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

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Tavernier, Florida

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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 complex 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 complex 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.

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 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, you will probably die due to bone marrow failure in a week or two.

A sievert is a large amount of joules per kg. We live in a sea of natural radiation. The background dose rate on this planet from natural radioactive sources varies from about 0.001 Sv/year to more than 0.010 Sv/year. 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 2,500 gigawatts(GW). But the distribution is horribly uneven as Table 1.1 shows. The USA consumes 1,400 watts per person. The Scandinavian

	W/person		W/person		W/person
Norway	2,922	China	396	Indonesia	92
USA	1,401	Iran	261	India	65
Australia	1,064	Brazil	258	Philippines	61
Russia	831	Mexico	208	Angola	28
France	815	Egypt	163	Nigeria	13
Germany	772	Iraq	125	Afganistan	9
Italy	582	Columbia	113	Haiti	3
South Africa	550				

Table 1.1: Electricity consumption per person

countries considerably more. But most of Latin America is below 250 W. Most of South Asia below 100 W. Most of Africa below 25 W. The national averages mask wide disparities. A billion humans have no access to electricity at all.

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

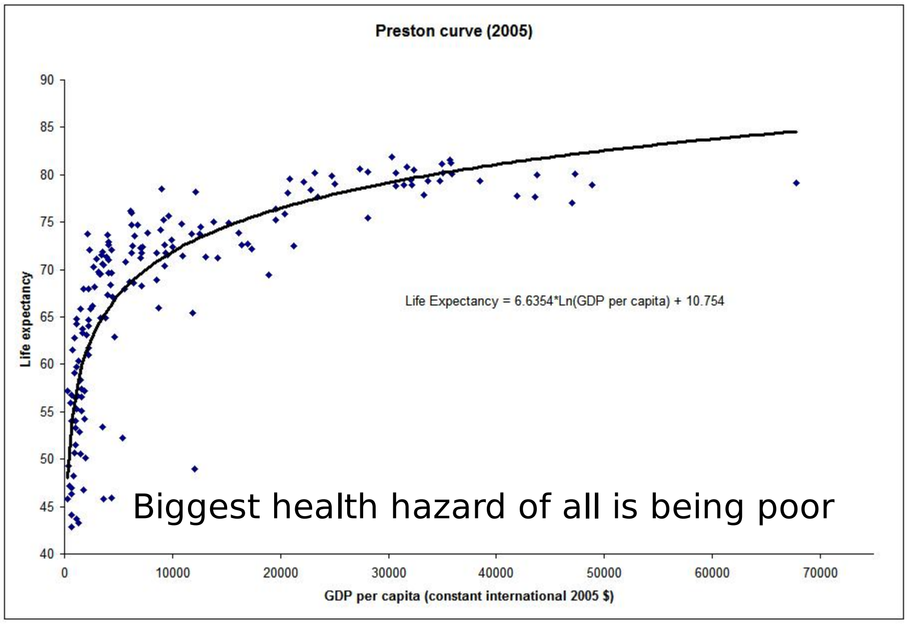


Figure 1.1: Life expectancy versus GDP. Each dot is a country. The dots hide large intra-country disparities. In the USA, a wealthy country, the difference in years of life expectancy between the top 1% in income and the lowest 1% is 14.6 (men) and 10.1 (women).

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. This figure makes 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.

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.

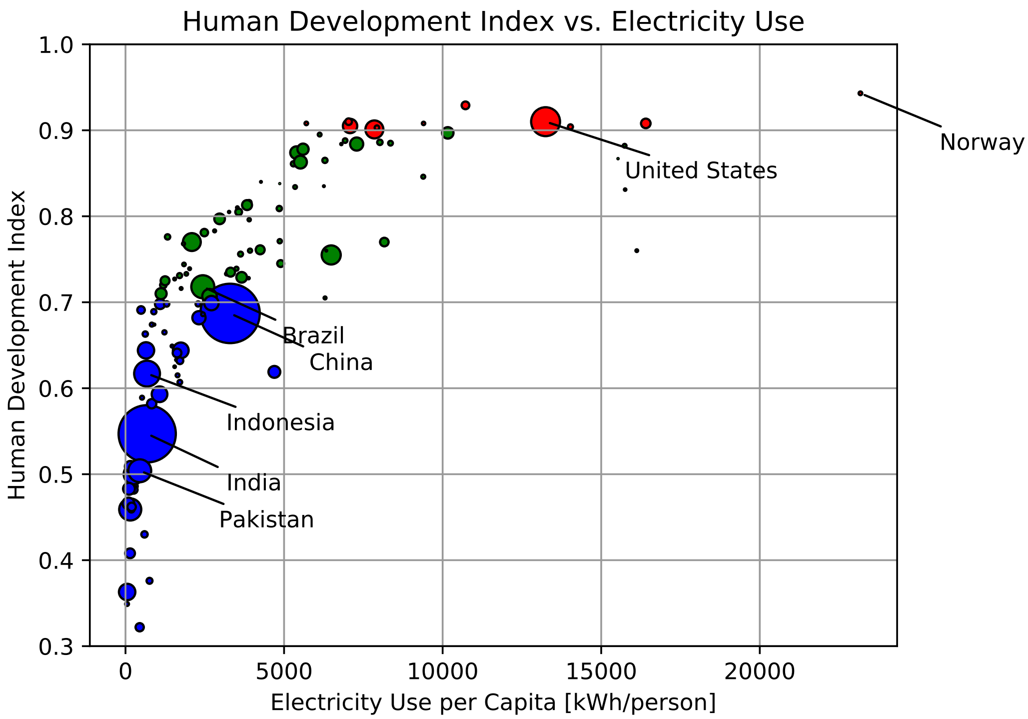
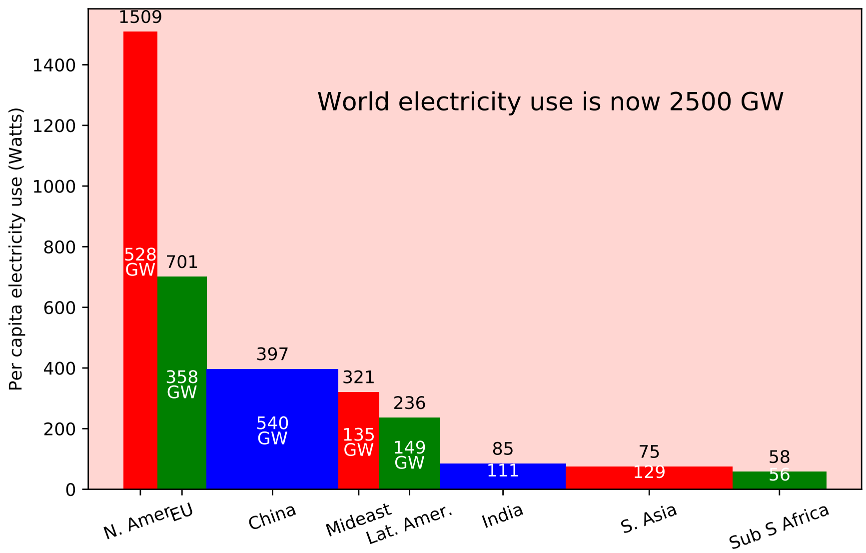


Figure 1.2: Human Development Index versus per capita electricity consumption. Credit: Touran

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.[145] 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.



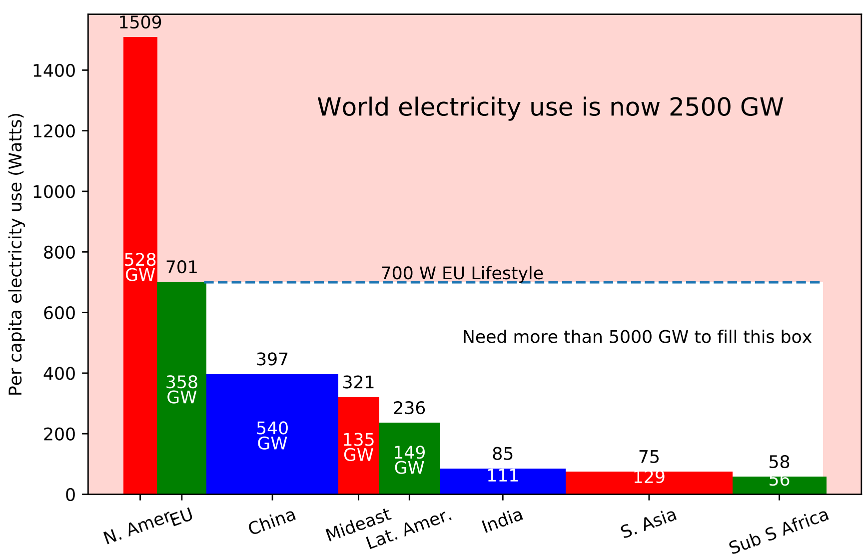


Figure 1.3: Regional distribution of electricity consumption, courtesy Hargraves. Width of each bar is regional population; height is per capita electricity; area is regional electricity consumption.

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.

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, dispatchable 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 the current Swedish very high per capita 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,*** 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 dispatchable power source that is not only cheap, that is, economical in its use of the planet's resources, but expandable on a grand scale.

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.[178] Desal requires about 3 kWh of electricity per m3. Using the UNESCO numbers, the planet will need 685 GW for desal in 2025.[2] Capital intensive processes like desal must operate 24/7 to be

[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] 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 artifical light are roughly 10 times that of conventional

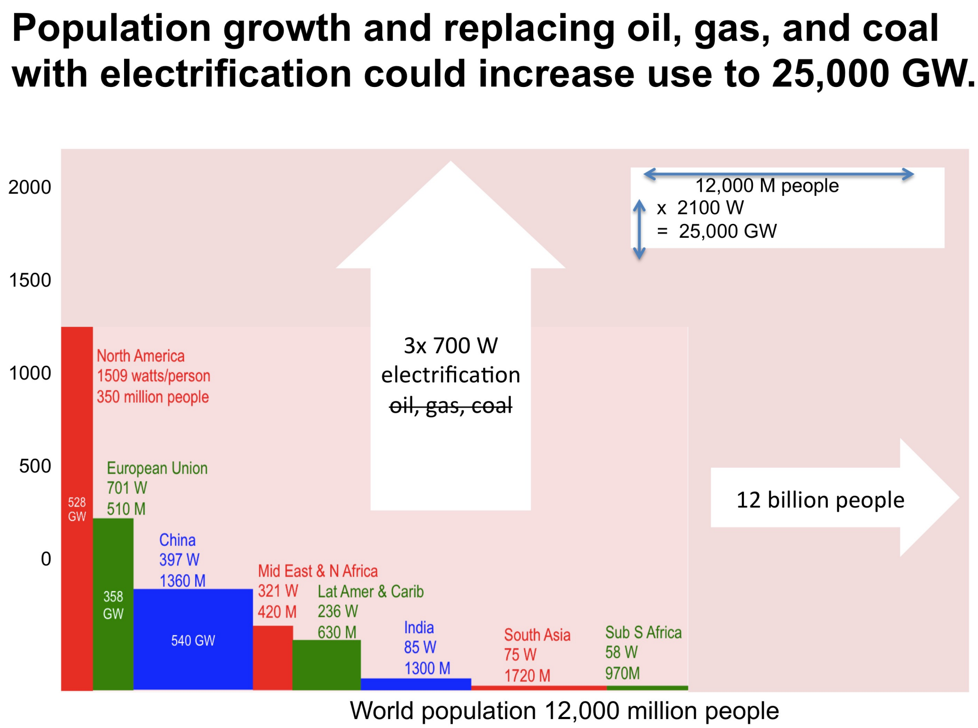


Figure 1.4: Electricity consumption in decarbonized world, courtesy Hargraves. To meet the demands of decarbonization, we need a grid capable of filling the entire pink box, a grid 10 times larger than current.

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

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green houses. Vertical farming only works if really cheap 24/7 electricity is available.

Chapter 2

Used Nuclear Fuel

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 complex has promulgated a very important lie, which we will discuss in Chapter 3

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.
>
> 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.

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. The shielding was a plastic bag and I presume the royal gloves. The Queen has 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 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.

[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.[100][Ch. 2] In both cases, everybody else in the room survived with little or no after effects.

[4] https://www.youtube/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.[37][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.[7]

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.

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 3,000 mSv/y for 21 years.[8]

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[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.[100][p 236-248]

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

[7] 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 Steven's blood stream, the experimenters guaranteed that Stevens would carry nearly all that plutonium to his grave. There are many materials 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.

[8] 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.

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. 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.[37][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.[138][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.[11] 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 chemicals such as chlorine, phosgene, and ammonia.[36][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.[170] 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.

2.2 A Beautifully Small Problem

If plutonium is an easily handled material, what are we worried about? What is the nuclear waste problem?

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.

Figure 2.2 shows the dry cask storage facility for Connecticut Yankee near Haddam Neck on the Connecticut River.

Connecticut Yankee (CY) was a 619 MWe pressurized water reactor that 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.[9] 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 2.2 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 feet high. The amount of solid waste per unit power produced by a nuclear power is 10 to 20

[9] 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.

Figure 2.2: 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.

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 2.3. 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.[10]

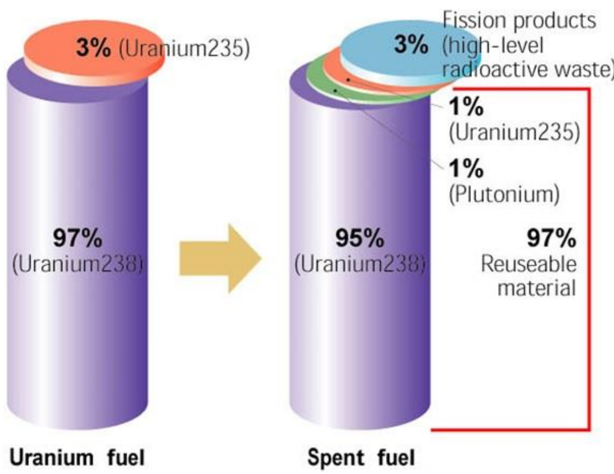

Figure 2.3: Composition of Used Fuel

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 do any damage, they must be ingested or inhaled.[11]

Transuranic decay tends to be very slow with some important TRU isotopes having half-lives

[10] 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.

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

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 2.2 are as big as they are. They provide the shielding that allows essentially unlimited access to the storage facility.

Cask hugging, Figure 2.4, 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 2.4: Cask Hugging at Palo Verdes. Credit: Paris-Ortiz-Wines

2.3 The Cost of Dry Cask Storage

But what about the economics of dry cask storage? Figures 2.6 to 2.9. 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.[77] 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 2.5 as a function of 60 year generations.

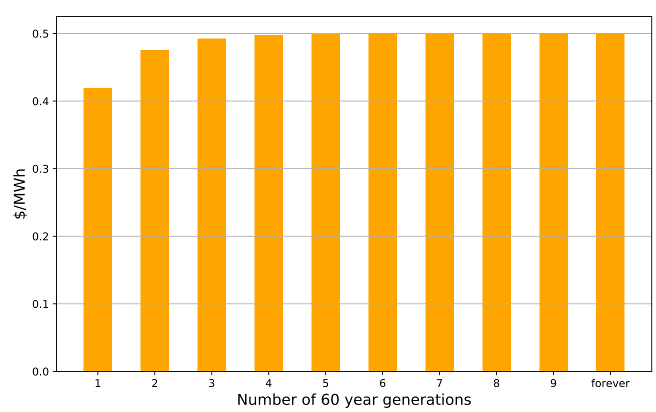

Figure 2.5: Hi-Store Unit Cost as a function of storage time

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.

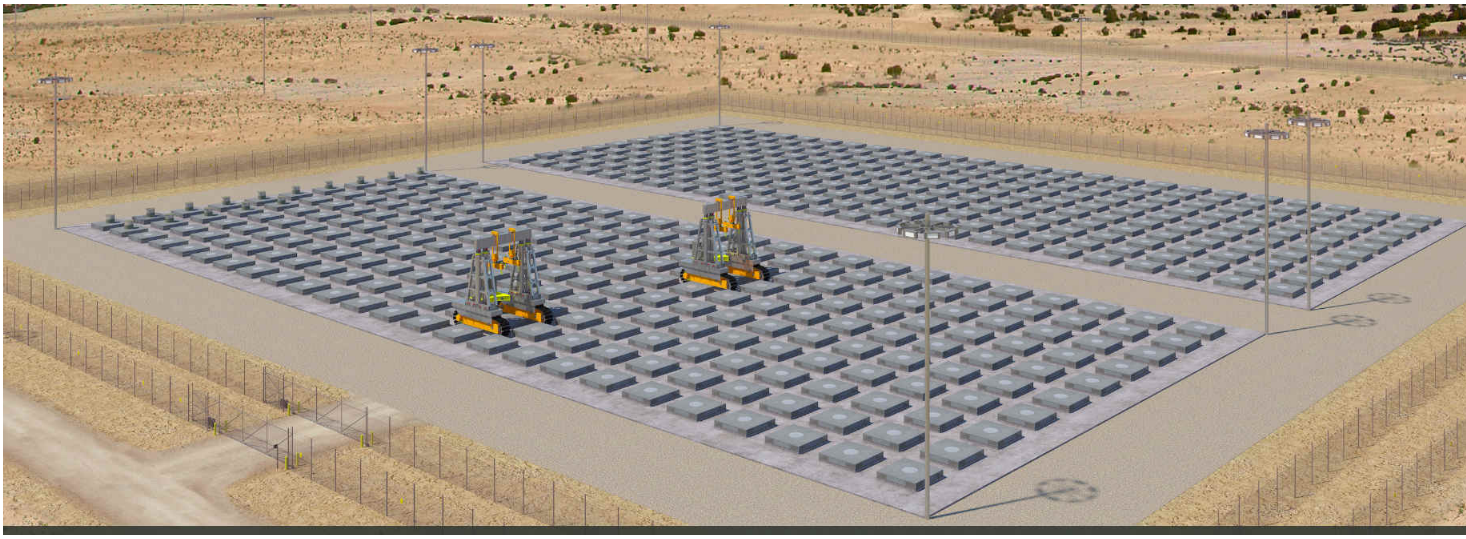

Figure 2.6: 500 cask Hi-Store pad. Hi-Store uses a vertical, below ground cask.

