the much touted Princeton study, which claims to have found another route to an all renewable grid.[140] In this work, the specious Jacobson dependence on hydro is gone, as in the Sepulveda-style dependence on batteries. Batteries are limited to 5-7 hours diurnal balancing which is still an impossible amount of batteries. See Table A.1.

The new solution to intermittency is hydrogen, produced by using wind and solar electricity to separate water into hydrogen and oxygen by electrolysis.[11] The hydrogen is stored, preferably in underground saltdomes, and then burned to generate electricity during the lulls in wind and sunshine.[12]

We can study this pathway by building on the ground breaking Ruhnau and Qvist study.[224]. These authors based their work on 35 years of German wind/solar data, 1982-2016. They built a model which produces the minimum cost combination of onshore wind, offshore wind, hydrogen storage, hydrogen electrolysis, and hydrogen powered electricity generation which meets the hourly German demand for every hour in that 35 year period. This Section uses a similar model. The model and the costing assumptions are described in reference [69] The model assumes that the cost of wind and solar does not increase as the installed wind and solar capacity increases. For area intensive and location sensitive technologies like wind and solar, this assumption is incorrectly optimistic, quite possibly misleadingly so.

---

[11] The Princeton study also proposes to use a staggering amount of Carbon Capture and Storage (CCS). To sequester 15% of current US GHG emissions, they require 65,000 miles of 1500 psi plus pipelines and a volume flow that is larger than the volume flow of all current oil US oil pipelines.[39] Demonstration projects to data have not been encouraging. And there is no guarantee that the CO2 will stay where they try to put it. Even if it does, CCS is not a truly low CO2 solution, as Figure A.7 makes clear.

[12] Burning hydrogen is not as simple as it sounds. The high flame speed leads to flashback and the high temperature to NOx, which is a greenhouse gas 310 times stronger than CO2. We optimistically assume that ways are found to burn H2 safely with no NOx.

Table A.2 shows the Base Case results for Germany.

Table A.2: H2 in Salt Caverns, Base Case, Germany, 1989 to 2004.

```
Jack 5 data, bonus, st=sp no onshore limit, 1-way transmission cost                          2022-01-01 20:41:30
Start = 1989-01-01T00              End = 2004-12-31T23       Hours=140160      Compute seconds = 11852.8
PV grid cost(BUSD) = 1441.1        LCOE/MWh = 164.85         Interest = 0.060           lp_jack8_140160_1
Electricity provided(TWh) = 8742.8 fraction= 0.721                               Average demand GW = 62.4
Electricity curtailed TWh = 3376.8 fraction= 0.279                                  Peak demand GW = 101.2
H2 storage cap(mt) = 1,442,958                                       Days ave demand fill/avail = 50.2/19.3
CO2eq tons emitted = 223,589,892                                                          gCO2/kWh =25.57
H2 storage vol Mm3 = 178.4         Pressure(MPa) = 13.80     Cushion pct = 0.23               Temp(C)= 37.8
HVDC buried km =1000               HVDC MUSD/km=4.0            HVDC $/kW=200           HVDC $(BUSD)=22.9

               Nameplate  Capac.  gCO2/   CAPEX     OPEX   VAREX  DECEX  Life   Effic   PV Cost
                Cap. MW   Factor   kWh    $/kW   $/kW-y   $/kWh   $/kW  Year    iency    B USD
PV Solar         115974    0.082   55.2    1040     15.2    0.00      0  25.0   1.000    179.3
Onshore          316257    0.181   15.6    1436     43.0    0.00      0  25.0   1.000    786.0
Offshore              0    0.000    0.0    4070    124.0    0.00      0  25.0   1.000      0.0
H2 to Power       80066    0.098    1.7    1084     14.1    0.00      0  25.0   0.600    126.7
Power to H2       67692    0.303    7.8    1250     20.0    0.00      0  25.0   0.640    127.6
               Nameplate  Capac.  gCO2/   CAPEX     OPEX   VAREX  DECEX  Life    Loss   PV Cost
               Cap. TWht  Factor   kWh   $/kWh   $/kWhy   $/kWh  $/kWh  Year   %/day    B USD
H2 saltdome       48.10    0.176    0.0    3.30      0.0    0.00      0  25.0   0.000    198.7
concrete mt=84,048,146   steel mt=47,406,749     copper mt=976,242  silver mt=2,319        ree mt=4,427
Area km2/at MW/km2: PV = 3741/31.0               Onwind = 63251/5.0                   Offwind = 0/10.0
```

Table A.2 claims it is theoretically possible to supply present German electricity demand with a combination of wind/solar and hydrogen storage. Germany is blessed with a large number of salt domes, almost ideally located in the northwest. The storage capacity required, about 19 days worth of average electricity demand, can easily be accommodated in these domes.

However to meet the demand will require installing 116,000 MW_i of solar and 316,000 MW_i of onshore wind capacity. It is conceivable that Germany could install this much solar. The current installed solar nameplate capacity is 53,600 MW_i, which is growing at 4000 to 5000 MW_i per year. Solar takes up a great deal of land; but it is not as intrusive as onshore wind. If the Germans spend enough money, eat up an enormous amount of the planet's resources, devote 1 to 2% of their land to solar panels, and drive the solar capacity factor down to 8%, they could install another 62,000 MW_i of solar panels.

The maximum reasonable land density of an onshore wind farm is about 5 MW_i/km^2. Pushing above that, results in sharply decreasing capacity factors, Figure A.9. 316,000 MW_i of onshore wind will spread across at least 63,000 km^2 of land. The total land area of Germany is 349,223 km^2. 20% of German land would be occupied by wind farms. Some are OK with this. Winfried Kretschmann, the first Green president of the Bundesrat, proclaimed "Es fuhrt kein Weg daran vorbei, die Landschaft auf diese Weise zu verschandeln".[234][p-239] [There is no way past it, but to ruin the landscape in this way.] A strange way for a Green politician to talk.

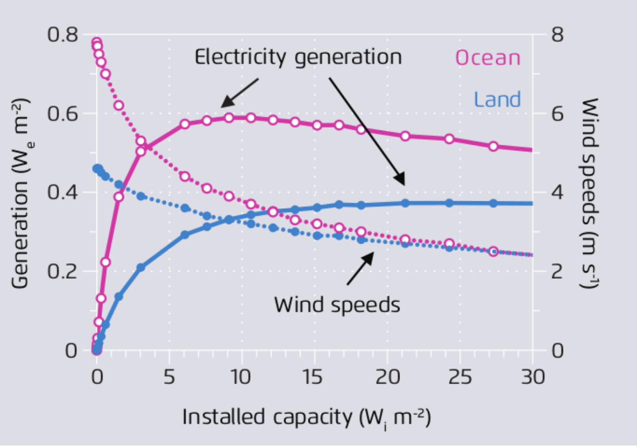


Figure A.9: Wind Output versus Land Density, reference [167]

Some disagree. The current German installed onshore capacity is 55,000 MW$_i$. In 2020, 1,400 MW$_i$ of new onshore wind was brought on line. In the first half of 2021, 971 MW$_i$ were installed and 140 MW$_i$ decommissioned. The best locations have been taken, and local opposition to more turbines has become suffocating. There are some 900 active citizen initiatives against wind expansion. Motives ranges from bird mortality to shadow flicker to loss in property values. Mostly people just hate what they do to the landscape, Figure A.10. Bavaria has enacted a law requiring turbines to be at least ten times their height away from a residence. Wind proponents claim this reduces the land available by half. Installing five times the current capacity is a non-starter.

Figure A.10: Wind Farms and People

Figure A.11: Offshore Wind Bases. Small is beautiful.

The Germans will have to go offshore. Offshore wind is the antithesis of soft energy, Figure A.11. The model does not like offshore wind. It is simply too expensive. This is reflected in current reality. At the end of 2021, Germany had just under 8000 MW_i of offshore wind. In 2020, only 219 MW_i of new offshore wind came on line. In 2021, that number was ***zero***. But we can force the model to use offshore wind by limiting the onshore capacity available to it. In Table A.3, I've limited the onshore capacity to 100 GW, roughly double current. Even this expansion will require draconian measures or very expensive compensation.[13]

With this limit on onshore wind, the program installs 84 GW of offshore wind, ten times current capacity. ***Germany cannot produce this much offshore wind in its Effective Economic Zone, at least not at the costs and the capacity factors the model assumes.*** We are talking roughly 300 TWh/year from offshore. Agora Energiewende, an outfit fully committed to an all-RE German grid, has done a study of the wind potential of the German Bight in the North Sea.[67] They concluded, Figure A.12, that attempting to produce this much wind from this area would reduce the standard capacity factors by about a third.

---

[13] Such compensation is not a transfer payment. Properly implemented, it internalizes the social cost of this externality.

Table A.3: H2 in saltdomes, Germany, 1989 to 2004, Onshore Wind limited to 100 GW.

Jack 5 data, bonus, st=sp onshore limit, 1-way transmission cost 2022-01-02 13:04:07
Start = 1989-01-01T00 End = 2004-12-31T23 Hours=140160 Compute seconds = 17733.3
PV grid cost(BUSD) = 1568.9 LCOE/MWh = 179.46 Interest = 0.060 lp_jack8_140160_100_1
Electricity provided(TWh) = 8742.8 fraction= 0.849 Average demand GW = 62.4
Electricity curtailed TWh = 1555.4 fraction= 0.151 Peak demand GW = 101.2
H2 storage cap(mt) = 1,718,603 Days ave demand fill/avail = 59.8/23.0
CO2eq tons emitted = 213,568,610 gCO2/kWh =24.43
H2 storage vol Mm3 = 212.5 Pressure(MPa) = 13.80 Cushion pct = 0.23 Temp(C)= 37.8
HVDC buried km =1000 HVDC MUSD/km=4.0 HVDC $/kW=200 HVDC $(BUSD)=21.9

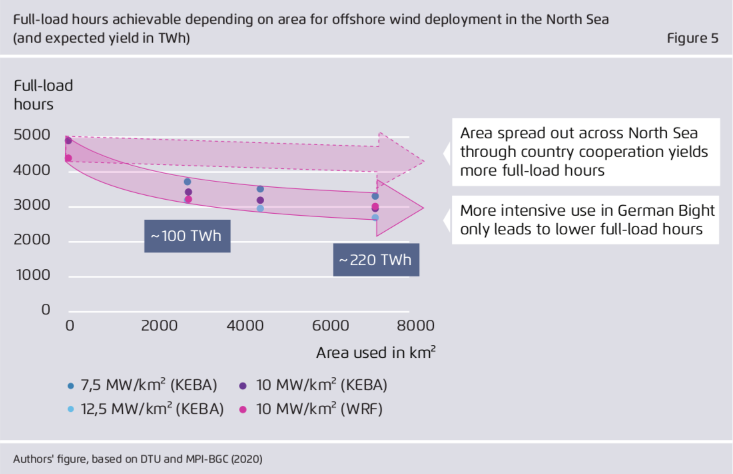
	Nameplate Cap. MW	Capac. Factor	gCO2/ kWh	CAPEX $/kW	OPEX $/kW-y	VAREX $/kWh	DECEX $/kW	Life Year	Effic iency	PV Cost B USD
PV Solar	140072	0.097	46.9	1040	15.2	0.00	0	25.0	1.000	216.5
Onshore	100000	0.213	13.2	1436	43.0	0.00	0	25.0	1.000	248.5
Offshore	84224	0.399	13.1	4070	124.0	0.00	0	25.0	1.000	596.1
H2 to Power	81379	0.104	1.6	1084	14.1	0.00	0	25.0	0.600	128.8
Power to H2	63917	0.346	6.8	1250	20.0	0.00	0	25.0	0.640	120.5
	Nameplate Cap. TWht	Capac. Factor	gCO2/ kWh	CAPEX $/kWh	OPEX $/kWhy	VAREX $/kWh	DECEX $/kWh	Life Year	Loss %/day	PV Cost B USD
H2 saltdome	57.29	0.235	0.0	3.30	0.0	0.00	0	25.0	0.000	236.6

concrete mt=67,636,707 steel mt=34,644,432 copper mt=902,244 silver mt=2,801 ree mt=2,579
Area km2/at MW/km2: PV = 4518/31.0 Onwind = 20000/5.0 Offwind = 8422/10.0

The problem is not the individual turbine wakes, which are allowed for in spacing the turbines; but the area-wide extraction of energy. The horizontal flux of wind energy is of the order of 500 W/m2. Horizontal energy extracted by a large wind farm needs to be replaced by the vertical inflow of energy from higher in the atmosphere, Figure A.13. Unfortunately, this flux is around 2 W/m2.