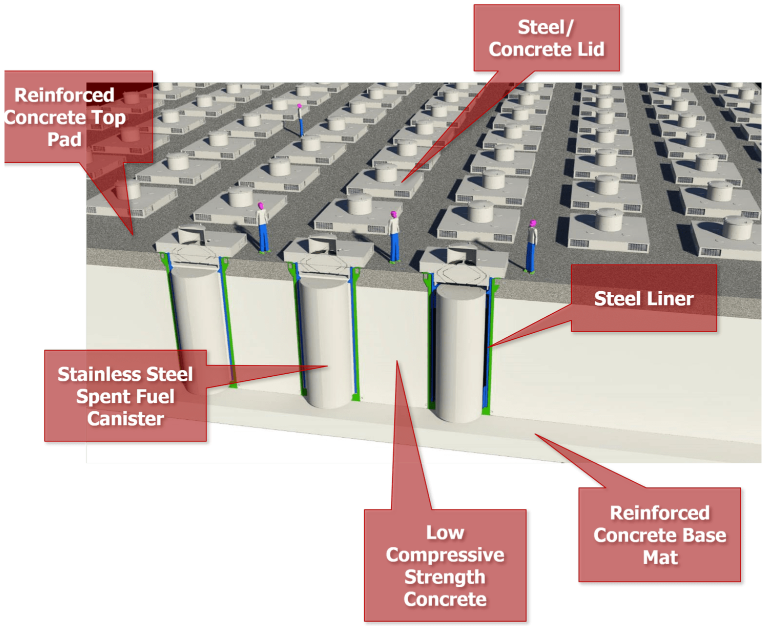

Figure 2.7: Cutaway view of the storage system

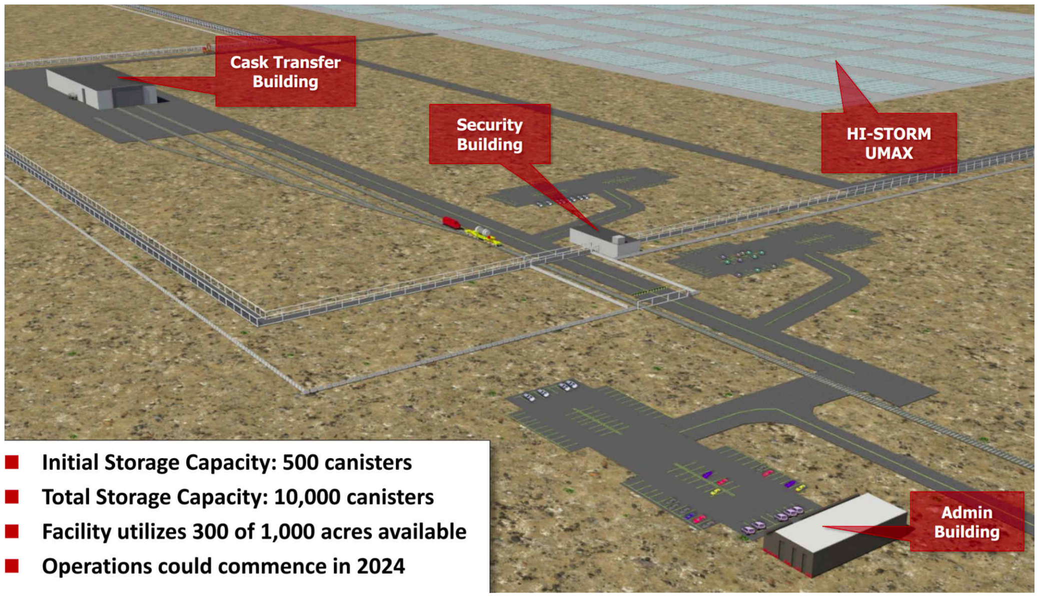

Figure 2.8: Overall view of the Hi-Store facility

Figure 2.9: 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.

2.4 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 7.8 — 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 complex created the nuclear waste problem.

2.5 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".[112] 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 complex 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 complex.[12]

2.6 Preserving Nuclear Ore

So at the end of the day, what should we do with the used fuel? Indefinite dry cask storage would be fine, but my favorite is a *vault*. Used fuel is a potentially valuable ore. Consider just two 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

[12] 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.

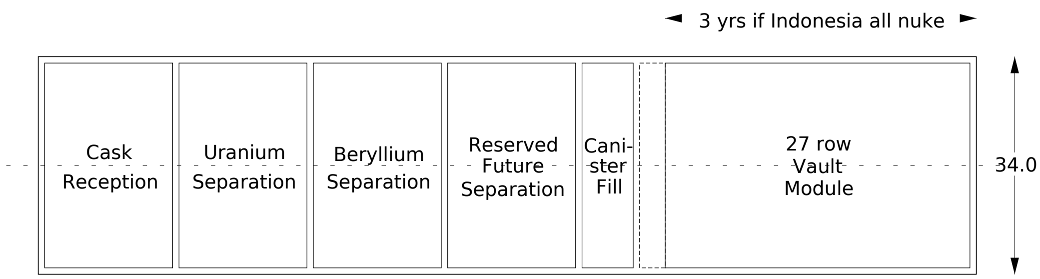

Figure 2.10: Conceptual Plan of Indonesian Used Fuel Recycling and Storage Center

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 thorium into the fuel, the used fuel will contain substantial amounts of ^{233}U. This ^{233}U can then be milked for its ^{229}Th.

Nuclear used fuel contains some 150 isotopes. 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. We don't know. All we can do is preserve the ore for our descendants and let them decide what to do with it.

The best way to do that is a vault. Figure 2.10 sketches 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 2.10. 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 2.11 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.

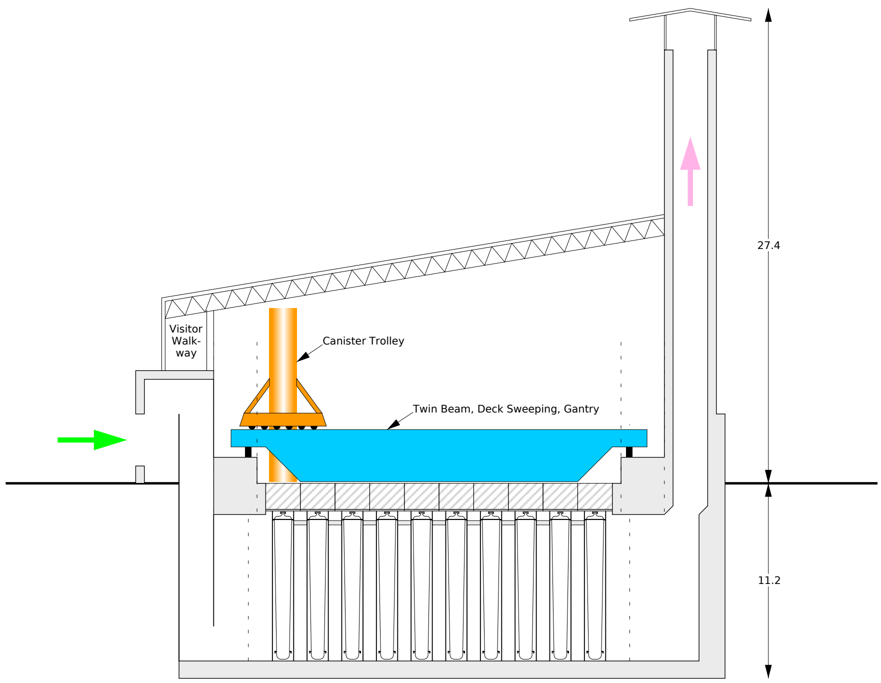

Figure 2.11: Section of Vault

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 2.12. Vaults become the centerpiece of a bustling, vibrant, high tech industrial park. The economic activity at MCC supports a small city.

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 2.12: Zheleznogorsk Mining and Chemical Complex

2.7 Geologic Disposal

As we have seen, the nuclear power complex's knee jerk solution is deep geologic disposal. 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.

Expensive geologic repositories send exactly the wrong message to the public and send it very clearly. 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? Should I trust their claims that the repository is safe?

Regulatory costs aside, deep geologic disposal could be done quite cheaply by using the horizontal drilling technology developed by the oil and gas industry. However, retrieval would be difficult to impossible. Horizontal borehole disposal is an option our descendants will have if sometime in the future they decide the value of the material remaining in the vault is no longer worth keeping it there. But it should be their decision, not ours.

Chapter 3

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.[175] 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 4.6.10. 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 4.1.

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.

3.1 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 failure 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.

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).[2] 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 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] 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.

Derivan was the Shift Supervisor at Davis-Besse, a similar plant to Three Mile Island. Six 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] 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.

(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.[3] 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 4.1.
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 4 and 5

3.2 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.

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

[3] 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.

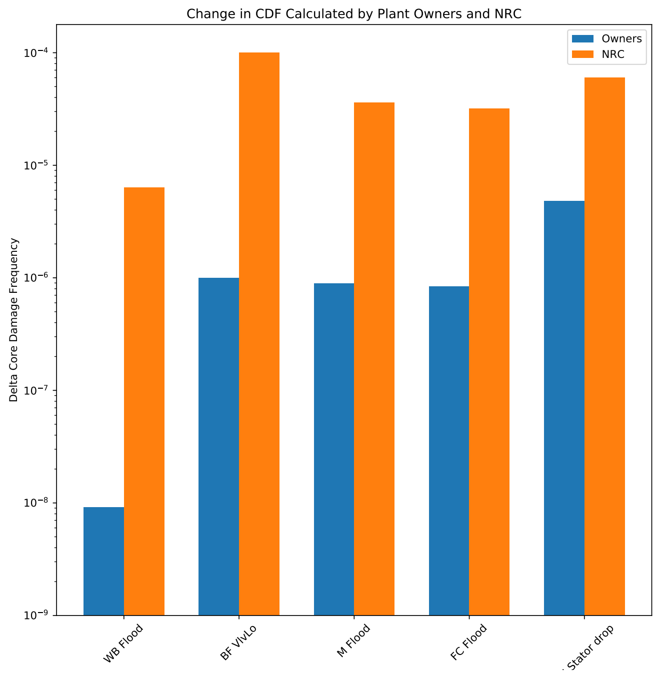

Figure 3.1: NRC vs plant estimate of increase in CDF due to fault

concoct them. To do this the applicant builds 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.

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 3.1 compares the two numbers for five of the yellow and red faults.[95] 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 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.[4] 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 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.

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

[4] 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.

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. 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.[5] 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, and at Columbia, 1998-06-17. See also Fukushima.

"Adding provisions to solve a non-problem merely provides additional paths to failure." Ted Rockwell.[140] 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 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 2.2. But dry cask storage adds about 0.03 to 0.06 cents to the cost of the electricity.[6]

All 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

[5] 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.

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.[10] 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."[56][p 77] At the time, the RSS results were considered fraudulent by almost all statisticians. 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 nature involving very low probabilities, we do not now have confidence in the presently calculated values of the probabilities."[93] 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.[56][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.[41]

Despite this, PRA was pounced on by the industry and NRC and quickly 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 complex's philosophy that any major casualty is unacceptable where major casualty is defined as any 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 release is impossible, we use PRA to produce astronomically low probabilities and use those to imply that it is virtually impossible.[6]

This is a stupid, self-defeating lie. Radioactive releases will happen and, when they do, public trust is lost for a very long time if not forever. While we should take reasonable measures to make casualties like 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 4.6.10, 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 complex had said

[6] 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.

> 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 complex would have been able to say:

> Damn, we had a major casualty. We will learn from it just like the airlines learn something from every crash, and use that 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.

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 a stress test of the EBR-1, the world's first breeder reactor at a remote Idaho test facility. 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.[100][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.

It's not the public that is stupid. It's the other way around. If the nuclear power complex 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.[7] Will they learn the lesson when the next major release occurs?

[7] 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 4

Nuclear Power Safety

> 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 this is an extremely scary event. 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.[81] If radiation is so scary, why are we here?

The answer is life evolved a system, an extraordinarily clever system, for handling this onslaught. 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 4.10 where we can start moving ahead again.

4.1 Killing People Statistically

4.1.1 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".[85] 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.[155] 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.[177]

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.[131]

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.

4.1.2 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.[38]

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.

4.1.3 Energy Related Sure Deaths

This is relevant to nuclear. It is indisputable that nuclear is the safest source of 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.[1] The ENSAD database contains 1870 such casualties totaling some 81,000 fatalities, Table 4.1.[21]

Exactly one of the those casualties is nuclear. Chernobyl (Section 4.6.10) 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 registered small nodules or cysts, far higher than expected from normal screening. This raised all

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

Table 4.1: 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

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.[179][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.[179][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 4.2 is a 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.[2]

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.

4.1.4 Statistical Deaths

The concern for nuclear power is statistical deaths, or far more precisely the impact on life expectancy. And the Lost Life Expectancy we are talking about is cancer. Radiation can

[2] 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 4.2: Major Energy Related Casualties, 1960-, Sure Deaths

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

damage a cell's DNA. A tiny proportion of that damage can escape the multiple repair and defense mechanisms that evolution has provided us with and eventually lead to cancer.

Cancer is an old folk's disease. BEIR VII recommends assuming a 10% increase in incidence of cancer per 1000 milli-Sievert, and roughly half of cancers result in the patient's death. This is based on the Linear No Threshold (LNT) hypothesis that mortality is linear and strictly cumulative in dose. How rapidly you receive the dose is irrelevant. According to LNT, receiving 1000 mSv in a minute has the same effect as receiving 1 mSv per day for a 1000 days. According to LNT, 1000 people receiving 1 mSv has the same impact as one person receiving 1000 mSv. In the next chapter, we will argue that there is indisputable evidence that these assumptions are seriously wrong. But for now let's see where they lead.

Assuming LNT, Cardis et al estimated the eventual deaths for the three groups shown in Table 4.3[Table IV].[27] This table is widely accepted as the official estimate of the statistical deaths from Chernobyl. Cardis's method was a marvel of simplicity: for each group multiply the man-sieverts times 0.1.[3] But for now our job is not to punch holes in this frail model, but rather to accept their numbers and ask what do they mean for life expectancy.

Table 4.3: Cardis et al estimate of statistical deaths from solid cancer from Chernobyl.

Group	Population	Average mSv	Expected deaths	Excess deaths	Percent increase
Liquidators	200,000	100	41,500	2000	4.8
Evacuees	135,000	10	21,500	150	0.7
SCZ residents	270,000	50	43,500	1500	3.4
Other Contaminated	6,800,000	7	800,000	4600	0.6
Total				8250	

I don't have mortality tables for Belarus and its neighbors. So let's assume we are dealing with male Americans. In this analysis, we are only looking for orders of magnitude. When you increase the cancer mortality of 135,000 members of the male US population by 0.7%, you get a LLE for this group of 10 days.[4] When you do the same thing for the Strict Control Zone residents you gets an LLE of 44 days. Table 4.4 summarizes the LLE numbers. The last two columns in this table try to convert the LLE numbers back into sure deaths. A casualty that kills a randomly selected group of people surely will reduce each victim's life by about 40 years on average. Table 4.4 simply divides the group LLE by 40. The resulting equivalent sure deaths is about half the mislabeled "Excess deaths" in Table 4.3.

[3] Cardis et al appears to conflate cancer incidence with cancer mortality. As a result their numbers are double the BEIR VII recommendations.

[4] In doing so I applied the same increase to all age groups. Cardis et al say this seems to be the case for solid cancers in the atomic bomb survivors with a lag of 5 to 10 years. However, for the liquidators I assumed they were all 20 when exposed. It turns out the differences are small. There is an arithmetic error in Other Contaminated. The expected deaths should be about 1,100,000 to match Cardis's other numbers, which yields an excess mortality rate of 0.44%.

Table 4.4: Loss of Life Expectancy according to Cardis and LNT

	LLE years	Group LLE	40 yr lives
Liquidators	0.203	40,600	1015
SCZ	0.120	32,400	810
Evacuees	0.028	3,800	95
Other contam.	0.017	115,600	2900
Total	0.026	192,400	4810

These calculations indicate that if we stubbornly want to compare sure deaths with statistical deaths due to cancer in terms of life expectancy, we should reduce the latter by roughly a factor of two.[5]

But it makes more sense to talk in terms of LLE, which is a better measure of the risk each of us is exposed to. The average LLE for Cardis' entire population is 9.5 days.

I say again Cardis's numbers depend on LNT. Chapter 5 argues that LNT is orders of magnitude high at near background dose rates. In Cardis's groups, only the liquidators were exposed to above background dose rates. But let's accept these LNT based LLE's for the moment. Whatever the number, Chernobyl represents almost all the statistical LLE associated with commercial nuclear power. Cardis's 7.5 million people represent almost all the LLE associated with Chernobyl. They also represent just about 1000th of the world's humans. According to LNT, nuclear power has an LLE of 0.0095 days or 14 minutes. For context, Dockery and Pope estimates the LLE associated with living in a mildly polluted city (15 μg/m3 $PM_{2.5}$) to be 292 days.[6] A moderately polluted city (25 μg/m3 $PM_{2.5}$) costs us 569 days.[50] A highly polluted city (Beijing) costs us 1,149 days. These numbers are roughly consistent with the Huai River study which found than a 10 mg/m3 increase in particulate matter reduces life expectancy by 234 days.[53]

Throughout most of the world, the dispatchable alternative to nuclear is coal. Cohen estimates the LLE associated with coal pollution at 23 days. This is an American number[38][p. 383] Cohen admits the number could be off by a factor of 3 either way. But that hardly matters, an LLE of 23 days is 2000 times higher than the Chernobyl number. Coal produces about 5 times as much electricity as nuclear. The coal LLE per power generated is very roughly 400 times larger. Markandya and Wilkinson using a completely different approach estimate that the statistical LLE of coal is about 500 times higher than that for nuclear and put that for gas at about 50 times nuclear.[101]

Bottom line: even if we accept LNT, nuclear has a very large advantage over fossil fuel ***in statistical LLE***. But accepting LNT would be (and was) a monumental mistake.

[5] BEIR-VII using a different method estimated the LLE of a cancer death at 11 years for American men and about 12 years for American women.[159][Table 12-4] This points to a factor closer to four.

[6] $PM_{2.5}$ is shorthand for Particulate Matter whose particle diameter is less than 2.5 microns.

4.2 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.[7] 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.[8] 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.

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 persion 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.[9] 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.

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[7] 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.

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

[9] The Union of Concerned Scientists LNT based estimate is 26,000, Table 5.2.

If LNT is not valid, Chernobyl killed about 50 people and may shorten the lives of perhaps 1500 more, Section 5.5. Almost all the currently restricted zone is safely livable and has been for more than 30 years.[10] 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. Almost all the evacuation and the 1600 plus evacuation related deaths could have been avoided. If LNT is not valid, almost all the evacuated area could have been reoccupied in less than a month, most of it immediately. 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.

4.3 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".[91] 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".[57] 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.

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[10] In fact, the restricted zone was reoccupied as early as the summer of 1986 by illegal "self-settlers". The explosion occured in April, 1986. In fall of 1986, two of the four units at the plant were restarted, Section 4.6.10. The last unit was restarted a year later. Up to 4000 people worked at these plants for the next 20 years.

> 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.[60]

In late 1945, the Foundation set up Herman Muller at Indiana University with a generous grant. 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.[22][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 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.[58]

In 1946, despite a somewhat 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 4.5. 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 4.5: Caspari Table 2. 52.5 r is 525 mSv. Gamma-rays are photons.[29]

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.[11]

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 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. 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 an acceptable *tolerance* dose below which there was a balance between injury and repair and no measurable 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.[24][page 13][12] Later that year, the BEAR I panel issued a report claiming "from a genetics point of view" all doses of radiation are harmful.[13] The New York Times immediately

[11] When Caspari finally published his results in 1948, he treated them as an anomaly, something to be studied further.[29] 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.

[12] 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 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,[173] 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.

[13] 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.

ran a front page story with the headline "SCIENTISTS TERM RADIATION A PERIL TO THE FUTURE OF MAN".[14] 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.[117] ***There was no evidence of any damage to children conceived after the bombs were dropped.***[15]

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 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.[16] 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.[92] 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.

Bronk did not object. Bronk was also the President of the Rockefeller Institute and on the Foundation's Board of Trustees.

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

[15] There has been a series of follow up studies extending into the 1990's.[118] They confirmed and strengthened the original results.

[16] The acrimonious correspondence shows that Muller was much more worried about funding than pushing LNT.[25] 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.

4.4 The Atom Bomb Survivors

4.4.1 Introduction

For regulatory purposes, the single most important source of cancer radiation risk 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.[80] 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. It is difficult to imagine what possibly could have happened between 2004 and 2012 which could change the estimated 1945 exposures so drastically.
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.

4.4.2 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 totally 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 4.3, 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.
2. There was a tremendous uncertainty in the individual doses.

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 4.6: UNSCEAR 1958 Table VII Leukemia Incidence

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?[17]

> 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.[162][para 31, page 165]

P_L is the extra probability of leukemia occurring per dose per year since exposure, the last column in Table VII. So 0.091, 0.069 and 0.025 (without the typo) are equal? What about the Zone D numbers?

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

> 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.[162][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 4.7.

Table 4.7: 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."[92][page 125] But if there is no difference between 50 mSv and zero, the relationship cannot be linear. The widely acclaimed and 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 positive responses again.

4.4.3 The RERF

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".[59][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.[18] Table 4.8 displays the result of ratioing solid cancer deaths to the number of subjects in each dose category. Figure 4.1 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.

Ozasa et al, Figure 4 show positive ERR's (Excess Relative Risk defined in Section4.4.1) in these two dose categories.[132] 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 4.8 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.[144] Sasaki suggests a possible explanation is that this group under-reported their dose to avoid harming their marriage prospects.

Figure 4.2 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

[18] 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.

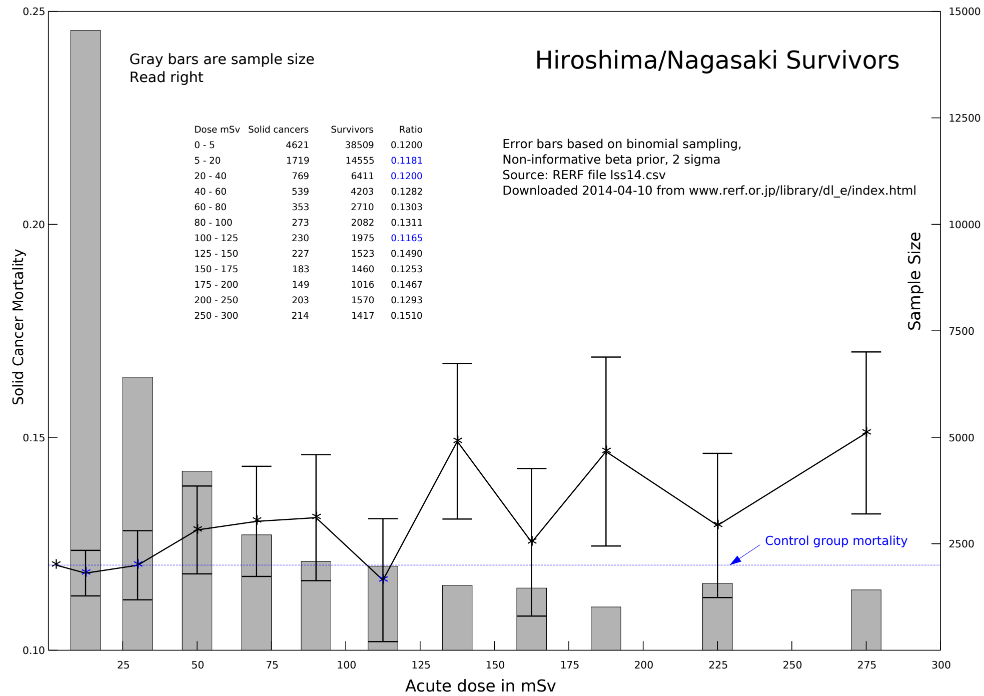

Figure 4.1: RERF Solid Cancer Mortality, 0 to 300 mSv

applicability to nuclear power plant releases, are strongly emphasized.

4.4.4 Summary

In summary,

1. The REFR data is based on acute doses while almost all nuclear safety issues involve chronic doses. 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].[132, 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.

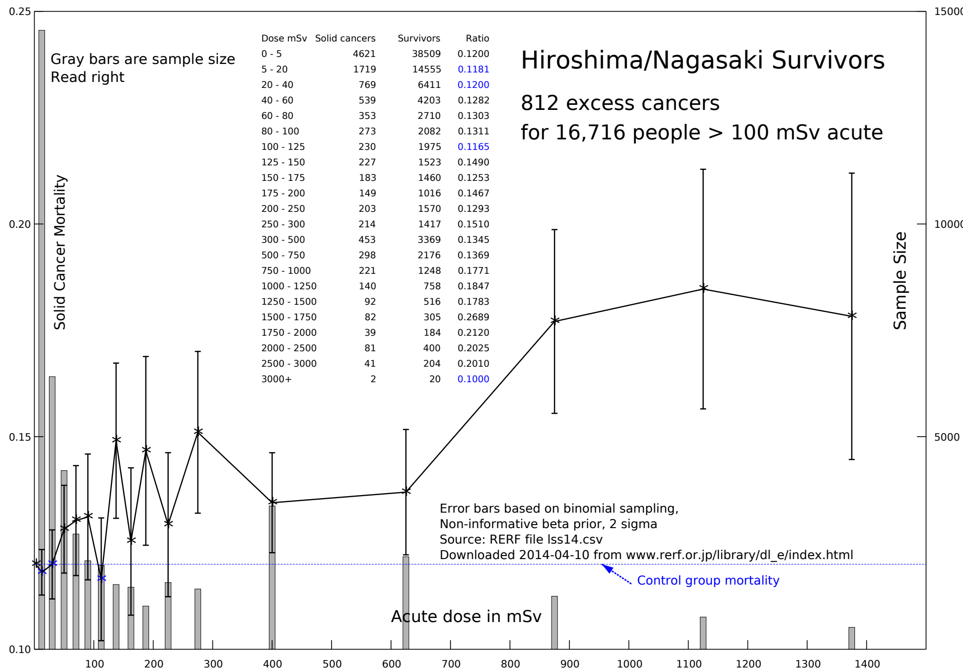

Figure 4.2: RERF Solid Cancer Mortality, 0 to 1500 mSv

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).[132, page 234]

An acute dose of 2000 mSv is far above the range of interest for most nuclear power plant safety issues.

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

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 4.8: RERF Solid cancer mortality from lss14.csv

4.5 Radiotherapy and LNT

In the explosion at Chernobyl (see Section 4.6.10), over a hundred plant workers and first responders received doses of 1000 mSv or more. 134 were treated for Acute Radiation Syndrome (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 4.9 shows short-term death rates of the 134 Chernobyl ARS victims against dose.[165][page 58]

		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
6100to 16000 mSv	20 out of 21	0.95

Table 4.9: Chernobyl ARS deaths as a function of dose

The Chernobyl ARS doses were acute doses. They were received over a period of a few hours or less. 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 4.3 plots the Table 4.9 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 4.3.

It is difficult to see in Figure 4.3, 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 4.3 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.[19] This is gospel as far as radiotherapists

[19] LNT is often defended on the grounds that it is conservative. But in fact it is only conservative at the low

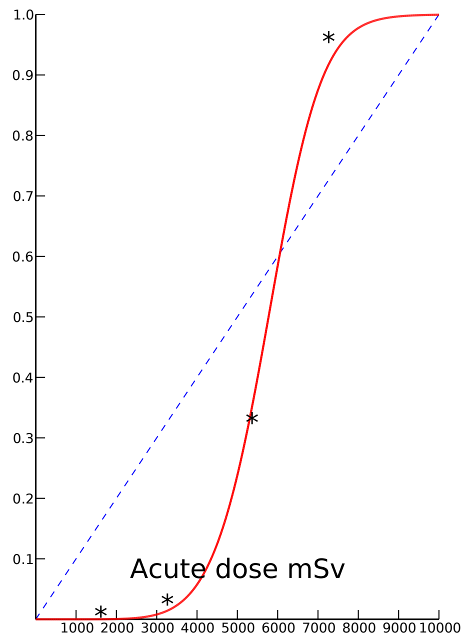

Figure 4.3: Chernobyl ARS deaths as a function of dose

are concerned. Here's a quote from the Royal College of Radiologists,[125].

> 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 4.3 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.[175]

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end. And then only if dose rate is unimportant.

As does the non-linearity. Figure 4.4 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.

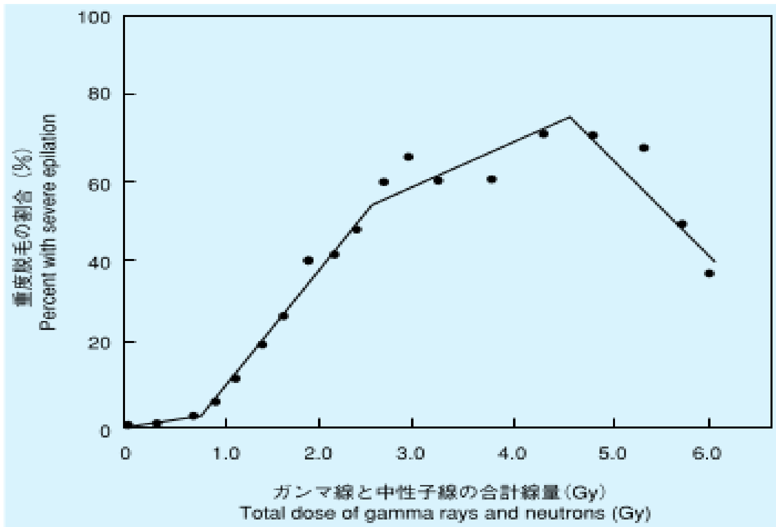

Figure 4.4: RERF survey of acute hairloss of atom bomb survivors, 1 Gy = 1000 mSv

Another fundamental principle of radiotherapy is *fractionation*. The doses required to kill tumors are enormous. Radtiotherapists 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.

4.6 Occupational and Other Exposures

4.6.1 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.[13] Table 4.10 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. The dose rates for this group have been estimated to be over 1000 mSv/y.[26] Early on radiologists calibrated their X-ray machines by sticking an arm

	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 4.10: Standardized mortality rates for British Radiologists

into the beam. If it caused a pink reaction, similar to sunburn, then it was set up properly.[99][p 238] 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 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 fron 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.[171] 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 4.10.

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

Wafeford 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.

4.6.2 UK Radiation Workers

In 2009, Muirhead et al updated the ongoing study of 174,000 UK radiation workers for which we have dose numbers.[109] 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).[20]

Table 4.11 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.

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 4.11 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

[20] 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."[28] 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. The only apply if the relationship is linear.

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 4.11: Deaths all causes from Muirhead, Table S2

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 4.11 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.

4.6.3 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.[28]. The authors start out by admitting that "Most [rad worker] studies to date showed little evidence of dose related increase in all cancer mortality". The goal of the combined study was to improve the statistical precision by combining the individual country cohorts.

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 risk 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.

The authors' bottomline is that there is a positive correlation between cumulative doses and deaths from all causes within the population and a stronger correlation between cancer deaths and dose. To get this positive correlation, they threw out two cohorts, INL and Ontario Hydro, which they admit showed "strong and statistically significant negative correlation between radiation dose and cancer risk". This was done because their summary table was somehow stratified by socio-economic status, and the information to perform that stratification was not available for 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.

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.

Fortunately, the authors summarize some of their results graphically in their Figure 1, our Figure 4.5. 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 4.5 is that the confidence limits dwarf the data.

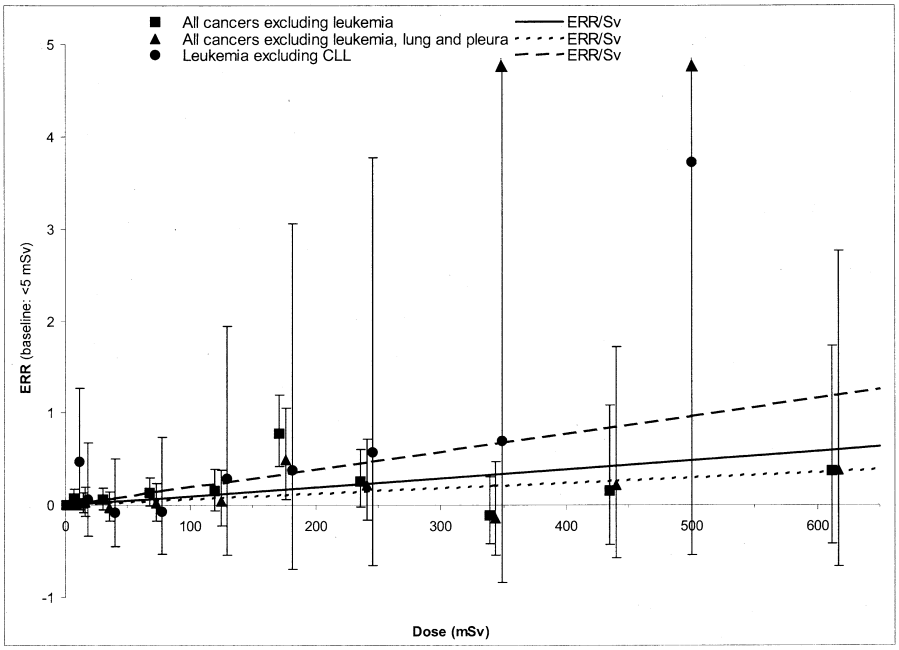

Figure 4.5: Cardis et al, Figure 1

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".[21] They continue

[21] 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[159]. 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.[159][p 194]

BEIR VII then decreed that "occupational studies are not currently suitable for the projection of population based risks."[159][p 206]

> 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. 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?

Bottomline: the failure to distinguish between acute dose and chronic dose, the exclusion of three important cohorts that showed negative correlation between dose and mortality, the selective use of a highly non-linear model to avoid negative correlations, while at the same time claiming that undisclosed portions of their study showed linearity and then retracting that claim make it very difficult to take the Cardis et al results at face value. But even taken at face value, the results are not a strong argument for LNT as their Figure 1 makes clear.

Postscript After the above was written, Canada withdrew a 3088 worker Canadian cohort which Cardis et al used, citing problems with the recorded doses. This should have come as no surprise.[34] This cohort of people first employed before 1965 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 assume LNT.

4.6.4 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. About the same time, people became aware that radon could build up in houses, especially basements. Radon became front page news.

The miner dose rates were 150 mSv/year and higher. 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 Pittsburg. In the late 1980's through the 1990's, under his direction, the University of Pittsburg undertook a massive study of USA radon exposure. They collected county by county data on radon exposure and lung cancer mortality.[39] They eventually ended up with data for 1600 counties. 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.

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 4.6. 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. Cohen made his raw data available to everyone.

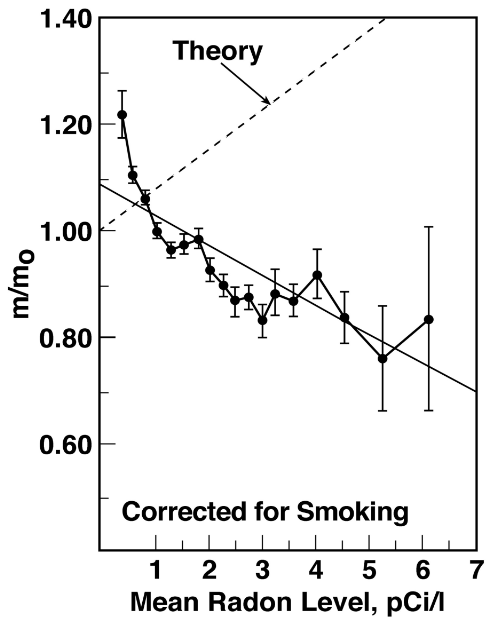

Figure 4.6: Mortality rate versus radon exposure, reference [39]

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.[166] 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.[70] 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

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 4.12: Relative Risk of Lung Cancer from Darby Table 2 (Jack dose)

uncertain to permit interpretation due to the limited number of counties with such dose rates.

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.[45]. Darby examined 7148 cases of lung cancer and 14,208 controls. Her results are summarized in Table 4.12. Radon exposure is almost always measured in Bq/m3, decays per second per cubic meter. 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.[30] I've use this factor in the last column of Table 4.12. Darby et al are examining pretty high lung doses.

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 4.13: Relative Risk of Lung cancer from Krewski, all subjects, Table 2 (Jack dose)

Table 4.12 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 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.[89] 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 4.13 summarizes the Krewski results.

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

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

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 4.14 emerges.

The Table 4.14 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. Kreski 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.[158] 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 4.15 summarizes the results.

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

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 4.15: Thompson Lung Cancer Risk from Table 3 (Jack dose)

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.[105] They then counted the number of oncogenic transformations, mutations which could lead to cancer, which occurred. Figure 4.7 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.***[22]

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

[22] 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.

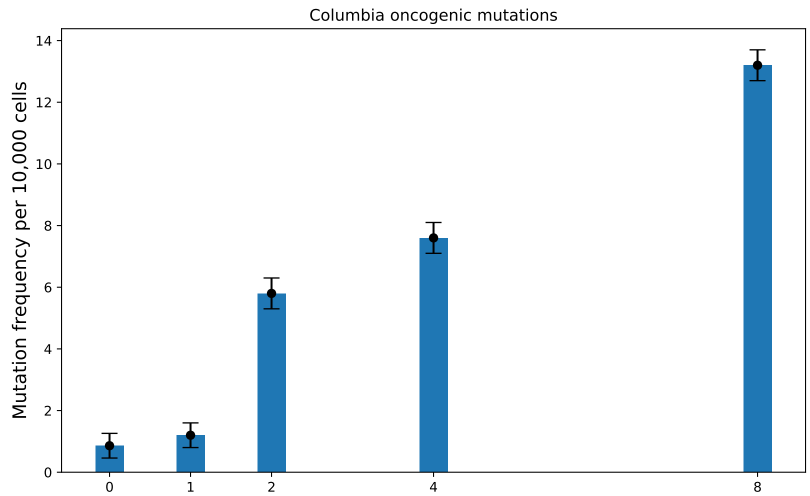

Figure 4.7: Columbia University alpha particle mutations

> 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.[105][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.[130] 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 communcation 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.

4.6.5 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.[31] ^{60}Co emits a high energy photon and has a half life of 5.3 years.[23] 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.[31]. Hwang et al put the excess dose lower, claiming a mean of 47.8 mSv with a range of 1 to 2,363 mSv.[75] According to Hwang, the cancers expected normally for this population is 115, the cancers actually observed was 95.[75][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 lymphotic 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.[76] 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%.[51] 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.

[23] There is no doubt that ^{60}Co can kill. In 2000, a Thai scrap dealer took apart a Cobalt-60 medical source to recover the lead shielding. Four people received acute doses in excess of 5000 mSv. Three of them died. Several others had horrible radiation burns.

4.6.6 The radium watch painters

Between 1915 and 1950, numerals on luminous watch dials were handpainted using radium paint for the most part by young women. Prior to about 1935, 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.[142] 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.[142][page 107] ***No bone cancers were found in the 2,110 women with less than 190,000 mSv dose.***[24] See Figures 4.8 and 4.6.6

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.[142][page 108]

[24] 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.

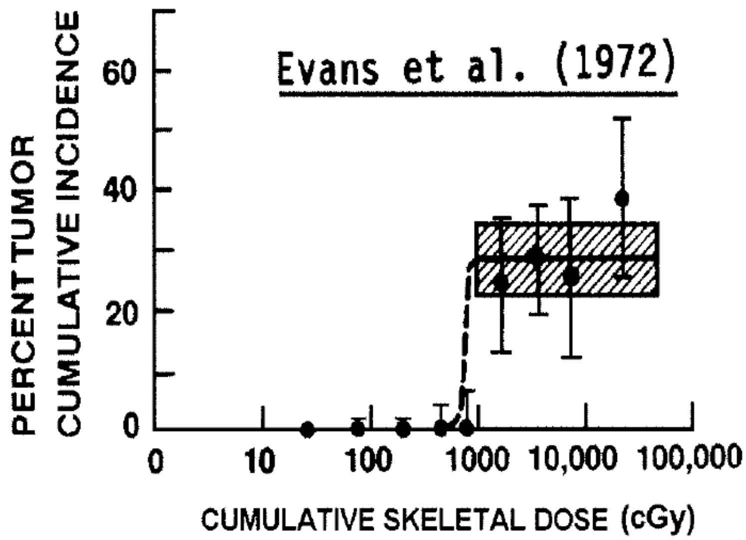

Fig. 11. Cumulative bone sarcoma incidence in people exposed to ^{226}Ra as a function of cumulative dose to the skeleton as reported by Evans et al. (1972).