The Agora authors conclude the only solution is inter-country *cooperation*. But assuming such cooperation takes place, much of the "German" offshore electricity will have to be produced in deeper water and farther from Germany than the model assumes. And if the other countries make similar demands on the resource, the capacity factors will suffer. In short, our model is unrealistically optimistic on the offshore wind front.

With the limit on onshore wind, the model also uses more H2 storage capacity. In the Base case, the model came up with enough usable electricity storage, to meet 19 days of average demand. With the limit on onshore wind, this number go to 23 days. In both Tables A.2 and A.3, the hydrogen discharge capacity is 20% more than the average demand.

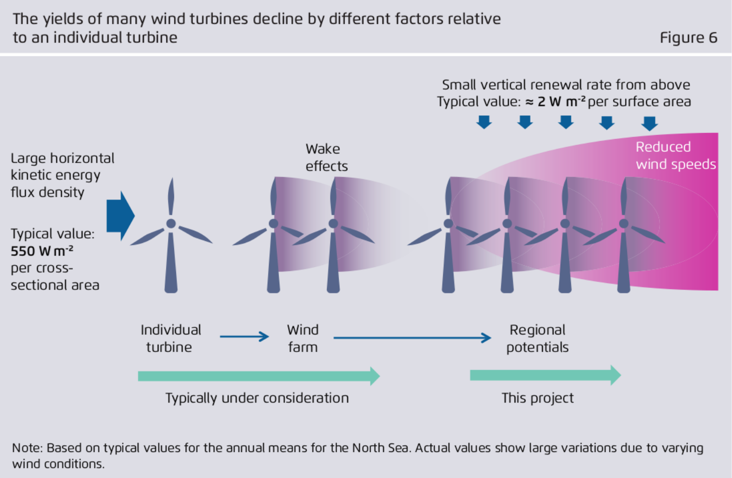


Full-load hours achievable depending on area for offshore wind deployment in the North Sea (and expected yield in TWh)

Figure 5

Authors' figure, based on DTU and MPI-BGC (2020)

Figure A.12: Loss in capacity factor in the German Bight



The yields of many wind turbines decline by different factors relative to an individual turbine

Figure 6

Note: Based on typical values for the annual means for the North Sea. Actual values show large variations due to varying wind conditions.

Figure A.13: Horizontal and vertical wind flux

Either way, Germany is supporting two systems:

1. an intermittent grid,
2. a quasi-dispatchable grid.[14]

This shows up in the cost of electricity. Despite the model's ignorance of the increase in cost and decrease in productivity with increasing installed capacity, the levelized cost is 16.5 cents per kWh without the limit on onshore power With the limit, the LCOE rises to 18 cents/kWh. These are wholesale numbers before distribution to the consumers. And they are based on the misleading assumption that there will be no increase in cost nor loss in productivity with increasing installed capacity. In an ALARA-free world, nuclear could supply wholesale electricity at 4 cents/kWh or less. And that number is scalable planet-wide.

The drain on the planet's resources will be immense. Figure A.1 hints at how profligate wind and solar are. Presumably the DOE carbon intensity numbers are based on the current USA capacity factors. In an all-RE grid these capacity factors will be much lower. In the German case, with salt domes, the solar capacity factor is about 0.09 and onshore wind is around 0.20. At these capacity factors, solar is 48 times as resource intensive as nuclear and wind is 19 times. And that does not include the hydrogen storage system nor the electrolysers.

The German solution does not scale planet wide. For areas which are not blessed with saltdomes in the right location, the costs rise to 20 cents/kWh and more. Such costs will be prohibitively expensive for much of humanity. They will either remain electricity impoverished or find a different solution.

Even with ample salt domes, an all W/S grid will have a CO2 intensity in excess of 25 $gCO2_{eq}$/kWh. But if the problem is CO2, we need to provide not only current electricity demand in a very low CO2 manner, but also generate enough power to electrify most transportation markets, most industrial markets, and most heating markets. And we need to provide synfuel to those markets for which direct electrification is impossibly expensive. If we are really serious about CO2, we need to at least triple present wealthy nation electricity generation rates. In the German case, just to provide current electricity demand we had to push the wind and solar resources very hard. Another factor of three isn't going to happen.

Green hydrogen may be far superior to batteries.[15] But it cannot solve electricity poverty nor planet heating.

---

[14] In the real world, it is worse. On top of the 123 GW of installed wind and solar capacity, Germany has 79 GW of fossil, 14 GW of hydro, 8 GW of nuclear, and 10 GW of biomass. The total 112 GW of dispatchable capacity is 10% higher than the peak hourly load in the 16 years and 80% higher than the average load.

[15] Batteries are so expensive that the least wasteful solution is to avoid them, even if it means installing staggering amounts of wind and solar, When the model was run for Germany using batteries for storage, it installed nameplate wind/solar capacity 14 times the peak hourly demand. This pushed the solar capacity factor down to 0.04 and onshore wind to 0.08. At these capacity factors, solar is 108 and wind 48 times as resource intensive as nuclear. The LCOE's were in the 50 cents/kWh range, and the CO2 intensities over 95 gCO2/kWh.

A.6 Nuclear and Wind/Solar

Wind and solar can solve neither electricity poverty nor global warming. ***But what wind and solar, sufficiently subsidized and mandated, can do is clobber nuclear.*** Wind and solar are high capital cost, low marginal cost sources. In fact, the marginal cost of wind and solar is effectively zero. Once in place they can provide unreliable power at zero marginal cost. Nuclear is also a high capital cost, low marginal cost source; but nuclear cannot compete with wind and solar on marginal cost. And nuclear cannot survive low capacity factors. If wind and solar can force the nuclear capacity factor down, then nuclear loses out to low capital cost/high marginal cost fossil fuel as the dispatchable power source.[16] If we put enough wind and solar in place, nuclear is dead and fossil fuel lives. The anti-nukes know this well. They brag about "death by capacity factor". Fossil fuel interests know this very well too.[17]

They just let their pawns in the anti-nuke movements do the public bragging.

Conversely, since nuclear is a low marginal cost, dispatchable source — nuclear's fuel cost is less than 0.5 cents/kWh — wind/solar adds almost no value to a grid in which the dispatchable source is nuclear. Once you've paid for the nuclear capacity, buying wind/solar capacity is a waste. So you don't. In a rational world, the optimal system will be almost all hydro and nuclear with a bit of fossil for peaking and backup.[18] Intermittents would be relegated to a few niche, globally unimportant markets.

Despite the fact that nuclear and W/S are in mortal combat, the nuclear establishment and most pro-nukes go to great lengths to avoid saying anything negative about wind or solar. This careful politeness is motivated by two schools of thought.

The MIT School These people think nuclear is inherently very expensive and there is nothing we can do (or should do) about it. Most of these people believe the Gold Standard is necessary and beneficial. So the only place where nuclear can compete is when the penetration of wind/solar pushes the cost of electricity up to societal crippling levels. No point in bad mouthing wind/solar under these circumstances. I call this the MIT school.

This is the counsel of despair and it won't work.

1. If deep W/S penetration forces the price of electricity up to say 25 cents/kWh, then nuclear can afford to cost 25 cents/kWh, and ALARA will inexorably push the cost of nuclear up

---

[16] According to DOE, Figure A.1, a natural gas combined cycle (NGCC) plant requires 60% as much material as a nuclear plant. A simple cycle peaker requires 70% as much as a NGCC but burns close to twice as much gas. Intermittent wind/solar not only favors gas over nuclear but CO2 intensive gas over less CO2 intensive.

[17] A particularly pernicious feature of wind and especially solar in deregulated markets is cannibalization. Intermittants often peak in periods of low diurnal demand. This pushes rates to near-zero or if production is subsidized to negative numbers in these hours. More intermittants only exacerbates matters, But the high demand, high rate hours are left to the fossil fuel "back up". They are perfectly happy with the resulting revenues despite the low capacity factors.

[18] A secondary reason for driving the cost of nuclear down and down is that this will allow nuclear to accept a lower capacity factor and an ever increasing role in load following.

to that level. Lather, rinse, and repeat.

2. More to the point, a nearly all renewable grid would ravish the planet and make electricity too expensive for the people who need it the most. The emerging nations will realize this and produce their electricity with coal.

The Must-Be-Cool School These people see a bright future for nuclear, but only if we can turn the public attitude toward nuclear around. To do this we must convince everybody we are not a bunch of stodgy, corporatist, conservative, climate deniers stuck in the 1960's. By saying nice things about wind/solar, we show we are open minded, climate concerned, progressive types. Renewables supporters will now listen to our arguments. And even if this rarely works, what's the harm in being nice?

The problem is, when people hear a nuclear supporter say wind/solar is a good thing or worse conceding that wind/solar is cheap — equating intermittent electricity with dispatchable electricity, two entirely different commodities — they reach the reasonable conclusion: even these guys think wind/solar can do most if not all the job; so why should I make myself uncomfortable and rethink everything I've been told about nuclear?

The need for tough love The only hope is to make people uncomfortable. Describe the problem in stark terms. Here's your choice:

1. In rich countries, subsidize and mandate wind and solar making a few rich people richer and everybody else poorer, while ravishing the planet's resources, and making a paltry dent in CO2 emissions. See Germany. In poor countries, either forego all the benefits of cheap electricity, shortening and brutalizing the lives of billions, or burn mountains of coal and the planet fries.
2. Get runaway nuclear regulation under control, and provide cheap, reliable, resource efficient, nearly CO2 free electricity to everybody.

Take your pick.

A.7 But Expensive Nuclear is Nowhere Good Enough

Table A.4 shows some more model results in which we varied the social cost of CO2 from zero to $1600/ton. We also ran a range of nuclear overnight CAPEXes, running from what nuclear should-cost, about $2000/kW, to prohibitively expensive ($32,000/kW). Reference [70] has the details. We started out with a pure wind and solar grid, and moved to an all of the above grid, adding source and storage technologies as we went.

Table A.4: Overall Results for Germany

	Unit Social Cost of CO2					
	$0/mt		$100/mt		$1600/mt	
	Grid Cost $/MWh	CO2 gCO2/kWh	Grid Cost $/MWh	CO2 gCO2/kWh	Grid Cost $/MWh	CO2 gCO2/kWh
Wind, sun, battery	560	178	561	176	574	154
Wind, sun, H2 dome	206	30	206	30	207	27
W/S, H2/batt, fossil	60	717	72	277	167	36
All, $8000/kW nuke	60	717	72	277	127	8
All, $4000/kW nuke	60	717	71	45	82	6
All, $2000/kW nuke	51	59	54	19	56	6

Wind, sun and only batteries is a non-starter. Prohibitively expensive, requires ludicrous amounts of wind and solar capacity, producing immense quantities of curtailed power, resulting in tiny capacity factors and a not particularly low CO2 intensity.

Thanks to Germany's salt domes, wind, sun and hydrogen storage is within the realm of possibility for the wealthiest of nations. This grid eats up all sorts of resources, requiring almost certainly infeasible amounts of wind, but generates reasonably low CO2 emissions. This solution is out of reach for most of the planet and does not scale to electrify non-grid markets.

Fossil broadens the options for low social cost of CO2 a lot, while reducing the required wind and solar capacity to manageable amounts. But if the social cost of CO2 is truly large, it is not much help.

Only nuclear can get Germany out of this bind. But if nuclear costs $8000/kW or more, nuclear can only play a role at very high CO2 social cost, and the power will be nearly triple the cost of coal. At $4000/kW, nuclear can play an important role. Germany can have expensive electricity and low CO2. But the grid cost will be nearly 40% higher than that of coal. It is only when nuclear approaches its should-cost of $2000/kW, that we have a solution that works not only for Germany, but for the entire planet; a solution that can be scaled to decarbonize non-grid markets.

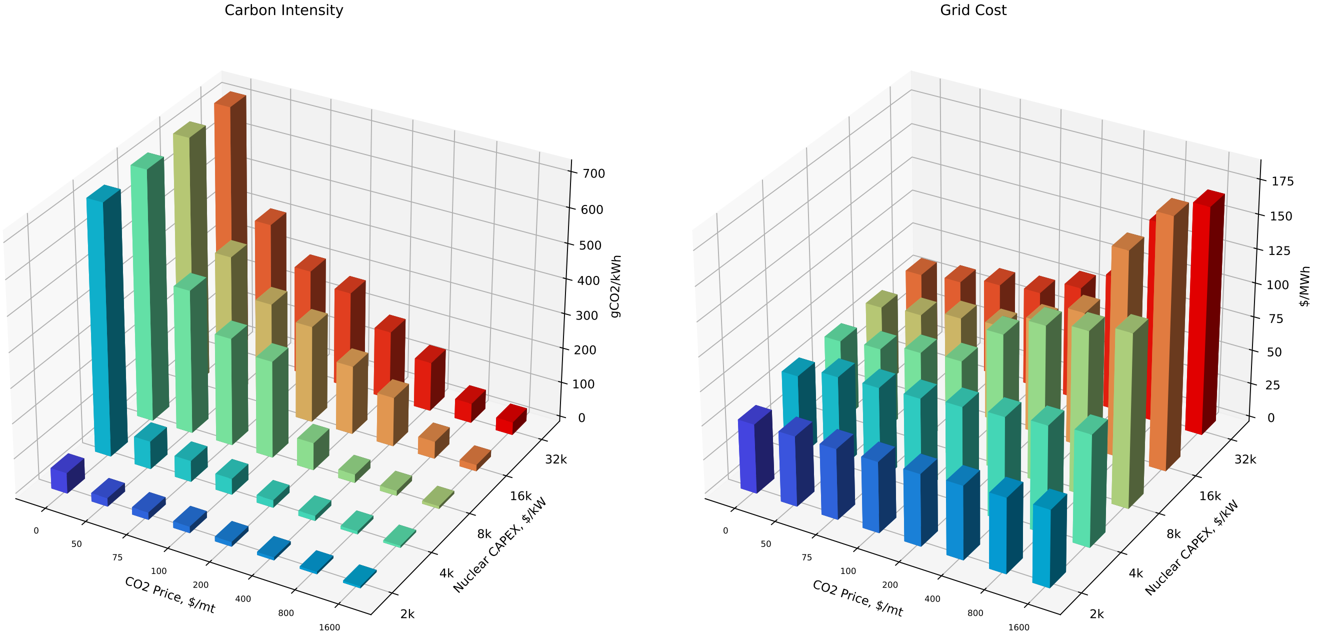


Figure A.14: Best CO2 intensities and Grid LCOE's, all of the above, Germany

Figure A.14 makes the point. If nuclear is expensive, Germany can either have reasonably price electricity or low CO2, but not both. If nuclear is near its should-cost, she can have both.

In the current mess, fossil fuel prices have temporarily outpaced ALARA. This will convince the nuclear establishment that ALARA and all its implications are acceptable. The Gold Standard works. All we need is more taxpayer money and everything will be fine.

This is a repeat of 1970's boom, described in Chapter 9, which took nuclear's real cost from less than 3 cents/kWh to multiples of that price. When fossil fuel prices crater, nuclear will be worse off than ever, and humanity will be screwed.

We must have truly cheap nuclear, like the nuclear we had in the late 1960's.

If and only if we have nuclear that is cheaper than fossil fuel's long run cost, will we have a low carbon, dispatchable source of electricity that the developing world can afford.

If and only if we have such low CO2, dispatchable electricity at less than 3 cents per kWh, do we have a shot at producing hydrogen at $1.50/kg. Then we can make ammonia for fertilizer without methane, and possibly convert primary steel making away from coal and coke.

If and only if we have hydrogen at this price, we may be able to produce synthetic liquid fuels, at a cost that is close enough to petroleum that a tolerable carbon tax will make them competitive.

Expensive nuclear is no where good enough. Expensive nuclear will continue to be a Flop.

Appendix B

The Non-Proliferation Non-Issue

> To the making of these fateful decisions, the United States pledges before you, and therefore before the world, its determination to help solve the fearful atomic dilemma — to devote its entire heart and mind to finding the way by which the miraculous inventiveness of man shall not be dedicated to his death, but consecrated to his life.[Eisenhower to the UN, 1953-12-08]

Nuclear weapons proliferation is not the reason the public is not embracing nuclear electricity. The proliferation argument simply does not resonate. Reasonable people realize that horse left the barn a long time ago. Any country that wants a bomb can have it, even a country as backward as North Korea.[1] I don't think I need to make that case. The well off elitists who think nuclear power should be hobbled to make weapons proliferation more difficult know the anti-proliferation argument does not sell. So they focus on radiation hazards or the dangers of used nuclear fuel in arguing against nuclear power. We've dealt with those issues.

But past attempts by the weapons states to preserve their weapons monopoly have resulted in some important barriers to nuclear power's ability to solve the Gordian knot, turning Eisenhower's promise into a sham. This chapter focuses on two of them.

1. The attempt by the weapons states to prevent countries that need nuclear electricity from enriching or recycling nuclear fuel.
2. The USA's attempt to maintain a non-existent monopoly on nuclear electricity.

(1) is in direct violation of the Nuclear Non-Proliferation Treaty which all the wealthy countries except Israel have signed. (2) is (1) plus just plain stupid.

---

[1] The only practical way to stop them is with force, as the Israelis did to Iraq. But I have never heard an anti-proliferation activist advocate this route.

B.1 The Right to Enrich and Recycle Fuel

191 countries have signed the Nuclear Non-Proliferation Treaty (NPT).[2] Article IV of the Non-Proliferation Treaty gives the signatories the “inalienable right" to nuclear power for peaceful uses. When the treaty was being negotiated in the late 1960’s, the non-weapons states wanted to make sure they did not get screwed twice:

1. giving up the bomb,
2. being on the outside in the peaceful use of nuclear electricity, which everybody figured was going to take over the world.

So they insisted on strong language that allowed them complete access to nuclear power for peaceful use. This includes fuel enrichment and recycling. This was subject only to Article II (peaceful use), enforced by allowing full inspections (Article III). Here’s the full text of Article IV.

> 1. Nothing in this Treaty shall be interpreted as affecting the inalienable right of all the Parties to the Treaty to develop research, production and use of nuclear energy for peaceful purposes without discrimination and in conformity with Articles I and II of this Treaty.
>
> 2. All the Parties to the Treaty undertake to facilitate, and have the right to participate in, the ***fullest possible exchange*** of equipment, materials and scientific and technological information for the peaceful uses of nuclear energy. Parties to the Treaty in a position to do so shall also co-operate in contributing alone or together with other States or international organizations to the further development of the applications of nuclear energy for peaceful purposes, especially in the territories of non-nuclear-weapon States Party to the Treaty, with due consideration for the needs of the developing areas of the world.[Emphasis mine.]

For a diplomatic document, the English is remarkably clear. Here’s William Foster, then head of the US delegation, testifying before the Senate in 1968 during ratification.

> It may be useful to point out several activities which the United States would not consider per se to be violations of the prohibitions in Article II. Neither uranium enrichment nor the stockpiling of fissionable material in connections with a peaceful program would violate Article II so long as these activities were safeguarded under Article III. Also clearly permitted would be the development under safeguards of plutonium fueled reactors, including research on the properties of metallic plutonium, nor would Article II interfere with the development or use of fast breeder reactors under safeguards.[170][p 344]

---

[2] The exceptions are India, Israel, Pakistan and South Sudan. North Korea withdrew.

Under the NPT, a signatory nation has the right to do whatever she wants to in an indigenous program, provided it is for peaceful use, which is enforced by allowing complete inspection.

The weapons states have continually violated the wording calling for the "fullest possible exchange" of technology, especially with developing countries. In fact, in violation of this wording, they formed the Nuclear Suppliers Group (NSG), which attempts to maintain the cartel by deciding who can and who cannot get fuel and other goodies.

Signatories to the NPT can sign away their inalienable rights and, under duress, some have. The USA is the biggest violator of the "fullest possible exchange" clause. Despite the NPT, if a country wants to have any real access to US nuclear power technology, it must sign a nuclear cooperation agreement with the USA. These are called *123 Agreements*, after the section in Atomic Energy Act that authorizes such agreements. Under a 123 Agreement, the US agrees to provide nuclear technology and fuel with all kinds of strings attached. One of those strings is that the country agrees to forego enrichment or recycling of the fuel. Some agreements require the non-US party to forego any enrichment or recycling.[3]

When the US was the leading provider of nuclear plants and fuel, signing such an agreement may have made some sense. But those days are long gone. The US is not only not a leading provider; it isn't even a competitive provider. There is no point in signing 123 agreements.

One of the cool things about nuclear is uranium and thorium (which can be transmuted into fissile uranium) is rather widely distributed around the planet. But no country should be dependent on a tiny handful of possibly adversarial enrichers for the fuel for her electricity, the life blood of her economy. In 1977, the Carter administration threatened to stop fuel shipments to any nation that undertook reprocessing.[50][p 235-236] Hard to imagine a more flagrant violation of the NPT. Nor a more counter productive one. Overnight, countries that thought they had a treaty, which said they could rely on the US to be their nuclear fuel supplier, knew this was not the case. They now had a strong incentive to become self-sufficient.

Any country who is a signatory to the NPT should invoke her inalienable rights. Buy or build enrichment facilities. Recycle fuel if she wants. Just forego a nuclear weapons program and let the IAEA inspect whatever they want. This is not only her inalienable right, but the NPT shows that the USA and all the other signatories recognize that it is her inalienable right.

---

[3] This provision is called the Gold Standard. Sound familiar?

B.2 American export controls

For Americans, the USA's violation of the NPT's “fullest possible exchange" provision represents yet another barrier to solving the Gordian knot. In a futile attempt to maintain a monopoly on nuclear power, the US has enacted a range of export controls. These include rules that prevent Americans from sharing any non-public data about their nuclear power plant design with citizens of any country that has not signed a Section 123 agreement with the US. A 123 agreement requires that a country cede a portion of its sovereignty to the USA, which many countries are unwilling to do. This effectively prohibits non-123 country vendors from competing to supply components to American designs. To make matters worse, any export of an American component to be used in a nuclear power plant requires a specific license. Any company, American or otherwise, targeting foreign markets cannot rely on American vendors, since the US government on a whim can prohibit exports of American nuclear power components.

There are procedures for getting around these rules; but they involve big lawyer bills, stacks of paper work, and lengthy, uncertain delays. And even after the necessary approvals have been granted, they can be rescinded without recourse, as Bill Gate's TerraPower Chinese effort discovered, wiping out a nine figure investment.[4] The overall effect is not only to suppress competition, and drive up costs, but also to put would be American providers of nuclear power at an impossible disadvantage relative to people like the Russians.

If the USA wants to play a role in cleaving the Gordian knot, nuclear electricity export controls must be done away with. The US must start complying with a treaty it signed 50 years ago.

---

[4] TerraPower is developing a sodium cooled, fast breeder reactor. By about 2013, they thought they were in a position to build and test a half-scale prototype. For all the reasons laid out in Chapter 9, Gates and his partners concluded this was not possible in the US. After a costly, multi-year lobbying effort, TerraPower obtained permission from the US government, to form a joint venture with China National Nuclear Power to build the prototype in China. The contract was signed in 2017. In October, 2018, the Trump Department of Energy announced new export rules, which TerraPower found impossible to comply with. The joint venture was dissolved.

Stomping on nuclear power development in the US has been a bipartisan effort. Nixon shut down a promising molten salt program in 1974. Carter shut down nuclear fuel reprocessing in 1977. Clinton shut down the government's fast breeder program in 1994. Trump stomped on TerraPower's privately financed venture in 2018.