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.***[25]

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. [1]

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

4.6.7 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

[25] The dial painter experience is sometimes offered as support for the LNT assumption that dose rate is irrelevent. All the counts is the cumulative dose. In fact, the data says that, if a dose is received slowly, it must be far, far larger than an acute dose, to have the same effect. If the ladies who received 190,000 mSv or more had received that dose in a few hours or less, they would have been dead in less than a week.

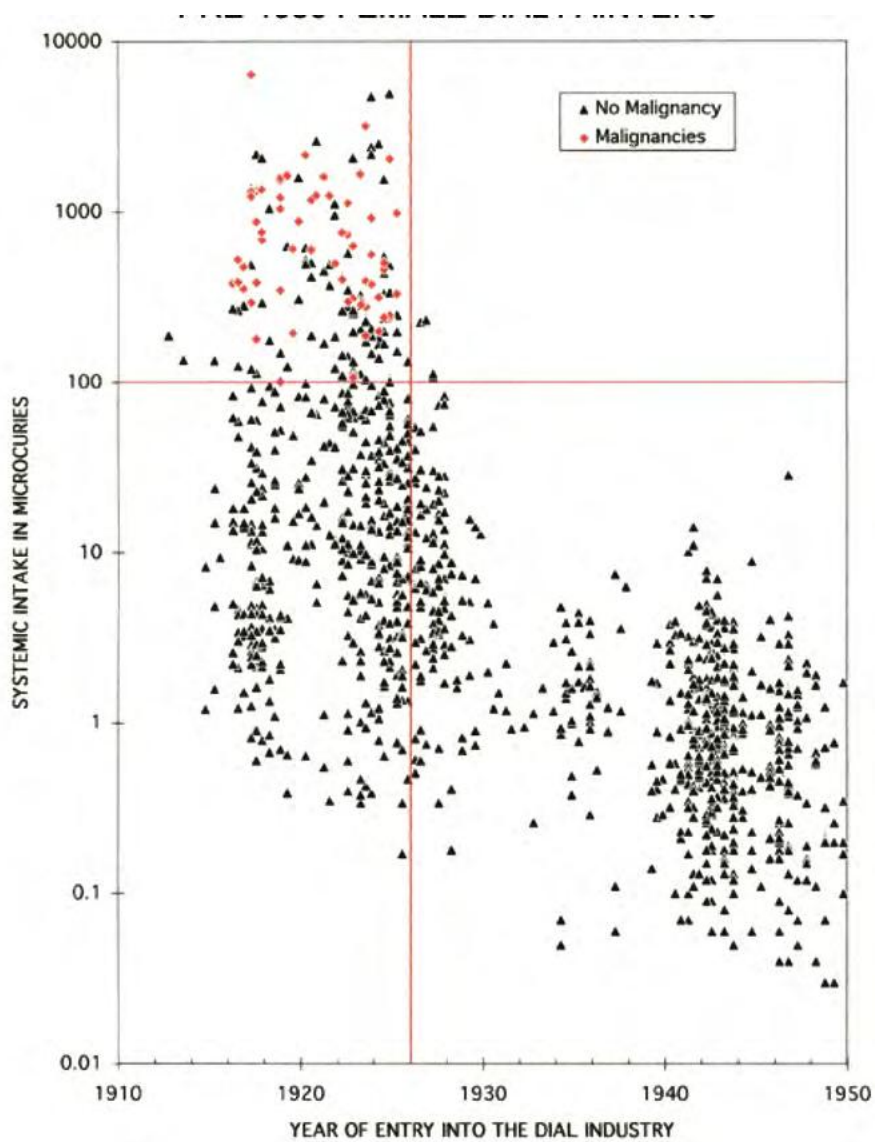

Figure 4.8: Scatter diagram of dial painter maligancies. 100 microCuries is about 12,000 mGy

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.[102] The study operated over a 13 year period until 1991. Table 4.16 summarizes the results.[102][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 4.16: 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 4.16 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 4.16 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".[148][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.

4.6.8 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 injested, the body is very inefficient at absorbing plutonium. Only about 30 ppm will be taken into the blood from the intestine.[71][page 44] The experimenters had to figure out a way around this.[26]

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.

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

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.

4.6.9 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.[32] 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 or 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.[32][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.

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.

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"[103][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.

4.6.10 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 4.9.

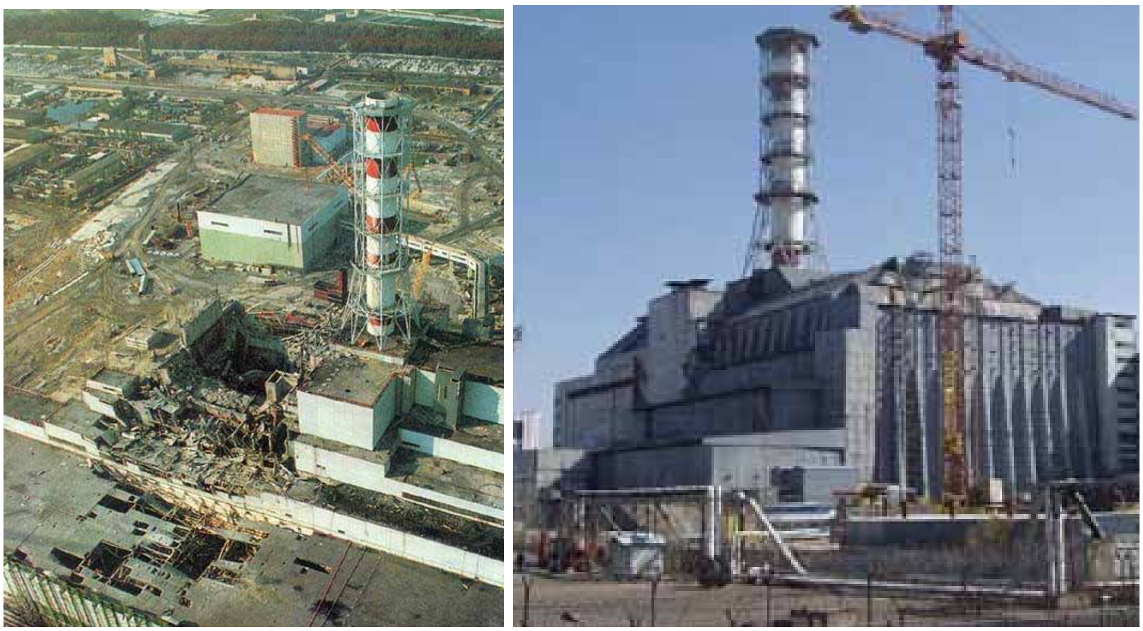

Figure 4.9: Left: Chernobyl Unit 4. Unit 3 is on the right. Right: Sarcophagus in place.

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.[3][Table 1] Hard to imagine a worse casualty.

After the disaster, the USSR conscripted some 500,000 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.[72][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. Nearly 4000 men were used in this operation.

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.[19][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. A micro-Sievert, μSv, is one one-thousandth of a milli-Sievert. 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.[110][p 14] In 2018, Stone et al measured 3.7 μSv/h next to the sarcophagus, Figure 4.10.

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.

Cancer Incidence

There have been attempts to reconstruct the cumulative doses.[82] 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.[27] 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 4.11 shows the distribution

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

Figure 4.10: Dose rate in μSv/h next to the sarcophagus, 2018. Credit: Robert Stone

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 4.17.

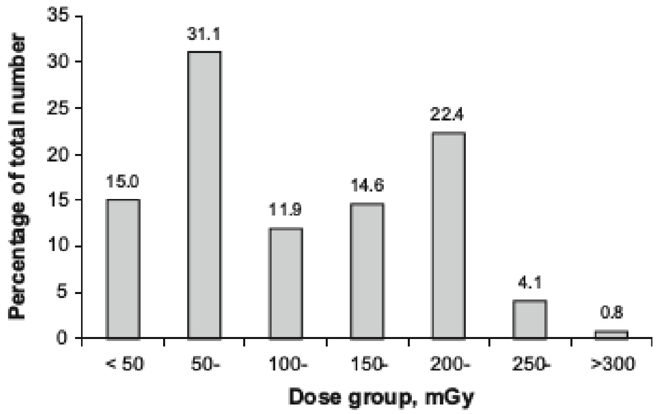

Figure 4.11: Kashcheev liquidator dose distribution

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 4.17: 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.[28] Figure 4.12 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 4.12 looks much like the Bomb Survivor data, Figure 4.1.

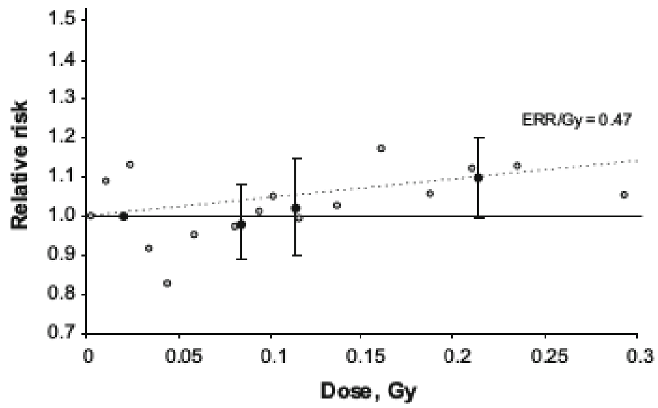

Fig. 4 Relative risk (RR) of all solid cancers by dose groups (*black point* estimates, *vertical lines*—95 % CIs) calculated from Eq. (5); *gray points* represent RR for all 16 dose groups (0–5 mGy is control group); *dashed line* represents the value RR(d) = 1 + ERR(d), where the ERR value was calculated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

Figure 4.12: Kashcheev et al Liquidator Relative Cancer Incidence vs Cumulative Dose

[28] 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)[82][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 4.13 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.

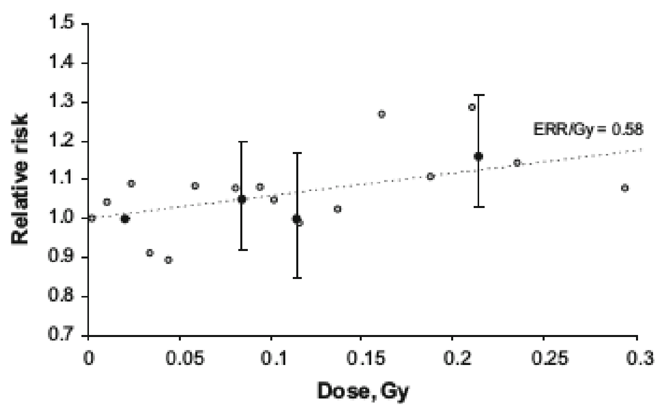

Fig. 6 Relative risk (RR) of all solid cancer deaths by dose groups (*black point* estimates, *vertical lines*—95 % CIs) calculated from Eq. (5); *gray points* represent RR for all 16 dose groups (0–5 mGy is control group); *dashed line* represents the value RR(d) = 1 + ERR(d), where the ERR value was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

Figure 4.13: Kashcheev et al Liquidator Cancer Death vs Cumulative Dose

Summary

Russians represented 30% of the first year liquidators.[69][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.

4.7 Animal Experiments

4.7.1 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 4.14.[7]

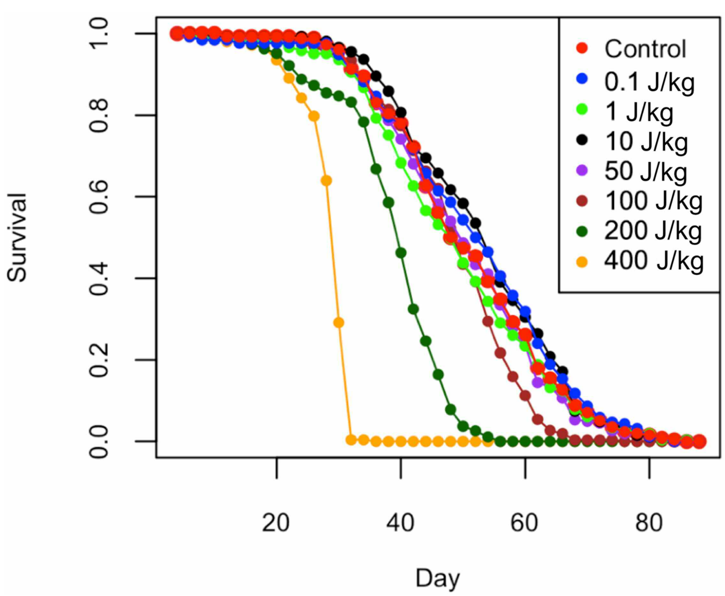

Figure 4.14: Fruit fly survivorship curves. The different curves are for incident photons. The authors estimate that 46% of the radiation was actually absorbed by the flies. Below 50 J/kg incident (23,000 mSv dose), there was no statistically significant difference in life span.

4.7.2 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 4.15 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.

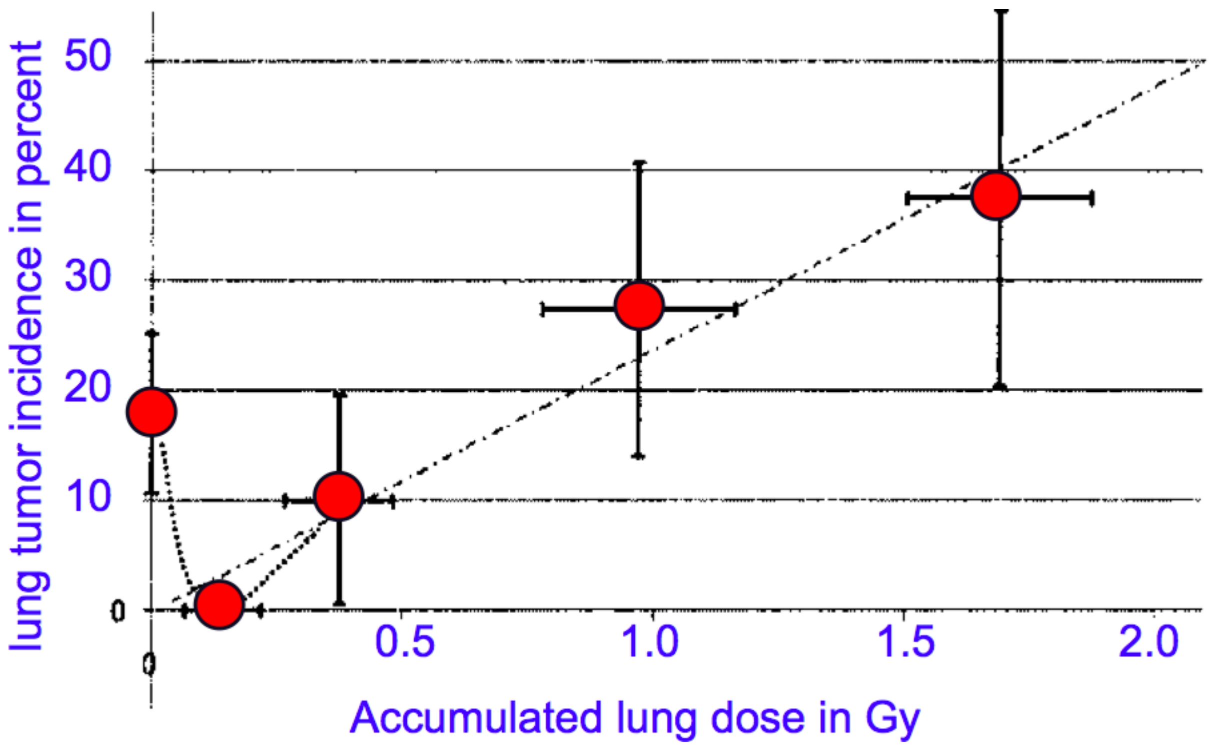

Figure 4.15: Effect of breathing plutonium oxide on lung tumors

Figure 4.16 shows the effect on beagle longevity from external photon radiation. There was not much response up to 1000 mSv/y. 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 1000 mSv/year but 50,000 mSv/y killed them rapidly. Overall, we have a highly non-linear S-shaped curve.

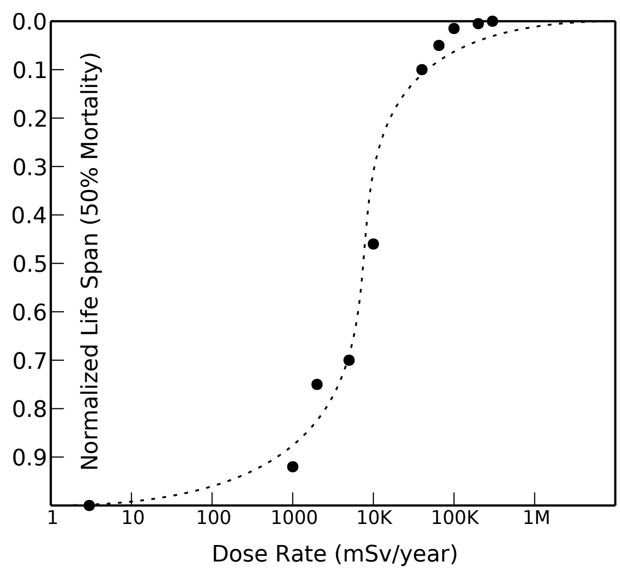

Figure 4.16: Effect of external photon (mGy = mSv) dose rate on beagle longevity

4.7.3 MIT Mice

This 2012 study focused on dose rate.[129] 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 1050 mSv/y. 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.[29] 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 1050 mSv/year, but not 70 mSv/minute. Dose rate is important even when the dose is very high.

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

4.8 Laboratory Testing

4.8.1 Repair Mechanisms

Our bodies are equipped with damage repair systems that are pretty darn effective at low dose rates. If this were not the case, then life would never have evolved as it has. Life started about 3 billion years ago when average background radiation was about 10 mSv/y, about 4 times the current average. Life without repair mechanisms would be impossible. But these repair mechanisms can be overwhelmed by high dose rate damage.

The repair mechanisms take a bewildering number of forms, all of which seem to have names requiring a dictionary. And the strategies are remarkably clever. At doses below 3 mSv, a damaged cell attempts no repair but triggers its premature death. However, at higher doses, it triggers the repair process.[30] This scheme avoids an unnecessary and possibly erroneous repair process when cell damage rate is so low that the cell can be sacrificed. But if the damage rate is high enough that the loss of the cell would cause its own problems, then the repair process is initiated. This magic is accomplished by activating/repressing a different set of genes for high and low doses.[160][page 15] LNT denies this is possible.

Even at the cell level, the repair process is fascinating. In terms of cancer, we are most interested in how the cell repairs breaks in its DNA. Single stand breaks are astonishingly frequent, tens of thousands per cell per day. Almost all these breaks are caused by ionized oxygen molecules from metabolism within the cell. MIT researchers observed that 100 mSv/y dose rates increased this number by about 12 per day.[129] Breaks that snap only one side of the chain are repaired almost automatically by the clever chemistry of the double helix itself.

The interesting question is: what happens if both sides of the double helix are broken? Double strand breaks (DSB) also occur naturally. Endogenous, nonradiogenic causes generate a DSB about once every ten days per cell. Average natural background radiation creates a DSB about every 10,000 days per cell.[55] However the break was caused, the DNA molecule is split in two.

Clever experiments at Berkeley show that the two halves migrate to “repair centers", areas within the cell that are specialized in putting the DNA back together.[119] Berkeley actually has pictures of this process, Figure 4.17 which is a largely complete in about 2 hours for acute doses below 100 mSv and 10 hours for doses around 1000 mSv. These experiments show that if a “repair center" is only faced with one DSB, the repair process rarely makes a mistake in reconstructing the DNA. But if there are multiple breaks per repair center, then the error rate goes up drastically. A few of these errors will survive 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.