Appendix C

Deep Geologic Hubris

C.1 Repository Studies

Despite the exceedingly low dose rates associated with long-lived radionuclides, the nuclear establishment agrees that these isotopes are an extremely difficult waste problem requiring deca-billion dollar investments in deep geological repositories.[1] And even then they are a lurking, barely contained danger. But there is little agreement about which isotopes we should worry about. Table C.1 summarizes the results of five major repository studies:

Table C.1: Worst isotopes in various deep repository studies

	No 1 iso	No 2 iso	No 3 iso	No 4 iso	Repository
Finland[108]	C-14	Cl-36	I-129	Cs-135	Olkiluoto
France[11]	I-129	Cl-36	Se-79		
Canada[200]	I-129	Cs-135	C-14	Cl-36	
Sweden[123]	Ra-226	I-129	Se-79	C-14	Forsmark
USA[189]	Pu-242	Np-237	Ra-226	I-129	Yucca Mt.

In the Finnish study, the top three exchange positions drastically depending on the scenario. These studies are based on a long chain of arguable and often arbitrary assumptions about what will happen over the next million years. The assumptions dictate the results, some of which are quite surprising.

1. ^{14}C and ^{36}Cl are not even fission products. They are activated scrap. Tiny amounts of scrap. ^{36}Cl arises from the activation of normal chlorine, ^{35}Cl. But no part of a light water reactor is made of chlorine. Some reactor components can be contaminated by chlorine at ppm or lower levels. This contamination is where the ^{36}Cl comes from. Nor is there much carbon in a standard light water reactor.
   Much is made of the fact that these elements are naturally in our bodies, so the uptake is high. But the biological half-life of carbon in a human is 40 days. For chlorine, it's 10 days. ^{14}C is so natural, it is something we ingest every day.

---

[1] This Appendix assumes a bit more technical background than the rest of the book.

2. In terms of activity, ^{99}Tc represents over 90% of the long lived fission products; and, like carbon and chlorine, in the form of the TcO_4 ion, it can be highly mobile. High uptake of 50 to 80%, about the same as carbon and chlorine. But it shows up almost nowhere in the repository studies, presumably because it has a very short (about 1 day) biological half-life.
3. ^{226}Ra is neither a fission product nor an activation product. It's a natural part of the ^{238}U decay chain. The amount of ^{238}U that is put back in the ground is slightly less than what was taken out. And the radium from this clean ^{238}U builds up very slowly. Yet according to the Swedes, this natural radiation is the most dangerous of all the isotopes. In their reference scenario, it represents close to 90% of the dose at the end of the study period.[123]
4. Plutonium is highly immobile. The plutonium created by the natural Oklo reactor in Gabon has moved less than 3 meters in two billion years, despite groundwater flowing through the formation.[169]. Human uptake is near zero. If plutonium somehow were ingested, 99.997% would be excreted in a day or two.[105] But somehow ^{242}Pu made it to the top of the USA list. Most of the other studies don't even mention plutonium. In the Finnish study, the worst case release of plutonium is one-trillionth of the worst case release of ^{129}I. See Table C.3. And that number does not account for the massive difference in uptake. The Yucca Mountain study is a weird outlier.

About the only thing, the studies agree on is that ^{129}I is important. ^{129}I has a half-life of 16.6 million years. It emits a modest (max 151 keV) beta and a weak 39 keV gamma. It concentrates in the thyroid. So let's take a look at ^{129}I, and throw in ^{99}Tc for good measure.

C.2 ^{129}I and ^{99}Tc

Table C.2 compares the effect of ingesting 1 nanogram of ^{129}I and ^{99}Tc with ingesting 1 nanogram of ^{131}I, potentially the most dangerous isotope in the first week or two after a release. The dose per gram from ^{129}I and ^{99}Tc is a billion times less than that from ^{131}I. Long lived is synonymous with decays-very-slowly which results in correspondingly low dose rates.

^{99}Tc is regularly injected into medical patients as a by-product of ^{99m}Tc imaging. ^{99m}Tc is by far the most popular form of internal photon imaging.[2] Reference [187] says “a total of approximately 38,000 diagnostic procedures involving radioactive isotopes are performed each day in the U.S. Most of these procedures use ^{99m}Tc."[187] (This is a 1996 number.) ^{99m}Tc has a decay half-life of 6 hours and a specific activity of 19.5e17 Bq/g, 300 million times higher than the ^{99}Tc to which it decays. It emits a 141 keV photon. Yet it is approved by the FDA for all sorts of diagnostic purposes, including children. The approved dose varies with use; but in many cases it is in excess 1.0e9 Bq or about 52 nanograms of ^{99m}Tc. This would be 65 mGy to the

---

[2] Isotopes decay in steps, as they fall from a higher energy level to a lower. Usually the time at each step is so small, it is negligible. But sometimes the half-life at a step is long enough to be important. ^{99}Mo decays to a high-energy state of Techtinium-99, denoted ^{99m}Tc, which then decays to ^{99}Tc.

	I-129	I-131	Tc-99
Decay Half life	1.660e+07y	8.020d	2.110e+05y
Biological Half life	128.000d	128.000d	1.000d
Body Uptake(%)	20.0	20.0	80.0
Thyroid Uptake(%)	15.0	15.0	1.5
Beta keV/decay	151	606	295
Gamma keV/decay	39	364	0
Activity: Bq/g	6.1856e+06	4.6018e+15	6.3426e+08
Thyroid kg	0.025	0.025	0.025
Human kg	70.000	70.000	70.000
J/decay	1.4305e-14	9.0651e-14	1.5749e-14
J/s per nanogram ingested	8.8483e-17	4.1716e-07	9.9890e-15
J per nanogram ingested	1.4118e-09	3.9244e-01	1.2451e-09
Body Gy/ng ingested	4.0336e-12	1.1213e-03	1.4230e-11
Thyroid Gy/ng ingested	8.4705e-09	2.3546e+00	7.4707e-10

Table C.2: Dose per nanogram ingested

body and 3.45 Gy to the thyroid.

EPA says this is safe because of the short decay half-life and the fact that the biological half-life is about 1 day.[4] Every atom of ^{99m}Tc that decays produces an atom of ^{99}Tc. The EPA claims ^{99}Tc is hazardous because of its long decay half-life.[4] Yet ^{99}Tc has the same 1 day biological half life as ^{99m}Tc. In other words, the EPA is saying a thyroid dose of 3.5 Gy in a day is safe; but a dose rate 100 million times lower is not. In any event, the dose the patient receives from the ^{99}Tc is about 100 millionth of the dose the patient receives from the ^{99m}Tc. The medical profession for once is correctly unconcerned.[3]

At Chernobyl, 383 g (6500 PBq) of ^{131}I was released.[115][4] The thyroid doses to affected children were in the range of 560 mSv (average Belarus) and 770 mSv (average Ukraine).[242] Almost all of this dose was from ^{131}I. A 770 mSv dose indicates 0.327 nanograms got to the thyroid and the child ingested about 2.2 nanograms of ^{131}I. The distribution was very roughly log-normal with about 15% of the children getting 1 to 6 gray, and 1% getting more than 5 Gy. The maximum measured thyroid dose was 39/42 Gy Belarus/Ukraine. These two kids must have ingested about 55 nanograms.

Table C.2 says a nanogram of ^{129}I results in eleven times the thyroid dose of a nanogram of ^{99}Tc or 10 millionth the ^{99m}Tc dose. Put another way, if a child ingested 55 nanograms of ^{129}I, the maximum at Chernobyl, she would receive a dose to the thyroid of 0.466 μG. To claim that ^{99}T or ^{129}I is a problem, you must come up with a delivery scenario that results in a rapid ingestion of a million times or more material than the largest ingestion after Chernobyl.

---

[3] But not the nuclear establishment. Dr. Jess Brewer worked at TRIUMF, the particle accelerator lab in Vancouver. Immediately after his ^{99m}Tc scan the doctors sent him home. But for the next 3 days (12 ^{99m}Tc half-lives), he set off the alarms passing through the lab gate.

[4] At the time, nobody bothered to try and measure the ^{129}I or ^{99}Tc release. They had no reason to. They knew the ^{129}I and ^{99}Tc dose rates would be completely insignificant. Later the distribution of ^{129}I at Chernobyl was tracked; but only in an attempt to reconstruct the ^{131}I doses. By that time, the ^{131}I was long gone.

C.3 Repository Release Rates

Towards the end of their study of the Finnish Olkiluoto repository, the authors did something interesting. They simply listed the number of atoms of each isotope that was released into the geosphere from the repository in the worst case scenario for that isotope over the period, 2020 to 17020. Table C.3 shows the results.

If you add up all the isotopes weighted by their activity, you come up with a total release of 1.3e10 Bq over the 15,000 year period. Chernobyl released 6.5e18 Bq of ^{131}I alone over 10 days. The Chernobyl release was 500 million times larger and took place 500,000 times faster. Of course, our ginned up Olkiluoto release will not be evenly spread over 15,000 years; but this error is in the noise compared with the error of combining mutually exclusive worst cases. For comparison, the Finns' reference case is shown in the right most column.

So how do they come up with max dose rates that are only a million or 10 million times less than the worst case at Chernobyl? The repository studies focus on a hypothetical *most exposed person*(MEP). You identify a dominate pathway in each scenario and you put your MEP at the end of that path. Our most exposed person drinks a couple of liters a day every day for a year out of the most contaminated well. The analysis invokes LNT multiple times — usually silently – including the assumption that dose rate is irrelevant.[5]

But it makes another unsupported assumption. It assumes that our descendants are even stupider than we are. We know how to detect radiation down to a few counts per second. Technically it is not difficult. If a thousand years from now our descendants are somehow still worried about dose rates that are orders of magnitude below background, do we think they won't have the capability to detect and respond to those dose rates? That's precisely what the repository studies assume.

The repository studies are exercises in monumental hubris. The idea that we can predict what will happen 100 years from now is preposterous. The idea that we can predict what will happen 1000 years from now — well, there is just no word for it. And then we assume this omniscient species which can foretell the future for millenia, all of a sudden forgets how to measure radiation.

The humble, prudent, common sense approach is;

1. Shield and cool the used fuel adequately. We know how to do this. It is not difficult.
2. Keep the material where you can repair the shielding as necessary and have easy access to the isotopes if they become valuable, which is quite likely.

Forget about predicting the future for millenia and trying to come up with a system that will last that long.

---

[5] The doses still come out negligibly low. The worst, worst case dose rate in the 2009 Olkiluoto study is 0.18 μSv/y.[108][Table 8.6] That's equivalent to eating two bananas a year.

Table C.3: Olkiluoto worst case releases to the geosphere, reference [108]

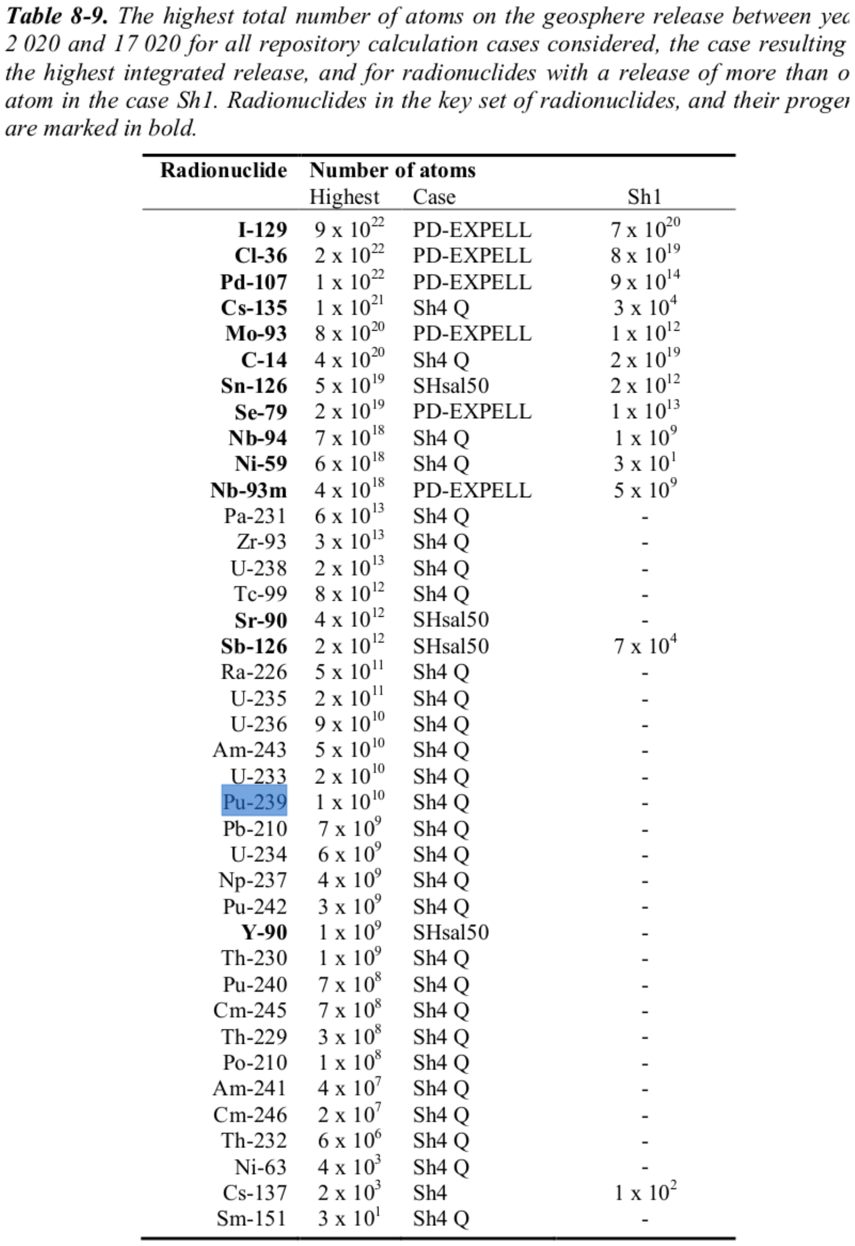


Table 8-9. *The highest total number of atoms on the geosphere release between ye 2 020 and 17 020 for all repository calculation cases considered, the case resulting the highest integrated release, and for radionuclides with a release of more than atom in the case Sh1. Radionuclides in the key set of radionuclides, and their proge are marked in bold.*

Radionuclide	**Number of atoms**		
	Highest	Case	Sh1
I-129	9×10^{22}	PD-EXPELL	7×10^{20}
Cl-36	2×10^{22}	PD-EXPELL	8×10^{19}
Pd-107	1×10^{22}	PD-EXPELL	9×10^{14}
Cs-135	1×10^{21}	Sh4 Q	3×10^{4}
Mo-93	8×10^{20}	PD-EXPELL	1×10^{12}
C-14	4×10^{20}	Sh4 Q	2×10^{19}
Sn-126	5×10^{19}	SHsal50	2×10^{12}
Se-79	2×10^{19}	PD-EXPELL	1×10^{13}
Nb-94	7×10^{18}	Sh4 Q	1×10^{9}
Ni-59	6×10^{18}	Sh4 Q	3×10^{1}
Nb-93m	4×10^{18}	PD-EXPELL	5×10^{9}
Pa-231	6×10^{13}	Sh4 Q	-
Zr-93	3×10^{13}	Sh4 Q	-
U-238	2×10^{13}	Sh4 Q	-
Tc-99	8×10^{12}	Sh4 Q	-
Sr-90	4×10^{12}	SHsal50	-
Sb-126	2×10^{12}	SHsal50	7×10^{4}
Ra-226	5×10^{11}	Sh4 Q	-
U-235	2×10^{11}	Sh4 Q	-
U-236	9×10^{10}	Sh4 Q	-
Am-243	5×10^{10}	Sh4 Q	-
U-233	2×10^{10}	Sh4 Q	-
Pu-239	1×10^{10}	Sh4 Q	-
Pb-210	7×10^{9}	Sh4 Q	-
U-234	6×10^{9}	Sh4 Q	-
Np-237	4×10^{9}	Sh4 Q	-
Pu-242	3×10^{9}	Sh4 Q	-
Y-90	1×10^{9}	SHsal50	-
Th-230	1×10^{9}	Sh4 Q	-
Pu-240	7×10^{8}	Sh4 Q	-
Cm-245	7×10^{8}	Sh4 Q	-
Th-229	3×10^{8}	Sh4 Q	-
Po-210	1×10^{8}	Sh4 Q	-
Am-241	4×10^{7}	Sh4 Q	-
Cm-246	2×10^{7}	Sh4 Q	-
Th-232	6×10^{6}	Sh4 Q	-
Ni-63	4×10^{3}	Sh4 Q	-
Cs-137	2×10^{3}	Sh4	1×10^{2}
Sm-151	3×10^{1}	Sh4 Q	-

Bibliography

[1] R. Adams. Personal communication. Technical report, Atomic Insights, March 2023. Based on 3 years at mPower.

[2] Energy Information Administration. Nuclear power generation and fuel cycle report. Technical report, US Department of Energy, September 1997. DOE/EIA-0436(97).

[3] Environmental Protection Agency. Federal register. Technical report, USA Environmental Protection Agency, 1991. Vol. 56. No. 138. pp 33050-127.

[4] Environmental Protection Agency. Epa facts about technetium-99. Technical report, USA Environmental Protection Agency, July 2002.

[5] Environmental Protection Agency. Pag manual, protective action guides and planning guidance for radiological incidents. Technical report, US EPA, January 2017. EPA-400/R-17/001.

[6] Nuclear Energy Agency. Chernobyl assessment of radiological and health impact: 2002 update of chernobyl ten years on. Technical report, OECD, 2002. NEA No. 3508.

[7] J. Ahn, C. Carson, and M. Jensen. *Reflections of the Fukushima Daiichi Nuclear Accident*. Springer Open, 2015.

[8] W. Allison. *Radiation and Reason*. Wade Allison Publishing, 2009.

[9] W. Allison. *Nuclear is for Life*. Wade Allison Publishing, 2015.

[10] A. Alvarez, J. Beyea, and K. et al Janberg. Reducing the hazards from stored spent power-reactor fuel in the united states. *Science and Global Security*, 11:1–51, 2003.

[11] ANDRA. Evaluation of the feasibilility of a geological depository in an argillaceous formation. Technical report, ANDRA, 2005.

[12] M. Antosh, D. Fox, T. Hasselbacher, R. Lanou, N. Neretti, and L. Cooper. Drosophila melanogaster show a threshold effect in response to radiation. *Dose Response*, 12, May 2014.

[13] L. Arnold. *Windscale 1957. Anatomy of a Nuclear Accident.* Palgrave Macmillan, 1992.

[14] H. Badri and et al. Molecular investigation of the radiation resistance of edible cyanobacterium arthospira sp. pcc 8005. *Microbiology Open*, 4(2):187–207, 2015.

[15] B. Balogh. *Chain Reaction: Expert debate and public participation in American commercial nuclear power.* Cambridge University Press, 1991.

[16] L. Battist, F. Congel, J. Buchanan, and H. Peterson. Population dose and health impact of the accident at the three mile island nuclear station. Technical report, US Nuclear Regulatory Commission, May 1979. NUREG-0558.

[17] A. Bell. *Our Biggest Experiment: An Epic History of the Climate Crisis.* Counterpoint, 2021.

[18] A. et al Benjamin. Spent fuel heatup following loss of water during storage. Technical report, Sandia National Laboratories, 1979. NUREG/CR-0649, SAND77-1371.

[19] B. Bennett. Transuranium element pathways to man. In *Transuranium Nuclides in the Environment*, 1976. IAEA Conference.

[20] B. Bennett, M. Repacholi, and Z. Carr. Health effects of the chernobyl accident and special health care programs. Technical report, World Health Organization, 2006.

[21] A. Berrington, S. Darby, H. Weiss, and R. Doll. 100 years of observation on british radiologists: mortality from cancer and other causes 1897-1997. *British Journal of Radiology*, 74:507–519, june 2001.

[22] BNL. Theoretical possibilities and consequences of major accidents in large nuclear power plants. Technical report, Brookhaven National Lab, March 1957. WASH-740.

[23] A. Bouville and V. Drozdovitch. Doses received from the chernobyl accident. Technical report, National Cancer Institute, November 2016. NAS, 1 November 2016.

[24] B. Bouwman and N. Crosetto. Endogenous dna double-strand breaks during dna transactions. *Genes*, 9, 2018.

[25] D. Brenner and et al. Cancer risks attributable to low doses of ionizing radiation: Assessing what we really know. *PNAS*, 100(24), November 2003.

[26] E. Bromet and J. Havenaar. Psychological and perceived health effects of the chernobyl disaster: A 20 year review. *Health Physics*, 93(5):516–521, 2007.

[27] A. Brooks. *Low Dose Radiation.* Washington State University Press, 2018.

[28] K. Brown. *Manual for Survival: A Chernobyl Guide to the Future*. W. W. Norton and Company, 2019.

[29] C. Bukro. *Higher Power*. Agate, Chicago, 2023.

[30] I. Bupp and J. Derian. *Light Water, How the Nuclear Dream Dissolved*. Basic Books, 1978.

[31] P. Burgherr and S. Hirshberg. A comparative analysis of accident risks in fossil, hydro, and nuclear energy chains. *Human and Ecological Risk Assessment*, 14:947–973, 2008.

[32] E Calabrese. The road to linearity: why linearity at low doses became the basis for carcinogen risk assessment. *Arch Toxicol*, 83:203–225, 2009.

[33] E Calabrese. The linear no threshold dose response model: A comprehensive assessment of its historical and scientific foundations. *Chemico-Biological Interactions*, 301:6–25, 2019.

[34] E Calabrese. The muller-neel dispute and the fate of cancer risk assessment. *Environmental Research*, 190:6–25, 2020.

[35] X. Cao, P. MacNaughton, J. Laurent, and J. Allen. Radon induced lung cancers may be overestimated due to failure to account for confounding by exposure to diesel engine exhaust in beir vi miner studies. *PLoS One*, 12(9), September 2017.

[36] E. Cardis, V. Ivanov, I. Liktarev, K. Mabuchi, and A. Okeanov. Estimated long term health effects of the chernobyl accident. Technical report, IAEA, July 1996. URCL-JC-125026.

[37] E. Cardis, V. Vrijheid, and M. Blettner. The 15 country collaborative study of cancer risk among radiation workers in the nuclear industry. *Radiation Research*, 167:396–416, 2007.

[38] E. Caspari and C. Stern. The influence of chronic irradiation with gamma rays at low dosages on the mutation rate in drosophila melogaster. *Genetics*, 33:75–95, 1948.

[39] M. Cembalest. 2021 annual energy paper. Technical report, J P Morgan, May 2021.

[40] J. Chen. A review of radon doses. *Radiation Protection Management*, 22(4), 2005.

[41] W. Chen, Y. Luan, and M. Shen. Effects of cobalt-60 exposure on health of taiwan residents suggest new approach needed in radiation protection. *Dose Response*, 5(1), 2007.

[42] W. Choi, M. Roh, and C. Kim. Innovative nuclear power plant building arrangment in consideration of decommissioning. *Nuclear Engineering and Technology*, 49(3):525–533, April 2017.

[43] M. Chougaonkar, E. Kp, T. Ramachandran, and R. Shetty. Profiles of doses to the population living in the high background areas in kerala, india. *Journal of Environmental Radioactivity*, 71(3):275–297, December 2014.

[44] B. Church and A. Brooks. Cost of fear and radiation protection actions: Washington county, utah and fukushima, japan. *International Journal of Radiation Biology*, 2020.

[45] C. Clack, S. Qvist, and J. et al Apt. Evaluation of a proposal for reliable low-cost grid power with 100 percent wind, water and solar. *PNAS*, 114(26), June 2017.

[46] CNSC. Verifying canadian nuclear energy worker radiation risk. Technical report, Canadian Nuclear Safety Commission, June 2011. CINFO-0811.

[47] CNSC. Managing public doses during a nuclear emergency. Technical report, Canadian Nuclear Safety Commission, March 2015. Fact Sheet.

[48] B. Cohen. The disposal of radioactive wastes from fission reactors. *Scientific American*, 236(6):21–31, June 1977.

[49] B. Cohen. The myth of plutonium toxicity. In *Nuclear Energy*, pages 355–365, 1985. Plenum Press, New York.

[50] B. Cohen. *The Nuclear Energy Option.* Plenum Press, 1990.

[51] B. Cohen. Catalog of risks extended and updated. *Health Physics*, 61(3):317–335, September 1991.

[52] B. Cohen. Lung cancer rate vs mean radon level in us counties of various characteristics. *Health Physics*, 72(1):114–119, 1997.