[30] To be a bit more precise, some repairs can only take place in the G2 phase just before cell division. Radiation to the cell above 3 mSv, activates the ATM-gene, which arrests the cell in the G2 phase. This allows time for the repair process to take place.

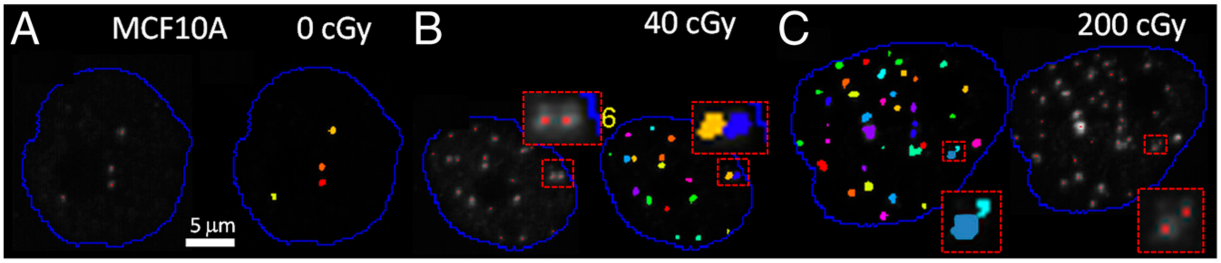

Figure 4.17: UCB pictures of cell repair. The bright spots in the screenshots are clusters of damage sensing and repair proteins, dubbed Radiation Induced Foci (RIF). Berkeley found that the number of RIF's increases less than linearly with dose. At 0.1 Gy, they observed 73 RIF's/Gy. At 1.0 Gy, they 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.

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.

4.8.2 The Alpha Paradox

LNT is rife with contradictions. LNTers don't worry about all sorts of low level radiation. They don't call for the closing of coal plants on the basis of coal ash radioactivity or the evacuation of high background radiation areas such as the U.S. Capitol or Finland. Few do anything about radon in their own homes. They are happy to live in high background areas such as Colorado. Some of its most vocal proponents spend a sizable portion of their lives flying from conference to conference. 20 long flights a year will increase their dose by 1 mSv.

But there is a deeper inconsistency. Why is an alpha particle 20 times more harmful than a photon or an electron with the same energy? The same joules per kg creates the same number of ionizations per kg on average. LNT claims the risk is proportional to the number of ionizations.

The difference is that the alpha damage is far more localized. It is a clumped around the short, straight line path of the alpha. Any breaks are more closely clustered. In a repair mechanism-less organism this would make no difference. In a real organism, it makes a big difference. The factor of 20 attempts to correct for this difference; but in so doing it violates a basic premise of LNT. LNT doesn't believe in LNT.

Figure 4.18: Dose Rate, μSv/h, Black Beach, Guarapari, Brazil. Credit: Robert Stone

4.9 High Background Radiation

The world average annual dose from all sources is about 2.4 mSv per year. But there is a large range. In Europe the average annual dose in the UK is less than 2 mSv; but it is about 6 in Sweden, 8 in Finland, and over 10 in parts of Norway, southeast Finland and northwest Spain.. In the US, the background dose in Florida is about 1 but about 4 mSv in Denver and still higher in other areas in the Rockies.[31]

Increasing background radiation by a factor of two or more does not take much. The average for Italy is about 3 mSv/y but the dose rate in St Peter's Square is about 7 mSv/y due to all the travertine stone. For the same reason, dose rates in Grand Central Station and the US Capitol are elevated by about 4 mSv/y.[32] The really hot spots are:

Ramsar, Iran This Iranian town on the Caspian Sea has background dose rates as high as 260 mSv/y from radon.[62] 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.[108] The radon levels in Ramak are up to 3700 Bq/m3, 19 times higher than the EPA limit for 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.

[31] Americans, more or less voluntarily, tack on another 3 mSv/y in medical exams and treatment. This is about five times the world average.

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

Guarapari, Brazil Guarapari is a coastal town whose popular beaches have peer reviewed dose rates up to 175 mSv/y. Figure 4.18 shows 30.3 microsieverts per hour in the sand, about the same as Chernobyl's Red Forest in 2018. This corresponds to 265 mSv/yr. 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 annual dose is about 5 mSv but with a max of 28 mSv.[44] As far as I know, there has been no quantitative study of the cancer incidence in the area, but the locals are unconcerned.

Finland The background dose rates in Finland are much higher than most of Europe, Figure 4.19. The Finns rank in the bottom third with respect to cancer incidence in first world countries.

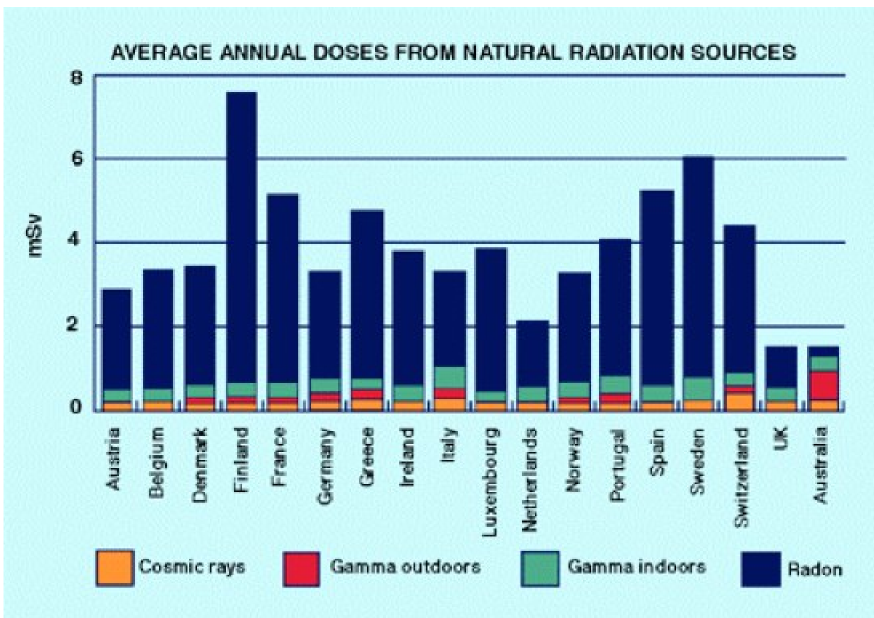

Figure 4.19: Dose rate by country

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 6.4 mGy per year and control group from a neighboring city with an average dose rate of 2.4 mGy per year. 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.[156]

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 76 mSv/y.[114] UNSCEAR measured mean dose rates of 28 mSv/y inside buildings in the village of Kadipattam.[163][Annex B, page 55] The max was 39.5 mSv/y. 173,000 residents of this area were studied for 15 years. Table 4.18 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 11 mSv/y.

Table 4.18: Risk of all solid cancers, [115][Table 4]

	Cumulative Dose (mSv)				
	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.*** According to LNT, the latter should have a 6% higher cancer rate. 42 mSv/year for 15 years had no noticable effect.

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.[16][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.[115].

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.

4.10 Selling LNT

With all this evidence, how has LNT survived and indeed flourished? The answer is by specious, if sometimes well-intentioned, salesmanship. For the radiation protection establishment LNT has become a dogma to be defended rather than a hypothesis to be examined. Often this bias is embarrassingly transparent. This bias takes several closely related, over-lapping forms:

1. 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 both 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 in examining 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 they were 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.[159][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. [83][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.

2. 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.

3. 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.[126][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*[126][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".[33] 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.

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[33] 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. 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]

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 LNTers have been abetted by a nuclear regulatory-industrial complex which nonchalantly accepted LNT without any argument in 1959. The nuclear complex 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.[34] 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.

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?

A crucially important but often overlooked consequence of the embrace of LNT was that, if a casualty 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 3.1.

Worse they had to come up with a regulatory process which was supposed to result in achieving these totally unrealistic numbers. This attempt was doomed to failure. ***There is no limit to the amount of money you can spend attempting to do the impossible.*** Current regulatory requirements at least double and probably quadruple the cost of conventional nuclear power. At the same time, they stifle competition and prevent normal technological progress.

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

[34] What makes this decision even more perplexing is that the AEC had funded both Caspari's fruit fly experiments and the Neel human genetics study, Section 4.3. They knew that LNT had crashed and burned genetically. The AEC also funded the Atomic Bomb Casualty Commission. They had access to the same leukemia data the WHO had, Table 4.6. They must have known the data showed a highly non-linear response. At the time, there was no solid tumor cancer data.

Chapter 5

An Alternative to LNT

> 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.[172][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 linear, 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.

[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, contrary to earlier hypotheses, no threshold existed for biological damage from radiation.[128] Okrent indicates the committee was surprised by this revelation. This is the earliest report I have found of the AEC moving away from the threshold position. 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 decisionmaking. 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.

5.1 Introduction

In order to reconcile the statistically significant increase in cancer that is observed for acute radiation doses of much more than 100 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 up to 500 mSv show no discernible increase in cancer, the dose response curve must be non-linear. But current radiation rules are based on the Linear No Threshold hypothesis. Linear No Threshold (LNT) is inconsistent with what we know about cellular repair mechanisms; and epidemiological data shows that Linear No Threshold does a very poor job of modelling the health effects associated with radiation at the all important low dose rate end. But, if Linear No Threshold is invalid at low dose and low dose rate, which is where the most important policy issues arise, with what should we replace it? The public needs simple guidelines. Regulators need an easily understood framework. Can we come up with a simple model which does a better job of estimating cancer incidence from ionizing radiation than LNT, especially at the low end? I suggest the answer is yes.

Let's accept that cell damage is proportional to the energy deposited per kilogram of tissue, the dose, at the low end. But we combine this with a very effective repair system whose accuracy drops off the higher the dose. 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] Similarly, it makes sense to assume that the slope is zero at the always fatal, high end dose. As we approach the always fatal dose, there's nobody left to kill.

I propose that for the purposes of regulation we assume cancer incidence is a monotonically increasing function of dose. There is considerable evidence that low dose can stimulate protective responses. But it is equally clear that certain kinds of damage escape those responses.[149] We are looking at a very complex battle between a wide range of damages and a wide range of responses to these damages. And we can be sure that the outcome of this battle varies from individual to individual. So to be conservative, we go monotonic. From this point of view, up regulation of protective responses is just another reason why the response is non-linear.

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

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[2] For linear damage with repair, cancer incidence c_i is given by $c_i = ap_{nr}(d)d$ where d is the dose, a is the LNT slope, and $p_{nr}(d)$ is the probability that the repair fails. If the probability that the repair fails goes to zero at zero dose, then the slope of the response curve, $ap_{nr}(d) + adp'_{nr}(d)$ must go to zero at zero dose. In a model that recognizes repair, the repair probability can depend on the type of radiation, avoiding the alpha paradox.

Assuming the probability of repair drops off linearly as the dose increases, leads to a quadratic dose 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. Entirely different behavior at the low dose end. Both the quadratic and linear-quadratic models are nonsense at the high end, as is LNT.

responses meeting these basic rules. This is neither radical nor original.[49, 153] It embodies the establishment position: no 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.

5.2 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 4.2. 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 5.1 compares a least squares linear fit with the best logistic fit I was able to come up with.

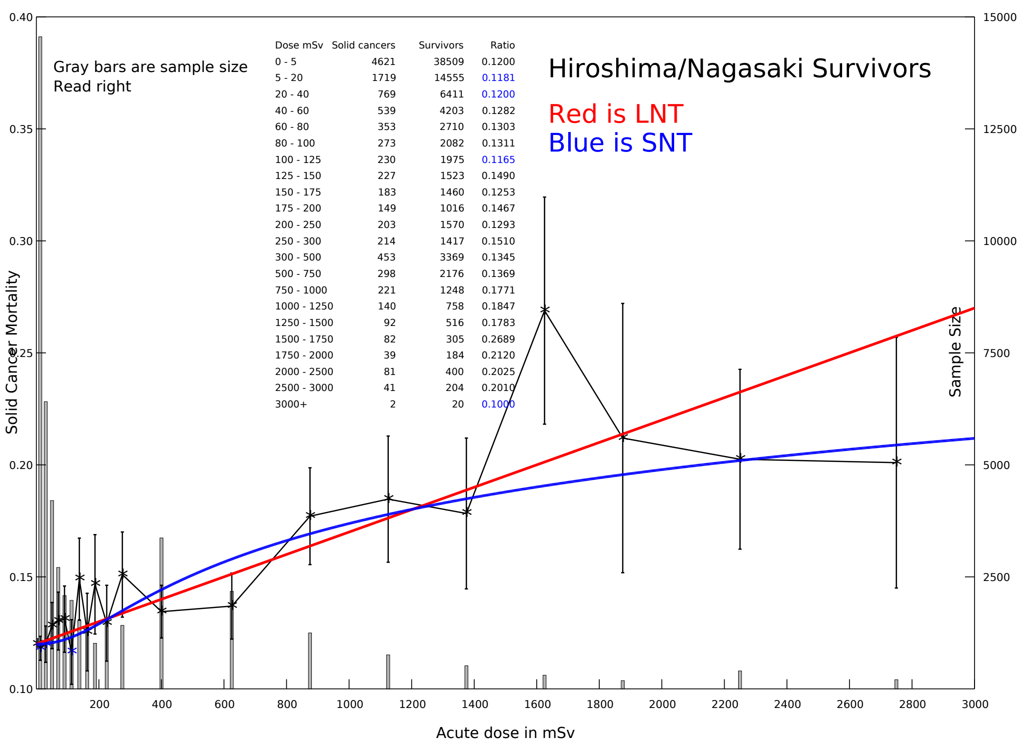
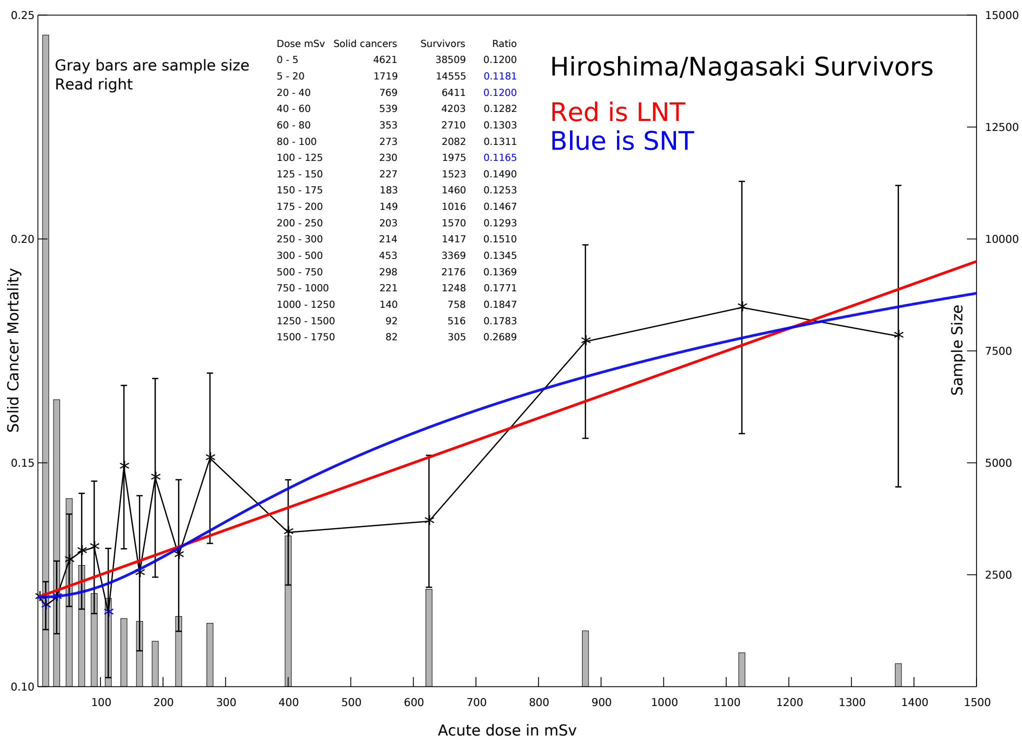


Figure 5.1: Linear versus Sigmoid NT for RERF Solid Cancers: 0 to 3,000 mSv Acute Dose

Figure 5.1 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 5.2 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
1250 - 1500	92	516	0.1783
1500 - 1750	82	305	0.2689

Figure 5.2: 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.[153, 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,[125].

> 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 5.1. 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 5.1 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 5.3, which is what we are really interested in, we start to see how large the ***relative*** differences are.

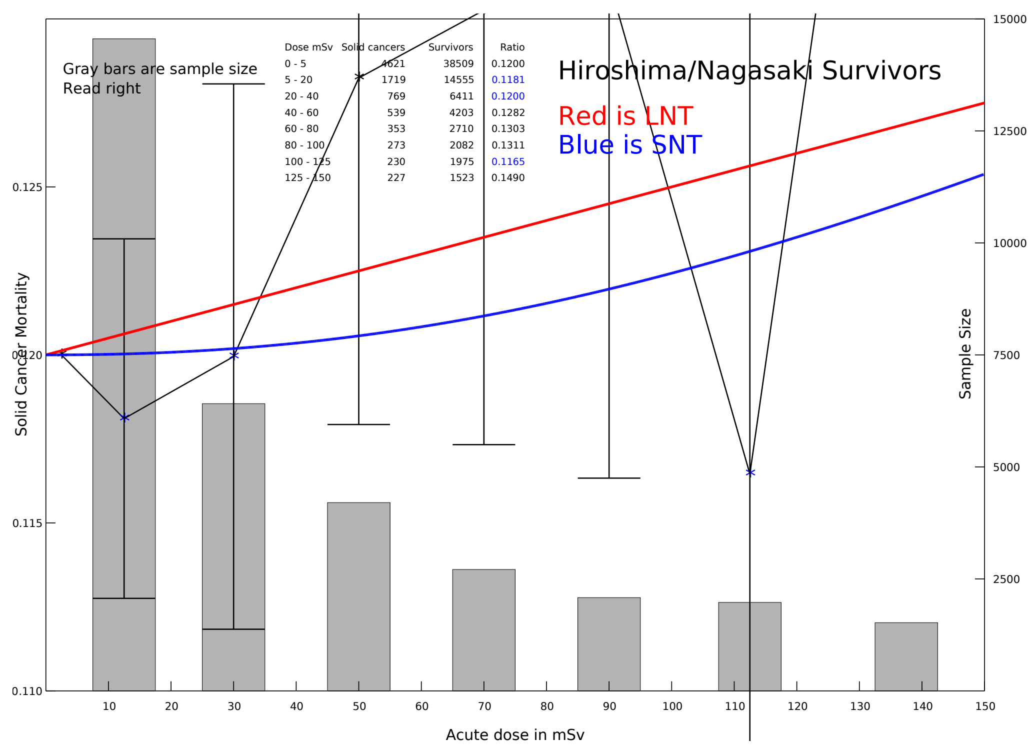


Figure 5.3: Linear versus Sigmoid NT for RERF Solid Cancers: 0 to 150 mSv Acute Dose

But to really appreciate how large this relative difference is, we need to look at the numbers, Table 5.1. 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.