[53] W. Cole, T. Mai, J. Logan, and D. Steinberg. 2016 standard scenarios report: A u.s. electricity sector outlook. Technical report, National Renewable Energy Laboratory, November 2016. NREL/TP-6A20-66939.

[54] Nuclear Regulatory Commission. Nrc statement on risk assessment and the reactor safety study report in light of the risk assessment review group report. Technical report, US Nuclear Regulatory Commission, January 1979.

[55] Nuclear Regulatory Commission. Davis besse loss of all feedwater. pwr crosstraining course manual, ch 16. Technical report, US Nuclear Regulatory Commission, 2008. USNRC HRTD Rev 05/2008.

[56] L. Corrice. *Fukushima: the first five days.* Kindle, Amazon, 2014.

[57] G. Cravens. *Power to Save the World.* Random House, 2008.

[58] R. Crease. *The Leak.* MIT Press, 2022.

[59] T. Cullen. Review of brazilian investigations of areas of high natural radiation. part i. In *Proceedings of the International Symposium on Areas of High Natural Radioactivity*, pages 49–64, 1977.

[60] J. Cuttler. Commentary on fukushima and beneficial effects of low radiation. *Dose Response*, 11:432–443, 2013.

[61] S. Darby, D. Hill, A. Auvinen, J. Barros-Dios, and H. Baysson. Radon in homes and risk of lung cancer. *British Medical Journal*, 1, December 2004.

[62] V. Daubert and S. Moran. Origins, goals, and tactics of the u.s. anti-nuclear protest movement. Technical report, RAND, March 1985. N-2192-SL.

[63] F. Davis and et al. Solid cancer incidence in the techa river incidence corhort: 1956 - 2007. *Radiation Research*, 184:56–65, 2015.

[64] L. Davis. Prospects for nuclear power. *Journal of Economic Perspectives*, 26(1):49–66, Winter 2012.

[65] M. Derivan. Nuke news: A view from the cheap seats. Technical report, nukenews.com, 2014.

[66] T. Deryabina, S. Kuchmel, L. Nagorskaya, T. Hinton, J. Beasley, A. Lerebours, and J. Smith. Long term census data reveal abundant wildlife populations at chernobyl. *Current Biology*, 25, October 2015.

[67] M. Deutsch. Making the most of offshore wind. Technical report, Agora Energiewende, March 2020. Version 1.2.

[68] J. Devanney. *The Tankship Tromedy.* CTX Press, 2006.

[69] J. Devanney. Green hydrogen and dunkelflauten. Technical report, Gordian Knot Group, January 2022. downloadable from gordianknotbook.com.

[70] J. Devanney. Low carbon electricity: the options for germany. Technical report, Gordian Knot Group, May 2022. downloadable from gordianknotbook.com.

[71] S. Dingwall, C. Mills, N. Phan, K. Taylor, and D. Boreham. Human health and the biological effects of tritium in drinking water. *Dose Response*, 9:6–31, 2011.

[72] L. Dobrzynski, K. Fornalski, Y. Socol, and J. Reszczynska. Modeling of irradiated cell transformation: Dose and time dependant effects. *Radiation Research*, 186:396–406, 2016.

[73] D. Dockery and C. Pope. Lost life expectancy due to air pollution in china. Technical report, Swiss re, 2014.

[74] M. Doss. An analysis of cancer incidence in taiwan apartment residents subjected to low dose radiation. *blogspot.com*, September 2013.

[75] Drax. Drax electric insights quarterly, q1-2021. Technical report, Drax, 2021.

[76] B. Eakins and G. Sharman. Volumes of the world's oceans from etopo1. Technical report, NOAA, 2010.

[77] P. Ehrlich. An ecologist's perspective on nuclear power. *F. A. S. Public Interest Report*, May-June, 1975.

[78] P. Ehrlich and A. Ehrlich. *Population Resorces Environment*. W. H. Freemans and Company, 1970.

[79] A. Ellerman. The world price of coal. Technical report, MIT, November 1994. MIT-CEEPR 94-009.

[80] R. Evans. The effect of skeletally deposited alpha-ray emitters in man. *British Journal of Radiology*, 39(468):881–895, December 1966.

[81] D. Farley. Global trends of asme n-stamp certifications for nuclear component vendors. Technical report, Sandia National Laboratories, 2020. SAND2020-14254.

[82] D. Fisher and R. Weller. Carcinogenesis from inhaled 239puo2 in beagles. *Health Physics*, 99(3):357–362, 2010.

[83] D. Fishlock. The last retort. *Chemistry World*, 99, March 2005. 1 March 2005.

[84] T. Fliedner, D. Graessle, V. Meineke, and L. Feinendegen. Hemopoietic response to low dose rates of ionizing radiation. *Dose Response*, 10:644–663, 2012.

[85] D. Ford. *The Cult of the Atom*. Simon and Schuster, 1982.

[86] R. Fosdick. Letter from raymond b. fosdick to warren weaver, august 29, 1945. Technical report, Rockefeller Archive Center, August 1945. RAC, RG 3.2, Series 900, Box 31, Folder 167.

[87] N. Fossett, B. Byrne, and S. Kelley. The influence of large deletions on the mutation frequency induced by tritated water and x-radiation in male drosophila germ cells. *Mutation Research*, 307:213–222, 1994.

[88] Radiation Effects Research Foundation. A brief description. Technical report, Radiation Effects research Foundation, 2013.

[89] Rockefeller Foundation. Annual report, 1956. Technical report, Rockefeller Foundation, 1956.

[90] V. Fthenakis, H. Kim, and E. Alsema. Emissions from photovoltaic life cycles. *Environmental Science and Technology*, 42(6):2168–2174, 2008.

[91] J. Garland and R. Wakeford. Atmospheric emissions from the windscale accident of october, 1957. *Atmospheric Environment*, 41:3904–3920, 2007.

[92] M. Ghiassi, S. Mortazavi, J. Cameron, N. Niroomand, and P. Karam. Very high background radiation areas of ramsar, iran: Preliminary biological studies. *Health Physics Society*, pages 87–93, 2002.

[93] H. Ginzburg. The psychological consequences of the chernobyl accident. *Public Health Reports*, 108(2), 1993.

[94] J. Goldstein and S. Qvist. *A Bright Future*. Public Affairs, 2019.

[95] V. Golikov, M. Balonov, and P. Jacob. External exposure of the population living in areas of russia contaminated due to the chernobyl accident. *Radiation Environmental Biophysics*, 41:185–193, 2002.

[96] P. Gottschalk and J. Dunn. The five parameter logistic. *Analytical Biochemistry*, 343:54–65, May 2005.

[97] M. Gray and I. Rosen. *The Warning*. W. W. Norton and Company, 1982.

[98] L. Gronlund. How many cancers did chernobyl really cause? Technical report, Union of Concerned Scientists, April 2011.

[99] A. Grubler. The costs of the french nuclear scale up: A case of negative learning by doing. *Energy Policy*, 38:5174–5188, 2010.

[100] A. Guskova. Medical consequences of the chernobyl accident: Aftermath and unsolved problems. *Atomic Energy*, 113(2), December 2012.

[101] R. Haroldsen. *The Story of the BORAX Nuclear Reactor and the EBR-1 Meltdown*. Ray Haroldsen, 2008.

[102] M. Hatch, E. Ron, A. Bouville, and L. Zablotska. The chernobyl disaster: Cancer following the accident at the chernobyl nuclear power plant. *Epidemiologic Reviews*, 27:56–66, 2005.

[103] N. Hayashida, M. Imaizumi, and H. Shimura. Thyroid ultrasound findings in children from three japanese prefectures: Aomori, yamanashi, nagasaki. *PLOS One*, 8(12), December 2013.

[104] C. Heath, P. Bond, D. Hoel, and C. Meinhold. Residential radon exposure and lung cancer risk. *Health Physics*, 87(6):647–655, December 2004.

[105] T. Henriksen. *Radiation and Health.* Taylor and Francis, 2003.

[106] T. Henriksen. *Radiation and Health.* University of Oslo, 2013.

[107] A. Higginbotham. *Midnight in Chernobyl.* Simon and Schuster, 2019.

[108] T. Hjerpe, A. Ikonen, and R. Broed. Biosphere assessment report, 2009. Technical report, Posiva Oy, March 2010.

[109] R. Howarth, L. Bringezu, L. Martinelli, and R. Santoro. Introduction: Biofuels and the environment in the 21st century. In *Biofuels: Environmental Consequences and Interactions with Changing land Use*, pages 15–36, 2009.

[110] M. Hulleat. *Handbook of Black Coals.* Australian Government Publishing Service, 1991. Resource Report 7.

[111] S. Hwang, H. Guo, W. Hsieh, J. Hwang, and S. Lee. Cancer risks in a population with prolonged low dose-rate gamma radiation exposure in radiocontaminated buildings, 1983-2002. *International Journal of Radiation Biology*, 82:849–858, 2006.

[112] S. Hwang, J. Hwang, Y. Yang, W. Hsieh, and T. Chang. Estimates of relative risks for cancers in a population after prolonged low dose-rate radiation exposure: a follow-up assessment from 1983 to 2005. *Radiation Research*, 170:143–148, 2008.

[113] iaea. Management of waste containing tritium and carbon-14. Technical report, International Atomic Energy Agency, July 2004. IAEA Technical Report Series 421.

[114] iaea. The chernobyl i-131 release: Model validation and assessment. Technical report, International Atomic Energy Agency, 2008. Date uncertain.

[115] T. Imanaka, G. Hayashi, and S. Endo. Comparison of the accident process, radioactivity release, and ground contamination between chernobyl and fukushima-i. *Journal of Radiation Research*, pages 1–6, 2015.

[116] Holtec International. Underground cisf - financial assurance and project life cycle cost estimates. Technical report, Holtec, 2017. HI-2177593 Revision 0.

[117] Nuclear Enigineering International. China to begin construction of hualong two in 2024. Technical report, NEI Magazine, April 2021. 2021-04-15.

[118] T. et al Ishikawa. The fukushima health management survey: estimation of external doses to residents in fukushima prefecture. *Scientific Reports*, 5, 2015.

[119] M. Jacobson, M. Delucchi, M. Cameron, and B. Frew. Low cost solution to the grid reliability problem with 100 pct penetration of intermittent wind, water and solar. *PNAS*, 112(49), December 2015.

[120] Z. Jaworowski. Observations on the chernobyl disaster and lnt. *Dose Response*, 8:148–171, 2010.

[121] S. Jones. Windscale and kyshtym: a double anniversary. *Journal of Environmental Radioactivity*, 99:1–6, 2008.

[122] P. Karam and S. Leslie. Changes in terrestial natural radiation levels over the history of life. *Radioactivity in the Environment*, December 2005.

[123] Svensk Karnbranslehantering. Long term safety for the final repository for spent nuclear fuels at forsmark. Technical report, SKB, March 2011. SKB TR-11-01.

[124] V. Kashcheev, S. Yu, and M. et al Chekin. Incidence and mortality of solid cancer among emergency workers of the chernobyl accident: assessment of radiation risks for the follow up period of 1992-2009. *Radiation Environmental Biophysics*, 54:13–23, 2015.

[125] R. Kathren. Principles and application of collective dose in radiation protection. Technical report, National Council on Radiation Protection and Measurements, November 1995. NCRP Report No. 121.

[126] R. Kathren and R. Burklin. Acute chemical toxicity of uranium. *Health Physics*, 94(2):170–179, February 2008.

[127] D. Keith, G. Holmes, and K. Heidel. A process for capturing co2 from the atmosphere. *Joule*, 2:1–22, August 2018.

[128] J. Kemeny. The accident at three mile island. Technical report, The President's Commission, December 1979.

[129] P. Kharecha and J. Hansen. Prevented mortality and greenhouse gas emissions from historical and projected nuclear power. *Environmental Science and Technology*, 2013.

[130] D. Kocher. Perspective on the historical development of radiation standards. *Health Physics*, 61:519–527, 1991.

[131] S. Kodaira, M. Naito, and H. Hashimoto. Space radiation dosimetry at the exposure facility of the international space station. *Astrobiology*, 21(12), December 2021.

[132] C. Komanoff. *Power Plant Cost Escalation*. Van Nostrand, 1981.

[133] R. Koningstein and D. Fork. What it would really take to reverse climate change. *spectrum.ieee.org*, 2014. 18 Nov 2014.