Dose mSv	Logistic Fit	LNT Fit	Linear Loss of Life Expectancy, days	Logistic Loss of Life Expectancy, days	LNT excess risk over logistic excess risk
0.1	0.120000001	0.120005	0.0070	0.000001	6310.2
0.5	0.120000025	0.120024	0.0349	0.000037	944.6
1.0	0.120000114	0.120048	0.0698	0.000167	416.9
5.0	0.120003805	0.120237	0.3491	0.005593	62.4
7.0	0.120007923	0.120332	0.4888	0.011646	42.0
10.0	0.120017236	0.120475	0.6983	0.025336	27.6
25.0	0.120126639	0.121187	1.7459	0.186159	9.4
40.0	0.120350529	0.121900	2.7938	0.515296	5.4
50.0	0.120566573	0.122375	3.4926	0.832923	4.2
100.0	0.122430403	0.124750	6.9879	3.574071	2.0
200.0	0.129000669	0.129500	13.9870	13.250706	1.1
300.0	0.136832653	0.134250	20.9972	24.813535	0.8

Table 5.1: 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 5.4. 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.

According to the logistic fit and a conservative mortality calculation, a 25 mSv acute dose is equivalent to a Lost Life Expectancy (LLE) of 0.2 days.[4] 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.[38] Bernie estimates automobile use costs us 207 days. He puts 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

[4] To compute the LLE's, I used the mortality table for all US males. This is a group which is at the high end of cancer incidence worldwide. I compute the life expectancy for no excess cancer risk and the life expectancy with the extra cancer risk for each dose and model, assuming no lag. The differences are the LLE's shown in Table 5.1.

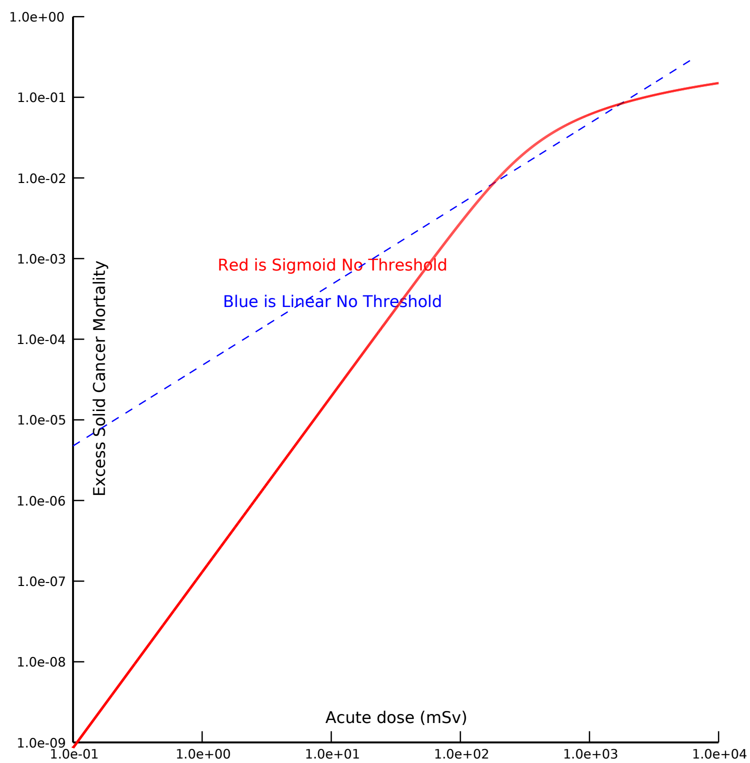


Figure 5.4: Loglog plot of Linear versus Sigmoid NT Excess Cancer Mortality

polluted city has an LLE of 292 days and living in a badly polluted city has an LLE of 1,150 days.[50] These are the sort of numbers we should compare with Table 5.1.

5.3 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. This is inconsistent with the fact that people living in high background radiation areas accumulate doses that are several hundred mSv. It is undisputed that an ***acute*** dose much above 100 mSv will result in a statistically observable increase in cancer. Yet there is no discernible increase in cancer incidence in these high background populations that have lived in such areas for 50 or more years. For example, in Finland, Figure 5.5, the average background annual dose is 7.6 mSv, more than double the world average.[66][Figure 2] The average 50 year old Finn accumulates a dose that is more than 200 mSv larger than people living in low background dose areas. Finland's age adjusted cancer mortality rate ranks in the bottom third of First World countries. In the Kerala study summarized in Section 4.9, people who over 15 years received a cumulative dose 600 mSv higher than their neighbors had a slightly lower cancer incidence.

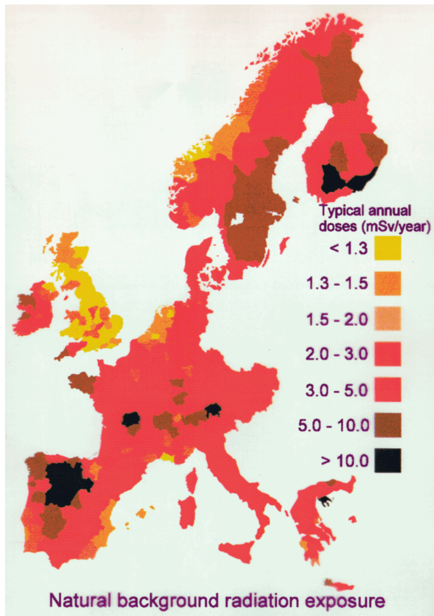


Figure 5.5: European background radiation: source European Commission

If we simplisticly accumulate dose, Sigmoid No Threshold will be even farther off than Linear No Threshold, once a person's dose reaches about 220 mSv. The solution is to recognize that almost all radiation damage is repaired. As we have seen in Section 4.8, Berkeley has pictures of this process. In double strand breaks (DSB's), the two halves migrate to "repair centers", areas within the cell that are specialized in putting the DNA back together. Repair is largely complete in about 2 hours for acute doses below 100 mSv and 10 hours for doses around 1000 mSv. If a "repair center" is only faced with one DSB, the repair process rarely makes a mistake in reconstructing the DNA. But if the damage rate gets ahead of the repair rate, and a repair center has to deal with multiple, unrepaired breaks, the error rate goes up drastically. A few of these errors will survive 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 highly rate dependent.*** The dose received within the repair period largely controls the efficacy of repair. This should be a focus of regulation.

How to implement that focus? Here's one possibility:

1. Assume an overly long repair period. We know most of the intra-cellular mechanisms operate on time scales of several hours or less. Radiotherapy effectively assumes a repair period of a day or two in fractionating very high level doses. If we assume a repair period of a month, then we are being extremely conservative.[5]
2. Apply Sigmoid No Threshold 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.
3. For the purposes of intervention, pick a repair period dose that has an LLE that balances the social costs of achieving that LLE against the social benefits.

For example, under these assumptions, Table 5.1 tells us each month of 25 mSv per month dose rate has an LLE of 0.19 days. 5 months of this rate has an LLE of 1 day. We know from Fukushima and Chernobyl that the LLE of prolonged evacuation is much larger than 1 day. With the possible exception of pregnant women, there is simply no argument for forcing an evacuation of an area where the dose rate is less than 25 mSv/month (35 μSv/h) or preventing people from returning to their homes once this level is reached. For context, 35 μSv/h is about the dose rate on the beaches at Guarapari, Brazil, Section 4.9. 35 μSv/h is 0.84 mSv/day, a little less than the 1 mSv/d limit through 1948, a limit that the NCRP admitted they had no evidence that anyone had been harmed by.

If the 35 μSv/h limit had been adopted at Fukushima, then only the area within 4 km of the plant would have been evacuated. By mid-April, people could have returned to everywhere except the SW quadrant of this area. By mid-May, this quadrant would have shrunk to within 2 km of the plant. This is an area of about 3 km2. An upper bound on the population density in the area might be 1,000 people per km2. At this point, the number of displaced people would be down to around 3000. By June 3rd only 4 of the 86 monitoring points outside the plant were measuring more than 35 μSv/h.

5.4 Implications of Sigmoid No Threshold

The Sigmoid No Threshold model has several important implications:

1. There is a cumulative effect. The model treats each month as a independent event. Thus the probabilities add. However, we are adding probabilities, not doses. If the dose in the first month is 25 mSv, and in the second month is 10 mSv, and in the third month is 5 mSv, then we can add the LLE's of each of those months to end up with $0.186 + 0.025 + 0.006 = 0.217$ days.[6] This is quite different from the LLE associated with a dose of $25 + 10 + 5 = 40$ mSv

[5] Too much so. Regulators should seriously consider a shorter, more realistic regulatory repair period, such as a week.

[6] LLE is an expected value, so it is proportional to the underlying probabilities. Strictly speaking, we should

or 0.515 days.
Suppose a person lives in a area which has a high background dose rate of 6 mSy/y. Then his monthly dose is 0.5 mSv which according to Table 5.1 has an LLE of 0.00004 days. If he lives in this area for 70 years (840 months), the model claims his LLE will be $840 \cdot 0.00004 = 0.03$ 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. According to LNT, this dose rate should have increased our septuagenarian's chance of becoming a cancer patient by 4%.[159, Table ES-1] This is an easily observable number. Gonzalez estimates that an exposed group and a control group of about 500 people each should result in a 90% confidence limit.[65]
Gonzalez also argues that to see the effects of 10 mSv with a 90% confidence level would require sample sizes in the millions. This he claims explains the apparent failure to see the cancers that LNT predicts. But as Figure 5.5 indicates, we have populations in the tens of millions, if not scores of millions, whose cumulative doses vary by 100 or more milliSieverts. And that's just in Europe.
The assumption of independent repair periods is not consistent with the undisputed existence of inter-period, carryover effects. These can be both positive (e.g. up regulation of immune responses) and negative (e.g. shortening of telemeres). The former appear to dominate in the low dose rate region. The latter become more significant as the dose rate increases.[18][page 96]
The best epidemiological example of cumulative effect we have is the radium dial painters, Section 4.6.6. Up to 1950, numerals on luminous watch dials were hand painted using radium paint for the most part by young women. Before 1935, the ladies used their tongues to form the tip of the brush into a point, sipping radium into their bodies. The total skeletal doses varied over a factor of 1000. But the maximum cumulative dose was a massive 444,000 mSv. 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. 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.[142][page 107] ***No bone cancers were found in the 2,110 women with less than 190,000 mSv dose.***
These numbers point to a lifetime dose limit of something like 50,000 mSv. Unless you are an astronaut on a Mars mission, such a rule will never be limiting. Regulation should focus on dose over the normal repair period.

2. Unlike Linear No Threshold, dilution is an effective countermeasure even if it increases the exposed population proportionally.[7]

multiply the probability associated with each succeeding month with the probability of reaching that month without fatal damage. This error is conservative.

[7] 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

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 0.833 days to $50 \cdot 0.00017 = 0.0085$ days. Sigmoid No Threshold accepts the idea of a collective dose, but argues that the impact of that dose falls off quickly. At 0.5 mSv, the difference between Linear and Sigmoid is more than a factor of 900. And as Figure 5.4 shows, this difference grows very rapidly at still lower doses. 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.[165, page 64]

5.5 Sigmoid No Threshold and Chernobyl

Even in a release as large as Chernobyl, dose rates well above background were confined to a few hundred thousand people.[27] However, the number of people exposed to a slightly elevated dose was in the hundreds of millions. LNT claims more cancers among the slightly elevated group than among those who have received unnaturally high doses and dose rate. 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.[67] Table 5.2 compares their analysis of cancers due to Chernobyl with an SNT based analysis using the same numbers.[8] UCS's estimate is 26,400 statistical deaths excluding thyroid cancer.

Table 5.2: UCS estimate of Chernobyl cancer deaths excluding thyroid versus SNT

Group	Population	Average Dose mSv	Exposure months	LNT deaths	SNT deaths
liquidators	530,000	145.00	1	4380	1525
evacuees	115,000	43.00	1	282	27
SCZ residents	270,000	59.00	12	908	7
Other contaminated	6,400,000	9.00	12	3283	3
Other USSR	92,000,000	0.90	12	4720	0.25
Other Europe	500,000,000	0.33	12	9405	0.15
Other N. Hemis.	3,000,000,000	0.02	12	3420	0.002
				26398	1562

To use SNT we must know the monthly dose rate. In Table 5.2, I have made a conservative guess at the period over which most of the dose was received and then assumed the dose was

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.[80] LNT in action.

[8] Overall the UCS dose numbers appear inflated relative to other sources. Compare Table 4.3 with Table 5.2 but we use them for illustration anyway.

received equally in each month of that period. For the liquidators and evacuees, I have assumed all the dose was received in one month. In other words, I have treated it as an acute dose. For the other groups, I assumed the period was a year.

In concocting Table 5.2, I assumed everybody in each group received the average dose. ***For SNT, this is a seriously unconservative error,*** since SNT gives more weight to the upper portion of the distribution than the lower. If dose-response is non-linear, then we cannot simply take the average dose of a group and apply a factor to it. We have to work directly with the individual doses. However, Table 5.2 says we need only worry about this error for the liquidators and possibly the evacuees. In the other groups, even a factor of 2 or 3 error will not change the overall number significantly.

The best data I have on the liquidator doses is from reference [82] summarized in Section 4.6.10. This study covered 67,500 Russian men involved in the first year of clean up. Many of these men at the high dose end received their dose over a period of minutes. Table 5.3 compares the Kashcheev et al LNT analysis of this data with SNT.

Table 5.3: SNT vs LNT for Russian, 1986 liquidators

Group	Population	Dose mSv	Months	LNT cancers	SNT cancers
0 to 50	10,135	20.00	1	5.56	0.47
50 to 100	21,013	84.00	1	46.78	20.70
100 to 150	8,040	114.00	1	25.61	15.55
150 to 200	9,864	170.00	1	51.14	44.58
200 t0 250	15,135	219.00	1	93.05	97.32
250 plus	3,310	293.00	1	27.96	34.00
Total	67,500			250.10	212.63

For this high dose over a short period cohort, LNT and SNT come out about the same in total solid cancers; but the distribution is quite different, fewer cancers in the under 100 mSv group and more cancers in the 200 mSv plus group.

Kashcheev et al estimated that the early deaths due to radiation in this group at 173. Russians represented 30% of the first year liquidators. If we blithely assume that the other 70% received the same dose, then we are talking 600 early deaths for LNT and very roughly the same for SNT. The second year and later liquidators received considerably smaller doses over longer periods. For these groups, there will be a large difference between LNT and SNT, but for now let's just accept the LNT numbers for the liquidators as an upper bound. And if you like, we can double the evacuee number since half of them will receive more than median dose.

The whole point of Table 5.2 is that when you account for non-linear dose response and the repair period, the statistical radiation induced deaths associated with Chernobyl are totally concentrated in the liquidators and the evacuees.[9] The deaths outside these groups are reduced

[9] Childhood thyroid cancer was included in the sure deaths in Section 4.1.

by a factor of 1000 or more relative to LNT.

The deaths in Table 5.2 are delayed cancer deaths. Per Section 4.1 if we want to compare them with sure deaths in terms of Lost Life Expectancy, we should divide these numbers by about a factor of two. Of course, in doing so we are ignoring the fact that liquidators are actually living longer than non-liquidators, presumably because their cancers were diagnosed earlier, and treated better.[82] From a life expectancy point of view, it is better to have been a liquidator than a non-liquidator.

LNT is often defended by people who accept that it is 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 patterns 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 Cardis et al and UCS have done. 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.

5.6 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.[2] 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 this phase, the amount and spatial distribution of the radionuclides is 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 5.6, 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".

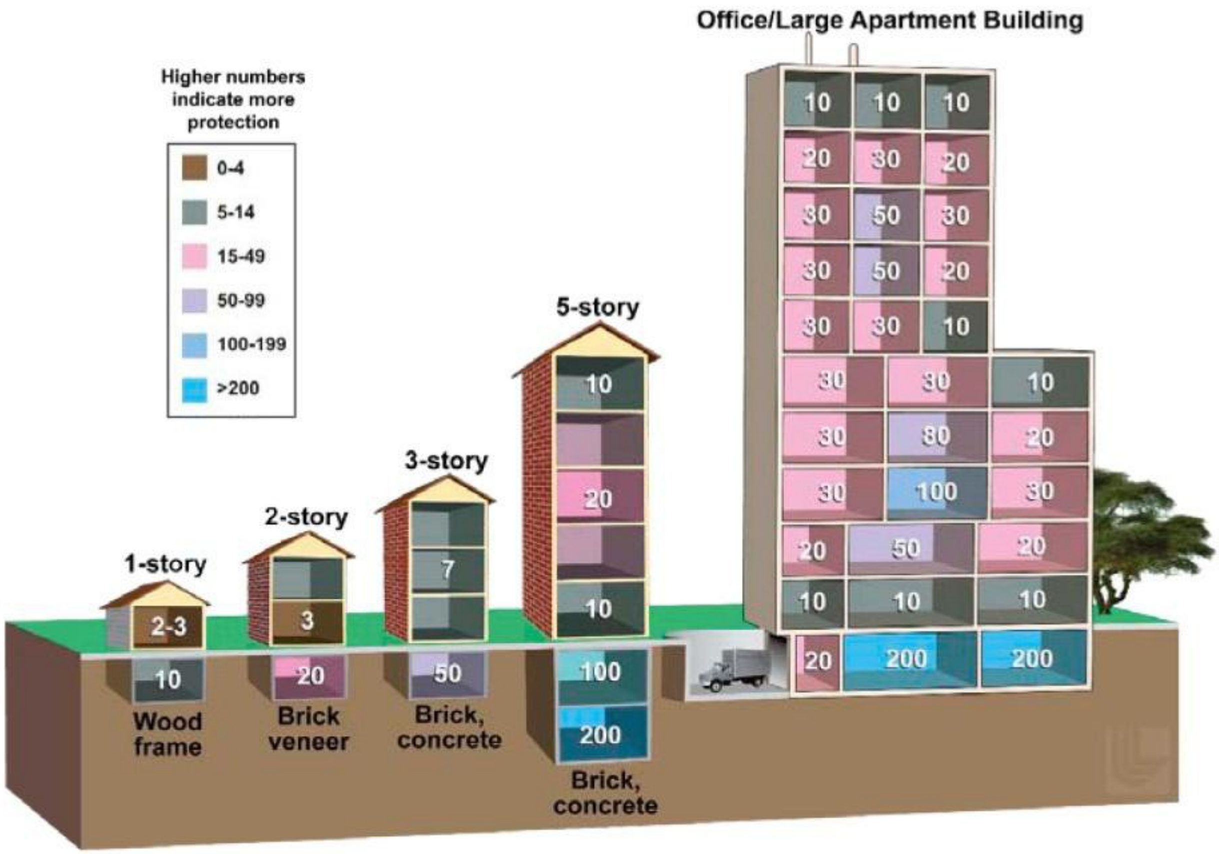


Figure 5.6: EPA estimate of dose reduction from staying in doors during Early Phase. 10 means the indoor dose is one-tenth the outdoor dose.

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. (2.5 mSv/d or 100 μSv/hr). This is based on accepting a probability of 0.0002 of mortal cancer from the dose.[10] From Table 5.1, that's an LNT Lost Life Expectancy(LLE) of about 0.35 days. 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

[10] 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.

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.[11] The manual is firmly in the only thing that counts is the cumulative dose camp. It claims that these numbers are derived from an acceptable once-in-a-lifetime additional dose of 50 mSv. Per Table 5.1, that's an LNT LLE of 3.5 days.

Imagine a world in which EPA magically switched from LNT to SNT but kept the same acceptable LLE's. For the Early Phase, the SNT dose that results in an LLE of 0.35 days is 33 mSv or 340 μSv/hr. In this case, there's only a factor of 3 difference between LNT and SNT.

For the Intermediate Phase, the PAG accepts 25 mSv in the first year, and 5 mSv/y thereafter without relocating. For now let's focus on the first year. According to LNT, 25 mSv has an Excess Relative Risk (ERR) of 0.0013, meaning 25 mSv increases your probability of developing fatal cancer by a little over 1 chance in 1000. EPA accepts this given the risks and costs of relocation.

To convert this acceptable risk to an SNT dose, we need to know the monthly doses through time. In an actual release, these can be estimated from the distribution of the radionuclides. For now just to get a feel for how SNT works, I assumed exponential decay in dose rate in both the first and second year, but with different decay rates. I wanted 5 mSv in year two, and then looked for the decay rate in year 1 that resulted in the same ERR as the PAG manual accepts for year 1.

Table 5.4 shows the results. According to SNT, a total dose of 140 mSv in the first year plus 5 mSv in year 2 will increase your probability of a fatal cancer by a little less than 1 chance in 1000, meeting the EPA Year 1 criterion. The pattern in Table 5.4 is very important. For SNT the only thing that counts is the first few months. Once the dose rate gets down to 0.5 mSv per month (6 mSv/year), the ERR per month is less than 3 chances in 100 million. But we knew this already, since we cannot see any increase in cancer in high background area populations who have experienced these dose rates for 50 years. EPA's PAG for first year relocation is extremely conservative but not outrageously so. The guideline that recommends relocation at 5 mSv per year thereafter is outrageous.[12] By this logic a wide swath of the US mountain west including Denver should be depopulated.

Inexplicably the EPA PAG Manual refuses to provide a quantitative guideline for reoccupation. But it seems obvious that, if relocation is not recommended below 5 mSv/y, reoccupation as soon as the rate is below that level should be acceptable. A far better policy would be to educate people and let them make their own choice. According to SNT, 10 mSv/y for a year has an ERR of 1 chance in a million, 200 times below EPA's acceptable 1 chance in 5000, the ERR associated with 5 mSv. Coincidently, 10 mSv per month for a year has an SNT ERR of about 1 chance in 5000.

[11] 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.

[12] It is also inconsistent with the IRCP trigger to lift evacuation of 35 mSv/y.

Dose file:			dose_140_5.
Year 1 dose = 140 mSv			Year 2 dose = 5 mSv
Month	Monthly dose mSv	SNT Expected Absolute Risk	Cumulative SNT ERR
0	45.01	0.120452089	0.000452089
1	30.69	0.120197641	0.000649730
2	20.93	0.120086045	0.000735775
3	14.27	0.120037392	0.000773167
4	9.73	0.120016236	0.000789403
5	6.63	0.120007048	0.000796451
6	4.52	0.120003059	0.000799509
7	3.08	0.120001327	0.000800837
8	2.10	0.120000576	0.000801413
9	1.43	0.120000250	0.000801663
10	0.98	0.120000108	0.000801771
11	0.67	0.120000047	0.000801818
12	0.58	0.120000035	0.000801854
13	0.55	0.120000031	0.000801884
14	0.51	0.120000026	0.000801911
15	0.48	0.120000023	0.000801933
16	0.45	0.120000020	0.000801953
17	0.42	0.120000017	0.000801970
18	0.39	0.120000015	0.000801985
19	0.37	0.120000013	0.000801998
20	0.34	0.120000011	0.000802009
21	0.32	0.120000010	0.000802019
22	0.30	0.120000008	0.000802027
23	0.28	0.120000007	0.000802034
Total SNT Excess Relative Risk:			0.0008
Total LNT Excess Relative Risk:			0.0012
Ratio LNT ERR/SNT ERR			1.48
			2020-05-31T15:01:52Z

Table 5.4: SNT Cancer Mortality Risk, 140 mSv in year 1, 5 mSv in year 2

5.7 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.[13] But the competition here is not perfection but LNT. Table 5.5 summarizes the score in that contest.

Table 5.5: 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.[14] 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.

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[13] I'd also be the last to claim that I have done a good job of implementing Sigmoid No Threshold. Somebody far better qualified need 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.

[14] As of late 2013, the number of deaths blamed on the evacuation was put at 1656.[131] Had there been no evacuation, almost no one would have received a dose of 100 mSv.[177] UNSCEAR, using conservative assumptions, estimates that the average dose that would have been received in year 1 in the three towns closest to the plant, Tomioka, Okuma, and Futaba at 51, 47, and 38 mSv respectively,[176][Table C11, page 191] Among UNSCEAR's conservative assumptions was the photon dose actually received is 0.6 times the outdoors photon dose 1 meter above ground as measured from low flying aircraft. Later studies which compared the outdoors dose rate with actual dosimeter readings in nearby Date City found that the average dose received was 0.15 times the outdoors aircraft number.[78]

In 2012, using their standard pathway models, UNSEAR estimated the thyroid dose to evacuated 1 year olds to be between 15 mSv and 82 mSv.[175] Actual measurements of children from the evacuated areas showed 98.8% at less than 15 mSv with a mean of 2.2 mSv.[113] The standard models were conservative by an order of magnitude or more.

Chapter 6

Fear Induced Deaths

6.1 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."[12][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."[63] 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.[17]

Others are no so restrained. Kate Brown's book "Manual for Survival" paints a very different picture.[19] 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."[19][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.[19][p 13,15]

Everywhere she 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. She 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.[19][p 311] Where are all the Chernobyl area health problems in these milk drinking Americans?

She 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 weeks, the main source of radiation was Cesium-137. She claims that half of ^{137}Cs will still be around for 180 to 320 years.[19][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.

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.[164][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 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."[15] 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 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 90 and 110 days.[71][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."[15] 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.[19][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.[19][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.[19][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 120,000 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.[47] 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.[152] 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.

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[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.[68]

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.

6.2 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.[175][p 10-11][4] According to Section 4.1.1, approximately 1600 elderly people died in the botched, unnecessary evacuation,

[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 [136] 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 0.09%. Under these assumptions, there is a 99.9% probability, the exposure did not cause his death.

It seems 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. Apparently, this guy qualified; so radiation caused his death.

most of them within a week or two.[5] Some sources now put the total toll among 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.*** As of 2015, 85,000 people had not returned to their homes.[157]

One reason is 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, 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 I thought the government's policy was rational, I wouldn't return either.

6.3 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.[9] This number assumes no evacuation and a number of other purposely conservative assumptions. The LNT estimate of the number of additional fatal cancers to these 2 million people is 1. 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.[6] 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.[7] I have a great deal of sympathy for the evacuees. There was not just fear. There was anger. These people had been

[5] There is a good chance that the severity of the release was magnified by orders of magnitude by misplaced fear.[42] 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. 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 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, 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.

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 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.

[7] Bishop Keeler of Harrisburg was so convinced his flock faced imminent annihilation that he declared general absolution. Father Keeler was later promoted to Cardinal.

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?

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.[37][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.[8] 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.

6.4 Who is to blame

If these fear induced impacts are inherent in nuclear electricity, then we have to view these dangers very seriously. On the basis of sure deaths, Fukushima moves up from 2 to something like 1600, or 5th on Table's 4.2 list of deadliest energy related casualties. Put another way, unless people can be convinced that dose rates less than 50 mSv/year will have no measurable impact on their health, simply estimating radiation induced cancer deaths greatly underestimates the social cost of a release.[9] Conversely, if people were to accept this fact, then nuclear electricity can be regulated in much the same manner as a coal plant.

But it won't be a industry that

1. nonchalantly accepted LNT in 1959, blithely proclaiming to one and all that low dose rates are orders of magnitude more dangerous than they are;
2. bases its claim to safety on bogus release probabilities, destroying any claim 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 was abetted and at times promoted by the nuclear power regulatory/industrial complex itself.

[8] 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.

[9] As we shall see, prior to 1948 people accepted 1 mSv/day as a permissable dose rate.

Chapter 7

Nuclear Power Regulation

Cost is key to solving the Gordian knot of electricity poverty and global warming. Cost is not dollars. Rather it 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.

7.1 Unless you are cheaper than coal, don't bother

A modern coal plant, Figure 7.1, is a marvelous piece of engineering.

Figure 7.1: 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 7.2, dried, pulverized, and mixed

[1] These coal numbers are based on a good (6700 kcal/kg), low sulfur Australian Thermal Coal.[74][p 91] For a sub-bituminous coal the numbers will be considerably larger.

Figure 7.2: 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. 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 7.1, the turbine hall is in front of the boiler. The boiler towers over the turbine hall. But what we don't see in Figure 7.1 is all the stack gas treatment equipment which is on the other side of the boiler. Figure 7.3 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 requirements are. According to the IPCC median estimate, life cycle, a coal plant will produce 1001 grams of CO2 equivalent gas per kWh.[107][Table A.II.4]

[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.

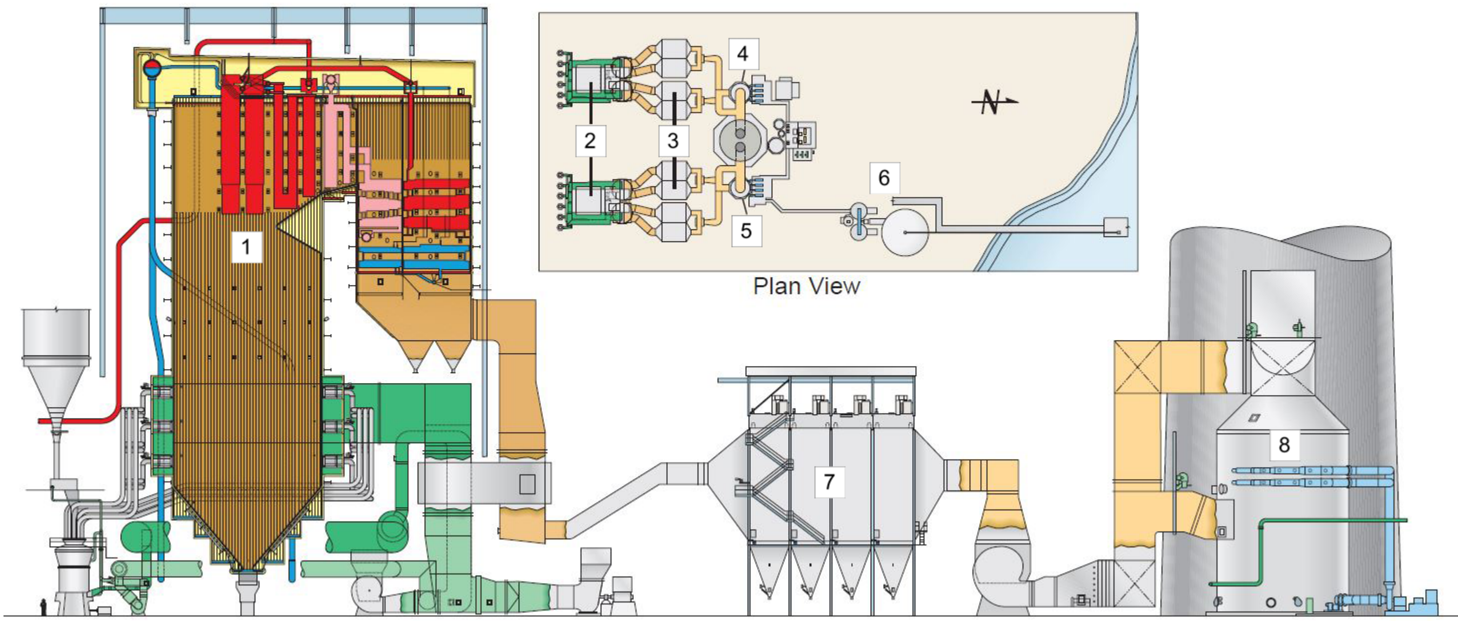

Figure 7.3: 660 MW Tanjung Jati boiler and gas handling equipment. 1. Furnace, 2. boiler house, 3,7. Electrostatic Precipitators (modern baghouse), 4,5,8 scrubbers, 6. wet scrubber limestone silo

7.2 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 7.4.

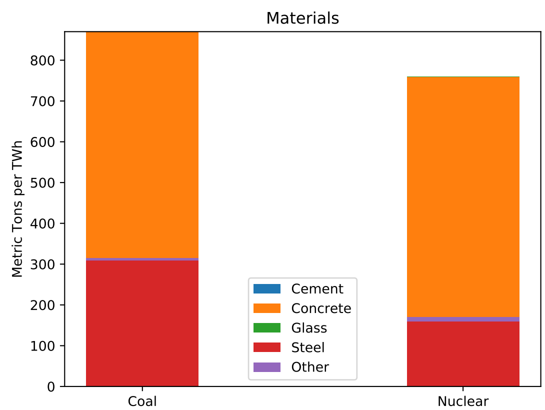

Figure 7.4: Concrete and steel, coal versus nuclear.[123][Table 10.4]

Interestingly, nuclear steel per megawatt is nearly twice what it was in 1970. Concrete has gone up by close to a factor of three.[134] 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 7.5 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

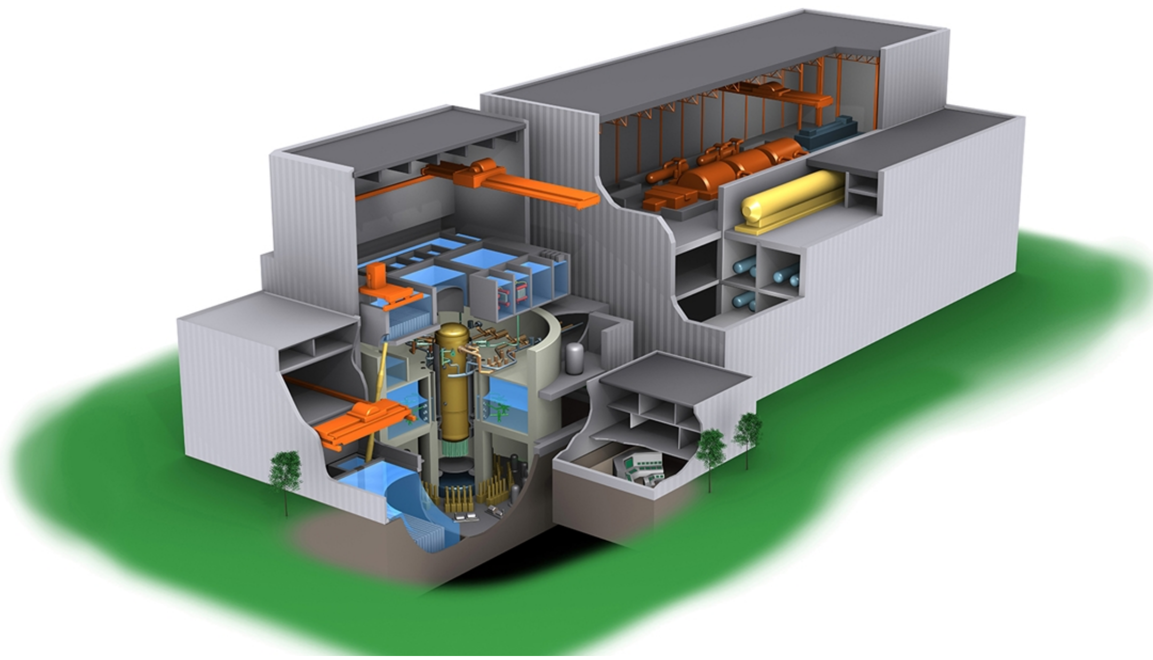

Figure 7.5: 1500 MW ESBWR power plant.

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. 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 IPCC, life cycle, given the current power mix, the plant will produce 16 grams of CO2/kWh, 60 times less than the coal plant.[3] In an nearly all nuclear grid, the ESBWR will produce less than 1% 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 7.1 and 7.2) or the ESBWR, Figure 7.5, 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.

[3] 16 g/kWh is the median IPCC estimate.[107] The IPCC sample of estimates included studies whose estimates were sometimes ridiculously biased against nuclear power. Most industry studies, including audited Swedish declarations, put nuclear's carbon intensity in the 2 to 5 grams per kilowatt-hour range.[168]

7.3 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 7.6 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.

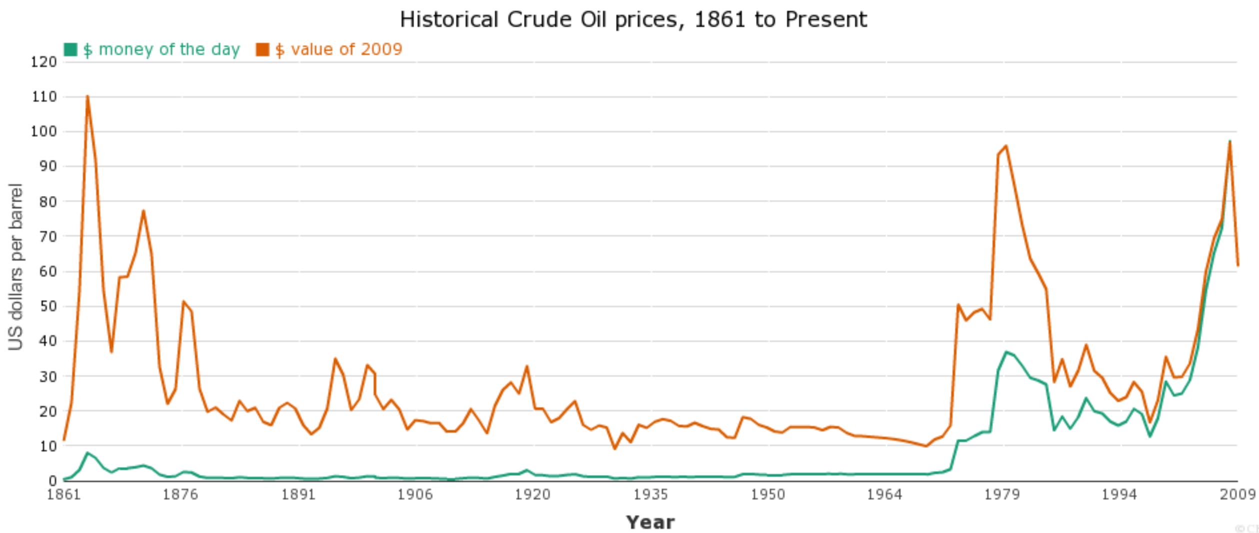

Figure 7.6: Oil price 1861 to 2009, BP Statistical Review of World Energy

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 7.7. 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 7.8. 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.

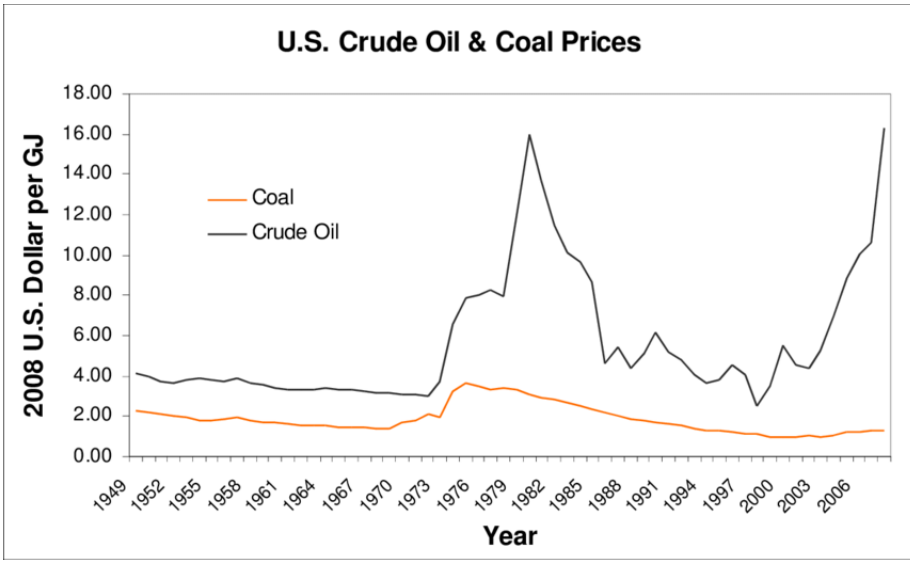

Figure 7.7: USA coal and oil prices, 1949 to 2009, reference [73][page 16]

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.[37][p 269] Support for nuclear power was plank Number 1 in JFK's 1960 Democratic party platform.[8][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.[56][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 1965, GE had to show TVA that it would produce electricity for less than 3.7 mills per kilowatt hour.[20][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.[86][p 20] Nuclear's fuel cost advantage tipped the LCOE in favor of nuclear.