[134] R. Korman. Witness to the origins of a huge nuclear construction flop. *Engineering News Record*, November 2017. ENR, 2017-11-01.

[135] V. Kostyuchenko and L. Krestinina. Long term irradiation effects in the population evacuated from the east urals radioactive trace area. *The Science of the Total Environment*, 142:119–125, 1994.

[136] D. Krewski, J. Lubin, J. Zielinski, and M. Alavanja. Residential radon and risk of lung cancer. *Epidemiology*, 16(2):137–145, March 2005.

[137] L. Lamerton and H. Mole. *Radiosensitivity and Spatial Distribution of Dose*. Pergamon, Press, 1969. ICRP Pub. 14.

[138] P. Lang. Nuclear power learning and deployment rates; disruption and global benefits forgone. *Energies*, 10, December 2017.

[139] T. Lark, N. Henndricks, and A. Smith. Environmental outcomes of the us renewable fuel standard. *PNAS*, 119(9), February 2022.

[140] E. Larsen, C. Grieg, and J. Jenkins. Net zero america: Potential pathways, infrastructure, and impacts. Technical report, Princeton University, October 2021.

[141] J. Law, T. Garn, and D. Herbst. Development of cesium and strontium separation and immobilization technologies. Technical report, Idaho National Laboratory, February 2006. INL/CON-05-00970.

[142] E. Lawrence. Letter from ernest o. lawrence to warren weaver, august 20, 1945. Technical report, Rockefeller Archive Center, August 1945. RAC, RG 1.1, Series 205D, Box 13, Folder 191.

[143] K. Leung, G. Shabat, and P. et al Lu. Trends in solid tumor incidence in ukraine 30 years after chernobyl. *Journal of Global Oncology*, August 2019.

[144] K. Leuraud, D. Richardson, E. Cardis, and R. Daniels. Ionizing radiation and risk of death from leukaemia and lymphoma in radiation monitored workers (inworks): an international study. *Lancet Haematology*, 2:e276–81, July 2015.

[145] M. Levenson and F. Rahn. Realistic estimates of the consequences of nuclear accidents. *Nuclear Technology*, 53, May 1981.

[146] E. Lewis. Leukemia and ionizing radiation. *Science*, 43(3255):965,972, May 1957.

[147] H. et al Lewis. Report to the american physical society by the study group on light water reactor safety. *Review of Modern Physics*, 47, 1975.

[148] M. Lieber. The mechanism of double strand dna break repair by the nonhomologous dna end joining pathway. *Annu Rev Biochem*, 79:181–211, 2010.

[149] D. Lochbaum. Price-anderson and nuclear safety good buys. Technical report, Union of Concerned Scientists, August 2014. All things nuclear. Fission Story 169.

[150] D. Lochbaum. Atomic speedometers. Technical report, Union of Concerned Scientists, September 2015. All things nuclear. Fission Story 196.

[151] J. Lovering, A. Yip, and T. Nordhaus. Historical construction costs of global nuclear reactors. *Energy policy*, 91:371–382, 2016.

[152] R. Macfarlane. *Underland*. W W Norton, 2019.

[153] D. MacKay. *Sustainable Energy, without the hot air*. UIT Cambridge Ltd, 2009.

[154] R. Macklis, M. Bellerive, and J. Humm. The radiotoxicology of radithor. *Journal of American Medical Association*, 264(5):619–621, August 1990.

[155] D. Madigan, Z. Baumann, and N. Fisher. Pacific bluefin tuna transport fukushima-derived radionuclides from japan to california. *PNAS Early Edition*, 2012.

[156] J. Mahaffey. *Atomic Awakening*. Pegasus Books, 2009.

[157] J. Mahaffey. *Atomic Accidents*. Pegasus Books, 2014.

[158] J. Mahaffey. *Atomic Adventures*. Pegasus Books, 2017.

[159] A. Markandya and P. Wilkinson. Electricity generation and health. *Lancet*, 370:979–990, September 2007.

[160] G Matanoski. Health effects of low level radiation in shipyard workers. Technical report, Johns Hopkins University, June 1991. DOE Report DE-AC02-79EV10095.

[161] H. Matsumoto, Y. Shimada, and A. Nakamura. Health effects triggered by tritium. *Journal of Radiation Research*, 62(4):557,563, April 2021.

[162] J. Mauro and N. Briggs. Assessment of variations on radiation exposure in the united states. Technical report, US EPA, July 2005. EPA Contract Number EP-D-05-002.

[163] R. McNally, R. Wakeford, and P. James. A geographical study of thyroid cancer incidence in north-west england following the windscale nuclear reactor fire of 1957. *Journal of Radiolgical Protection*, 36(4):934–952, December 2016.

[164] D. Miles. *The Phantom Fallout Induced Cancer Epidemic in Southwestern Utah*. 2008.

[165] B Miller. A law is passed: the atomic energy act of 1946. *University of Chicago Law Review*, 15(4):799–821, Summer 1948.

[166] D. Miller and J. Hansen. Why fee and dividend will reduce emissions faster than other carbon pricing policy options. Technical report, November 2019. Testimony to House of Representatives.

[167] L. Miller and A. Kleidon. Wind speed reduction by large scale wind turbine deployments lower turbine efficiencies and set low generation limits. *Proceedings of the National Academy of Sciences*, 113(48):13570–13575, 2016.

[168] R. Miller, G. Randers-Pehrson, C. Geard, E. Hall, and D. Brenner. The oncogenic tramnsforming potnetial of the passage of a single alpha particle through mammalian cell nuclei. *Proceedings of the National Academy Sciences*, 96:19–22, January 1999.

[169] W. Miller. *Geological Disposal of radioactive Wastes and Natural Analogues.* Pergamon, 2000.

[170] S. Montgomery and T. Graham. *Seeing the Light: The Case for Nuclear Power in the 21st Century.* Cambridge University Press, 2017.

[171] W. Moomaw, P. Burgherr, G. Heath, M. Lenzen, J. Nyboer, and A. Verbruggen. 2011: Annex ii: Methodology. Technical report, IPCC, 2011. IPCC Special Report on Renewable Energy Sources and Climate Change.

[172] S. Mortazavi, M. Ghiassi, and M. Rezaiean. Cancer risk due to exposure to high levels of radon in the inhabitants of ramsar, iran. *Health Physics Society*, pages 436–437, 2005.

[173] C. Muirhead, J. OHagen, R. Haylock, and M. Phillipson. Mortality and cancer incidence following occupational radiation exposure: third analysis of the national registry for radiation workers. *British Journal of Cancer*, 100:206–212, 2009.

[174] M. Mycio. *Wormwood Forest.* Joseph Henry Press, 2005.

[175] D. Myers and M. Werner. A review of the health effects of energy development. *Nuclear Journal of Canada*, 1:14–24, 1987.

[176] S. Nadis. The sub-seabed solution. Technical report, The Atlantic, October 1996.

[177] M. Nair, S. Nambi, S. Amma, and P. Gangadharam. Population study in the high natural background radiation area in kerala, india. *Radiation Research*, 152:S145–S148, 1999.

[178] M. Nair, B. Rajan, and S. Akiba. Background radiation and cancer incidence in kerala, india, karanagappally cohort study. *Health Physics*, 96:55–66, January 2009.

[179] NCRP. *Permissible Dose from External Sources of Ionizing Radiation.* National Bureau of Standards, 1957. NSB Handbook 59.

[180] NCRP. Implications of recent epidemiologic studies for the linear nonthreshold model and radiation protection. Technical report, National Council on Radiation Protection and Measurements, May 2018. NCRP Commentary No. 27.

[181] J. Neel and W. Schull. The effect of exposure to the atomic bombs on pregancy termination in hiroshima and nagasaki. Technical report, National Academy of Sciences, 1956. NAS Publication 461.

[182] J. Neel and W. Schull. *The Children of Atomic Bomb Survivors: A Genetic Study*. National Academies Press, Washington, DC, 1991.

[183] T. Neumaier, J. Swenson, and C. Pham. Evidence for formation of dna repair centers and dose-response nonlinearity in human cells. *PNAS Early Edition*, 2011.

[184] T. Newcomb. Jacobs team beat four others for 6.4b doe clean up contract in idaho. *Engineering News record*, 2021-05-28, May 2021.

[185] R. Niebuhr. *Moral man and Immoral Society*. Scribners, 1933.

[186] Department of Data and Analytics. Who methods and data sources for global burden of disease estimates, 2000-2019. Technical report, World Health Organization, December 2020. WHO/DDI/DNA/GHE/2020.3.

[187] Department of Energy. Medical isotopes production project: Molybdenum-99 and related isotopes. Technical report, Department of Energy, April 1996. DOE/EIS-0249F.

[188] Department of Energy. Tritium handling and safe storage. Technical report, Department of Energy, December 2008. DOE-HDBK-1129-2008.

[189] Department of Energy. Yucca mountain repository license application: Safety analysis report, chapter 2. Technical report, USA Department of Energy, June 2008. DOE/RW-0573.

[190] Department of Energy. Final tank closure and waste management eis for the hanford site. summary. Technical report, USA Department of Energy, November 2012. DOE/EIS-0391.

[191] Department of Energy. Hanford site environmental report for cy2012. Technical report, Department of Energy, 2013. DOE/RL-2013-18.

[192] Department of Energy. Quadrennial technology review, an assessment of energy technologies and research opportunities. Technical report, Department of Energy, September 2015.

[193] Office of Nuclear Regulatory Research. Regulatory guide 1.18. quality assurance program criteria. Technical report, US Nuclear Regulatory Commission, June 2010. Revision 4.

[194] Royal College of Radiologists. Radiotherapy dose fractionation. Technical report, Royal College of Radiologists, 2006.

[195] Office of Science Advisor. An examination of epa risk assessment principles and practice. Technical report, USA Environmental Protection Agency, March 2004. EPA/100/B-04/001.

[196] N. Ohlendorf and W. Schill. Frequency and duration of low wind power events in germany. *Environmental Research Letters*, 084045, August 2020.

[197] D. Okrent. *Nuclear Reactor Safety*. University of Wisconsin Press, 1981.

[198] W. Olipitz, D. Wiktor-Brown, J. Shuga, and B. Pang. Integrated molecular analysis indicates undetectable changes in dna in mice after continuous irradiation at 400 fold natural background radiation. *Environmental Health Perspectives*, 120:1130–1136, August 2012.

[199] Committee on Remote Handled Waste. Characterization of remote handled waste for the waste isolation pilot plant, interim report. Technical report, National Academy of Sciences, 2001.

[200] Nuclear Waste Management Organization. Used fuel repository conceptual design. Technical report, Canadian NWMO, December 2012. Project Report TR-2012-16.

[201] World Health Organization. *WHO Handbook on Indoor Radon, A Public Health Perspective*. WHO, 2009.

[202] T. Otake. Evacuation of fukushima elderly riskier than exposure to radiation. *Japan Times*, February 2014. 2014-02-20.

[203] K. Ozasa, Y. Shimuzu, A. Suyama, F. Kasagi, M. Soda, and E. Grant. Studies of the mortality of atomic bomb survivors, report 14, 1950-2003. *Radiation Research*, 177:229–243, 2012.

[204] R. Partanen and J. Korhonen. *The Dark Horse*. 2020.

[205] B. Pastzor. Statistical summary of commercial jet airplane accidents, 1959-2018. Technical report, Boeing Commercial Airplane Company, April 2019. 50th Edition.

[206] S. Penninckx, P. Pariset, and S. Costes. Quantification of radiation induced dna double strand break repair foci to evaluate and predict biological responses to ionizing radiation. *NAR Cancer*, 3(4), December 2021.

[207] P. Peterson, H. Zhao, and R. Petroski. Metal and concrete inputs for several nuclear power plants. Technical report, University of California, Berkeley, February 2005. UCBTH-05-001.

[208] D. Phung. Economic of nuclear power: Past record, present trends and future prospects. *Energy*, 10(8):917–934, 1985.

[209] S. Plokhy. *Chernobyl: The History of a Nuclear Catastrophe.* Basic Books, 2018.

[210] D. Preston, E. Ron, S. Tokuoka, S. Funamoto, and N. Nishin. Solid cancer incidence in atomic bomb survivors: 1958-1998. *Radiation Research*, 168:1–64, 2007.

[211] Dreux R. Toxic management erodes safety at world's safest nuclear plant. *Japan Times*, March 2013. 2013-03-11.

[212] J. Rask, W. Vercoutere, and B. Navarro. Space faring: The radiation challenge. Technical report, NASA, 2009.

[213] D. Richardson, E. Cardis, and R. Daniels. Risk of cancer from occupational exposure to ionising radiation: retrospective cohort study of workers in france, the united kingdom, and the united states (inworks). *BMJ*, 351, 2015.

[214] D. Richardson, K. Leuraud, and et al. Cancer mortality after low dose exposure to ionizing radiation in workers in france, the united kingdom, and the united states (inworks):cohort study. *BMJ*, 2023-08-16, 2023.

[215] C. Richmond. The plutonium controversy. Technical report, Oak Ridge National Laboratory, 1980. CONF-801075-1.

[216] C. Richmond. The plutonium controversy. Technical report, Oak Ridge National Laboratory, 1980. ORNL-CONF-801075.

[217] T. Rockwell. What's wrong with being cautious? *Nuclear News*, June 1997.

[218] T. Rockwell. Discussions of nuclear power should be based in reality. *The Scientist*, March 1998.

[219] T. Rockwell. Nuclear energy: Not a faustian bargain but a near-perfect providential gift. *Nuclear News*, pages 34–38, November 2008.

[220] M. Rogovin and G. Frampton. Three mile island, volume i. Technical report, NRC Special Inquiry Group, January 1980.

[221] M. Romare and L. Dahllof. The life cycle energy consumption and greenhouse gas emissions from lithium ion batteries. Technical report, IVL Swedish Environmental Research Institute, May 2017. IVL C 243.

[222] E. Rosa and R. Dunlap. Poll trends: Nuclear power: Three decades of public opinion. *The Public Opinion Quarterly*, 58(2):295–324, Summer 1994.

[223] R. Rowland. Radium in humans, a review of u.s. studies. Technical report, Argonne National Laboratory, September 1994. ANL/ER-3, UC-408.

[224] O. Ruhnau and S. Qvist. Storage requirements in a 100% renewable energy system: Extreme events and inter-annual variability. *Econstor*, October 2021.

[225] S. Sans. Un dia si y otro no en la central nuclear. *La Vangardia*, April 2020. 2020-04-13.

[226] M. Sasaki, A. Tachibana, and S. Takeda. Cancer risks pf low doses of ionizing radiation. *Journal of Radiation Research*, 55:391–406, 2014.

[227] C. Schearer, N. Mathew-Shah, M. Myllyvirta, A. Yu, and T. Nace. Boom and bust 2019, tracking the global coal plant pipeline. Technical report, Global Energy Monitor, March 2019.

[228] S. Schneider and D. Kocher. Systematic radiological assessment of exemptions for source and byproduct materials. Technical report, US Nuclear Regulatory Commission, June 2001. NUREG-1717.

[229] P. Selby. The selby-russell dispute regarding the nonreporting of critical data in the mega-mouse experiments. *Dose Response*, pages 1–13, January-March 2020.

[230] N. Sepulveda, J. Jenkins, F. deSisternes, and R. Lester. The role of firm low carbon electricity resources in deep decarbonization of power generation. *Joule*, 2, October 2018.

[231] Presidents Special Session. Low level radiation and its implications for fukushima recovery. Technical report, American Nuclear Society, June 2012.

[232] D. Siemer. *A Nuclear Green New Deal?* in prep, 2021.

[233] V. Smil. *Energy Myths and Realities.* AEI Press, 2010.

[234] V. Smil. *Power Density.* MIT Press, 2016.

[235] J. Smith. Review of manual for survival by kate brown. *Journal of Radiological Protection*, 2019.

[236] L. Smith. *Nearly Nuclear, A Mismanaged Energy Transition.* Michigan State University Press, 2021.

[237] Y. Socol and L. Dobrzynski. Atomic bomb survivors life span study: Insufficient statistical power to select radiation carcinogenesis model. *Dose Response*, 13(1), 2015.

[238] M. Song, A. Hildesheim, and M. Shiels. Premature years of life lost to cancer in the united states. *Cancer Epidemiology, Biomarkers, and Prevention*, 29(12), December 2020.

[239] B. Sovacool, M. Kryman, and E. Laine. Profiling technological failure and disaster in the energy sector. *Energy*, 90, 2015.

[240] S. Spignesi. *The 100 Greatest Disasters of All Time.* Citadel Press, 2002.

[241] W. Standring, M. Dowdall, and P. Strand. Overview of dose assessment developments and the health of riverside residents close to the mayak facilities, russia. *Int. Journal of Environmental Research and Public Health*, 6:174–199, 2009.

[242] N. Takamura, M. Orita, and V. Saenko. Radiation and risk of thyroid cancer: Fukushima and chernobyl. *The Lancet/dibetes-endocrinology*, 4, August 2016.

[243] K. Tanigawa, Y. Hosi, and N. Hirohashi. Loss of life after evacuation: Lessons learned from the fukushima accident. *The Lancet*, 379:889–890, 2012.

[244] Z. Tao, Y. Zha, A. Akiba, Q. Sun, and J. Zou. Cancer mortality in the high background radiation areas of yangiang, china during the period between 1979 and 1995. *Journal of Radiation Research*, 41:31–41, 2000.

[245] L. Taylor. *Radiation Protection Standards.* Butterworth, 1971.

[246] N. Taylor, W. Sinclair, and R. Gorson. In memoriam: Lauriston s. taylor. Technical report, Health Physics Society, 2004. hps.org/aboutthesociety/people/inmemoriam/lauristontaylor.html.

[247] I. Thierry-Chef, M. Marshall, J. Fix, and F. Bermann. The 15 country collaborative study of cancer risk among radiation workers in the nuclear industry; study of errors in dosimetry. *Radiation Research*, 167:380–395, 2007.

[248] P. Thomas. Coping after a big nucelar accident. *Process Safety and Environmental Protection*, 112:1–3, 2017.

[249] R. Thompson, D. Nelson, J. Popkin, and Z. Popkin. Case control study of lung cancer risk from residential radon exposure in worcester, massachusetts. *Health Physics*, 1, 2008.

[250] R. Thurston. *Steam Boiler Explosions: in Theory and Practice.* J. Wiley and Sons, 1903.

[251] Committee to Assess Risk of Low Level Radiation. Health risks from exposure to low levels of ionizing radiation. Technical report, National Research Council, 2006. BEIR VII Phase 2.

[252] H. Toki, T. Wada, Y. Manabe, and S. Hiroto. Relationship between environmental radiation and reactivity and childhood thyroid found in fukushima health management survey. *Scientific Reports*, 10, 2020.

[253] M. Tronko, G. Howe, and T. Bogdanova. A cohort study of thyroid cancer and other thyroid diseases after the chornobyl accident: Thyroid cancer in ukraine. *Journal of the National Cancer Institute*, 98(13), July 2006.

[254] UNECE. Life cycle assessment of electricity generation options. Technical report, United Nations Economic Commission for Europe, 2021.

[255] Idaho State University. Radiation information network. Technical report, Idaho State University, 2016. Tritium Information Section.

[256] UNSCEAR. Report of the unscear, 13th session, supplement no 17 (a/3838), annex g. Technical report, United Nations Scientific Committee of the Effects of Atomic Radiation, 1958.

[257] UNSCEAR. Report of the unscear, 1959 report. Technical report, United Nations Scientific Committee of the Effects of Atomic Radiation, 1959.

[258] UNSCEAR. Sources and effects of ionizing radiation. Technical report, United Nations Scientific Committee of the Effects of Atomic Radiation, 1988.

[259] UNSCEAR. Sources and effects of ionizing radiation, volume ii, annex j. Technical report, United Nations Scientific Committee of the Effects of Atomic Radiation, 2000.

[260] UNSCEAR. Sources and effects of ionizing radiation, volume ii. Technical report, United Nations Scientific Committee of the Effects of Atomic Radiation, 2011.

[261] UNSCEAR. Sources, effects and risks of ionizing radiation. Technical report, United Nations Scientific Committee of the Effects of Atomic Radiation, December 2021. Volume II. Annex B.

[262] J Valentin. The 2007 recommendations of the international commission on radiological protection. Technical report, ICRP, 2007. ICRP Publication 103.

[263] W. Van Pelt. Epidemiological associations among lung cancer, radon exposure and elevation above sea level. *Health Physics*, 85(4):397–403, October 2003.

[264] S. Van Verst and E. Antonio. 2003 external radiation survey along the columbia river shoreline of the hanford site's 100 area. Technical report, Washington State Department of Health, May 2004. DOH 320-032.

[265] E. Verdolini and D. Vena, F. amd Popp. Bridging the gap: Do fast reacting fossil technologies facilitate renewable energy diffusion? Technical report, National Bureau of Economic Research, July 2016. Working Paper 22454.

[266] M. Vilenchik and A. Knudson. Endogenous double strand breaks: Production, fidelity of repair, and induction of cancer. *PNAS*, 100(22):1281–1286, October 2003.

[267] G. Voelz, J. Lawrence, and E. Johnson. Fifty years of plutonium exposure to the manhattan project plutonium workers: an update. *Health Physics*, 73:611–619, October 1997.

[268] O. Voigt and E. Koch. Incident in the wurgassen nuclear power plant. In *Karsruhe Reactor Meeting, April 10, 1973*, April 1973. ASME Conference.

[269] I. Waddington, P. Thomas, R. Taylor, and G. Vaughan. J-value assessment of relocation measures following the nuclear power plant accidents at chernobyl and fukushima daiichi. *Process Safety and Environmental Protection*, 112:16–49, 2017.

[270] R. Wakeford. The cancer epidemiology of radiation. *Oncogene*, 23:6404–6428, 2004.

[271] J. Walker. *Containing the Atom.* University of California Press, 1992.

[272] J. Walker. *Three Mile Island.* University of California Press, 2004.

[273] R. Watts. *Public Meltdown. The story of the Vermont Yankee Power Plant.* White River Press, 2012.

[274] W.(ed) Weaver. Genetic effects of atomic radiation: Summary report of bear i genetics panel. *Science*, 123:1157–1164, 1956.

[275] A. Weinberg. *The First Nuclear Era.* American Institute of Physics, 1994.

[276] W. Weiss. Unscear's assessment of the levels and effects of radiation exposure due to the nuclear accident after the 2011 great east japan earthquake. Technical report, United Nations Scientific Committee of the Effects of Atomic Radiation, February 2013. Volume 1. Annex A.

[277] T. Wellock. *Critical Masses. Opposition to Nuclear Power in California, 1958-1978.* University of Wisconsin Press, 1998.

[278] T. Wellock. *Preserving the Nation.* Harlan Davidson Inc, 2007.

[279] T. Wellock. *Safe Enough? A History of Nuclear Power and Accident Risk.* University of California Press, 2021.

[280] R. White and J Vijg. Do dna double strand breaks drive aging? *Molecular Cell*, 63, September 2016.

[281] R. Wilson. Evacuation criteria after a nuclear accident. *Dose Response*, pages 480–499, 2012.

[282] WNA. Sites agreed for four more south korean reactors. *WNA web site*, November 2014. 2014-11-21.

[283] WNA. Desalination. *WNA web site*, March 2020.

[284] S. Yamashita, S. Suzuki, H. Shimura, and V. Saenko. Lessons from fukushima: Latest findings of thyroid cancer after the fukushima power plant accident. *Thyroid*, 28(1), 2018.

[285] D. Yergin. *The Prize*. Simon and Schuster, 1993.

[286] S. Yoshinaga, K. Mabuchi, and A. Sigurdson. Cancer risk among radiologists and radiologic technologists. *Radiology*, 233:313,321, 2004.

[287] L. Zablotska, E. Ron, A. Rozhko, and M. Hatch. Thyroid cancer risk in belarus among children and adolescents exposed to radioiodine after the chornobyl accident. *British Journal Of Cancer*, 104:181–187, 2011.

[288] L. Zupunski and et al. Breast cancer incidence in the regions of belarus and ukraine most contaminated by the chernobyl accident: 1978 to 2016. *International Journal of Cancer*, 148:1839–1849, 2021.

Index