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 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.

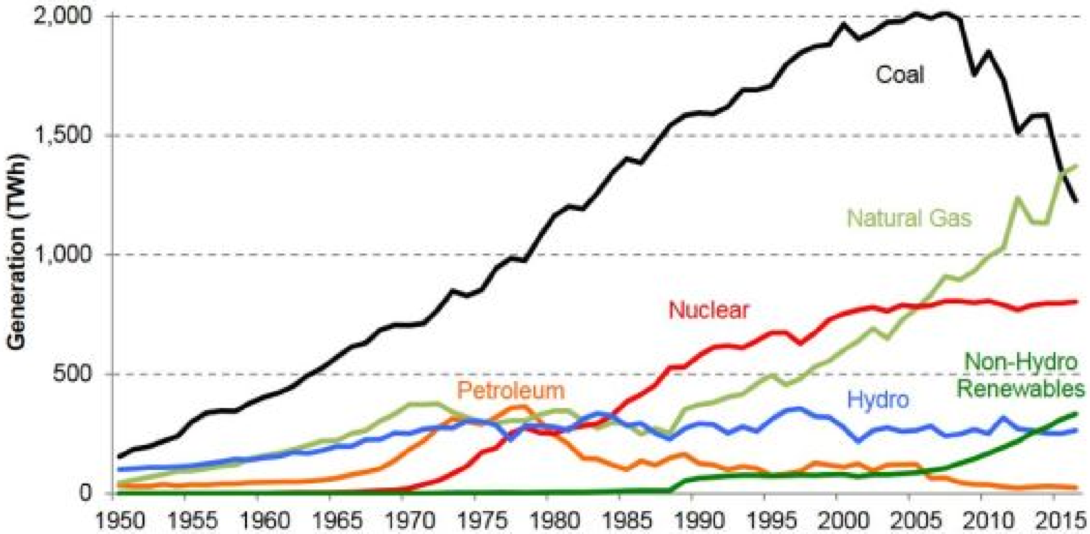

Figure 7.8: USA electricity generation by fuel from reference [40]

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.[180][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, three times what it was in 1969.

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.[54][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.[20][p 93] The real price of coal in 1977 was 2.5 times that of 1970, Figure 7.9. 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.

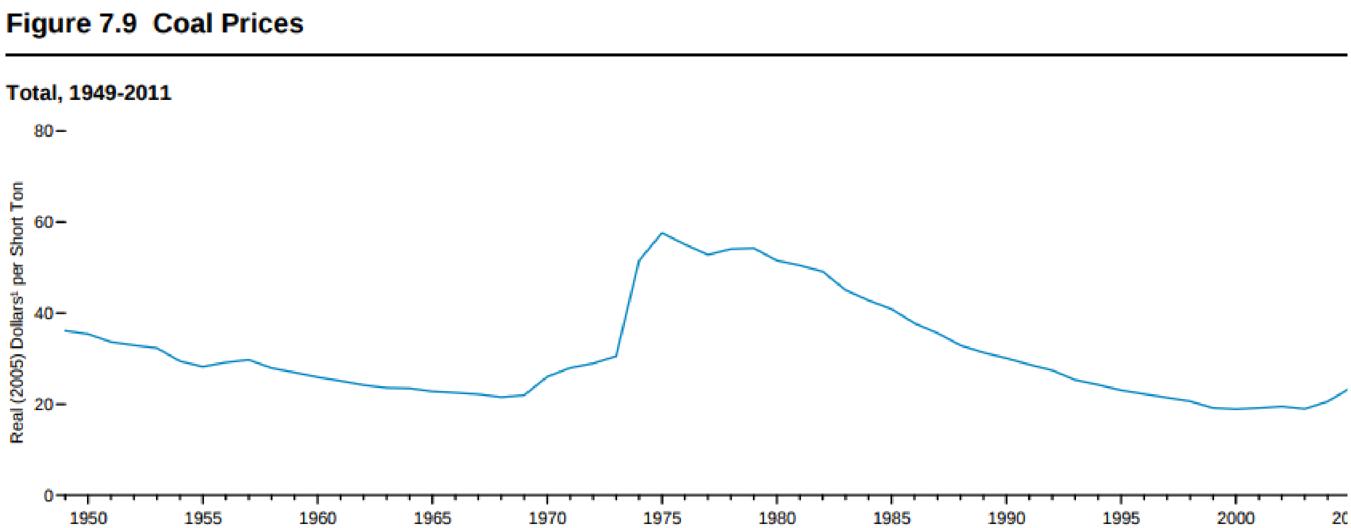

Figure 7.9: USA coal prices, 1950 to 2005, Source: EIA, Annual Energy Review 2011

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 scrambled 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.[20][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".[56][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 built under that balance have a far better safety record than the fossil fuel plants built at the same time.[5]

[5] Much has been made of the official separation of the regulatory and promotional functions mandated by

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,[86][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'.[86][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 of the primary loop piping as a credible failure. In this scenario, a section of the 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."[172][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, etc, requirements so severe that it pushed the designers into using developmental, unrobust technology.[128][page 138] A far more reliable approach is Leak Before Break by which the designer ensures that a stable crack will penetrate the piping before larger scale failure.

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.[151][page 36]

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the Nuclear Reorganization Act of 1974. But in fact the organizational split goes back to 1961. In 1963 the regulatory people were physically separated from the rest of AEC, moving from Germantown to their own offices in Bethesda.

[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.

7.4 The Arrival of ALARA

In 1971, the AEC introduced 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'[20][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?[7]

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 7.1, 7.2, 7.3 from reference [135] show just how much.

Table 7.1: 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 7.2: Change in material requirements, 1973-1978

Year	Concrete	Steel	Cable	Cable tray	Conduit
	Cubic yards	Short tons	Yards	Yards	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 7.2 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 7.3: 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

[7] 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 7.3 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.[8] New plant building halted and the inevitable weeding out process began.

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*.

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[8] Capacity factor is the ratio of actual output to nameplate output.

7.5 The American Plume and non-American experience

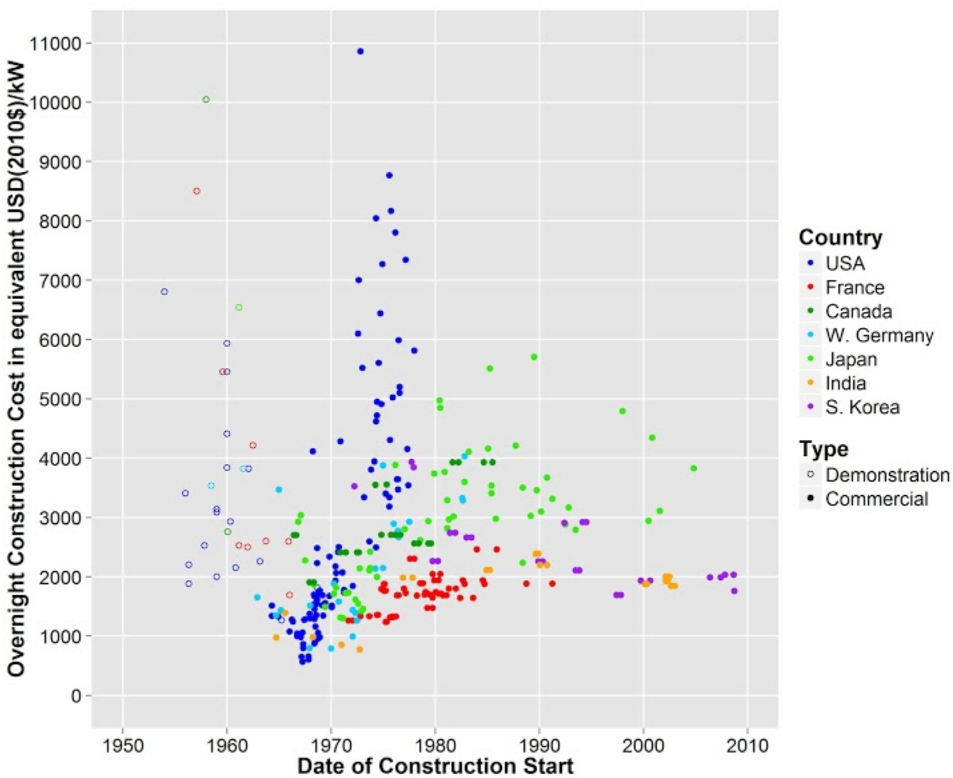

Figure 7.10: Overnight nuclear plant cost as a function of start of construction from [96]

Figure 7.10 from Lovering et al, reference [96], 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.[9]

3. The plume carried away the American nuclear dream. By the mid 70's, the USA nuclear boom was over. No US nuclear plant was ordered after 1974 in the 20th century. ***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.[10] The key to this was strong dirigisme from the top. French nuclear regulators were told what the plan was and what the reward would be for those who did not get with the plan. And the single national utility, EDF, was told the same. 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 7.10, is an instructive outlier. As late as 2013, post-Fukushima, South Korea was able to produce the APR1400 at less than $2500 per KW, Table 7.4. 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.[11]

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[9] A particularly debilitating feature of the continually tightening requirements under ALARA was *backfitting*. 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."[56][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.

[10] Sweden replaced essentially all her fossil fuel plants with nuclear in slightly less time.[64][p 22-25]

[11] There is considerable evidence that China is approaching the same cost level.

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 7.4: Korean APR1400 cost

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.[12] 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 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.***

7.6 The Working of the Regulatory Ratchet

Komanoff found a nearly linear relationship (R = 0.92) in the 1970's between USA plant cost and sector size, which he defines as amount of capacity operating and under construction (aka issued

[12] In a properly functioning competitive market, there is little money to bribe people to forge documents.

licenses)[86][page 26]. He argues this is due to a conscious policy of keeping the probability of a major casualty constant regardless of the amount of nuclear capacity.

There are three major problems with this hypothesis:

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 proportional 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.[37][page 142] The goal to make the probability of a casualty independent of sector size is unobtainable at any cost and that would have been obvious to everybody.

   As it turned out, the pre-1970 plants have the same superlative safety record as the post-1970 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.
3. Nuclear power 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 7.11.[90][p 7]

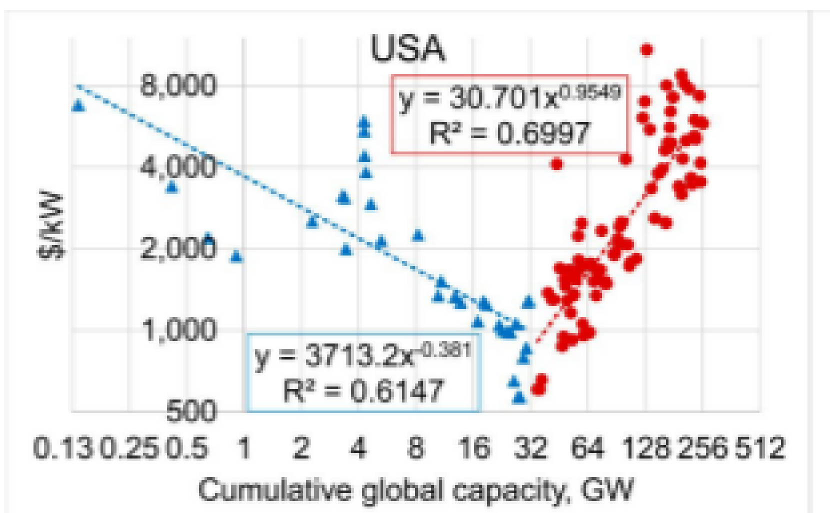

Figure 7.11: USA Unit cost versus capacity [from Lang-2017]

If people were worried about sector casualty probability prior to the late sixties, it did not show up in plant cost. Right around 1970, 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 is that, once cost pressures are removed, the regulatory ratchet operates in roughly equal steps.

7.7 Post-1980 Plant Labor Costs

Table 7.5: Breakdown of 1987 USA Power Plant Labor Costs 1987 $/kW, [37][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 7.5 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.

7.8 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.[13] 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 7.12 shows that fallout dose rates in the U.K. peaked at 0.15 mSv/y.[4][Figure 23] The solution was to argue that mortality was linear in dose however small and cumulative over both time and population. The solution was LNT.

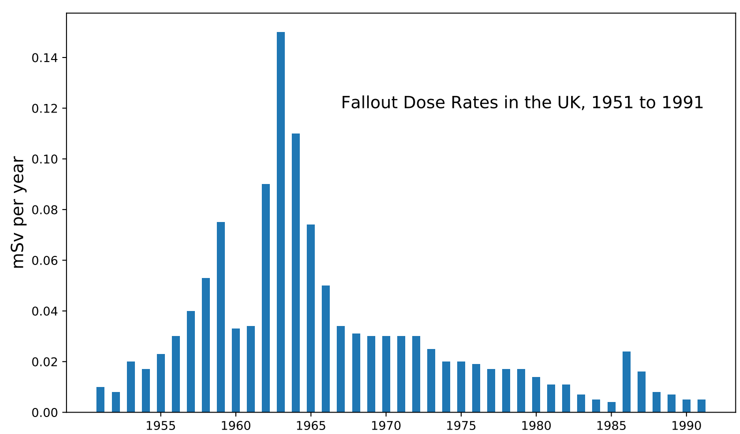

Figure 7.12: UK Fallout Dose Rates, 1951-1991. Peak was in 1963 as weapons states got as much atmospheric testing in as possible before the ban. Chernobyl shows up as a blip in 1986/1987.

[13] 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.[23] 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.

> 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.[116, page 1]

Opinion trends that are not based on data are hardly scientific.

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. It is not clear how effective this was in persuading the general population; but, with a major boost 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

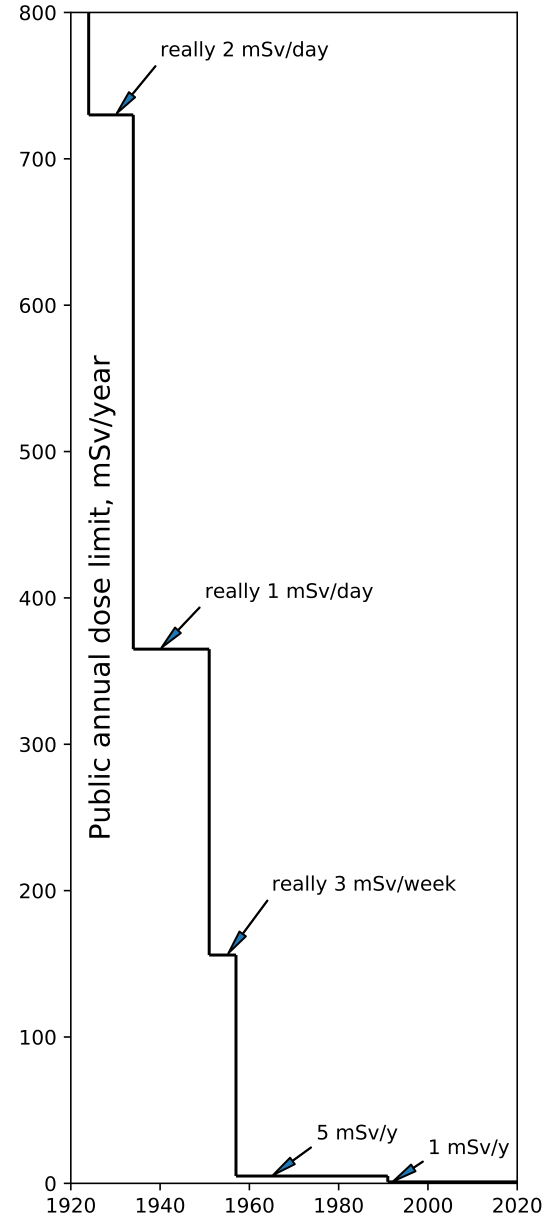

Figure 7.13: US Dose Limits

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. In all their *hot release* (300F) scenarios, very few people were killed.[14][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.[14] 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.[15] Daniel Ford, the UCS's Executive Director writes that in 1972 "Nuclear power still enjoyed strong support in Congress and in the general public."[56][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.[8][p 234]

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. The target was the social structure, the Man, as much as nuclear power. The general public was not much involved.

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[14] 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 1975 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 David 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."

[15] 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.

The first real non-NIMBY protest against nuclear power was at Wyhl in Germany in 1975. The RAND corporation did not start chronicling nuclear plant protests until 1977.[46] 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 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.

7.9 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.[174][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:

1. Regulator Incentives
2. 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.[16]

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. 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 and repeat. An accomplished regulator can keep this process going for the better part of a decade.[17]

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. ***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.

Bottom Line The conclusion is obvious: under the Gold Standard there will be no new nuke.

[16] 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.

[17] In order to keep this process going for as long as possible, the American nuclear power complex has one more trick up its sleeve. The DOE funnels taxpayer money to politically connected applicants calling it something like "Advanced Reactor Demonstration Program", which then uses the money to pay the NRC application fees. The taxpayer becomes the unwilling funder of the bureaucracy circulating her money to itself.

Chapter 8

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 the 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.

8.1 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 8.1 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 8.1: 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 the world 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 what it should cost and what it 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.[94] 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.

8.2 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.

8.2.1 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 still 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.

8.2.2 Bid everybody, trust nobody

In procurement, the most important weapon is competition. We must do everything possible to maximize competition among vendors.[4] 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.

8.2.3 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.

[4] 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.

When asked about quality, vendors will offer a long list of references and extol all their QA certificates.[5]

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.[6]

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.[7]

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 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.

[5] Test certificates can be forged, bribing an inspector if necessary. See Korea, Section 7.5. Forging guarantees is next to impossible. The guarantee will be pored over by dozens of guarantor people, and signed by somebody high in the guarantor's management. Won't happen.

[6] 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.

[7] 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.

8.2.4 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.

8.2.5 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.

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.

8.2.6 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.

8.2.7 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.

8.3 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.[8] Sometimes it's just a different bin. Manufactors 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.

[8] 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.

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 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 Voglte and V. Summer AP1000 projects was the construction of steel modules on an assembly line basis. The outfit chosen to do this work was Shaw Industries in Lake Charles, LA. ***But Westinghouse had nobody at the Lake Charles plant to check the modules.***[88] When the modules reached the plant sites, they were not to spec, did not fit, and had to be scrapped or undergo extensive rework. 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 module, witnessing the weld tests, making their own measurements. If a module is not to spec, it does not ship. Under formal quality assurance, such a team was deemed unnecessary. Instead we trust the paperwork.

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.[9] 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 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.

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[9] 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.

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.

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 10.1 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.[10]

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.

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

[10] 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 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.

Regulatory Guide 1.28.[11] 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.

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[11] 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.”[124][Page A-1] I have no idea what this means.

Chapter 9

Can't License without Testing. Can't Test without a License.

9.1 A Bit of History

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.

9.2 Protopark

The other day I ran across a conversation among nuclear advocates bemoaning the lack of US government funding of advanced nuclear concepts.

The last thing the US needs is more public money spent on nuclear "research". We don't need research. We need to start building. And even if there is an argument for still more research, it would bear no fruit in the current regulatory environment, regardless of how good the technology was. There's no point in throwing still more public money down that toilet. We need an entirely different approach.

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. Under the current regulatory process, there is no feasible way of taking advantage of this godsend. And by testing I mean not only tests that confirm that the design behaves as predicted under normal operation, but physical imposition of all the upsets and failures that the designers claim the plant can handle.[1] If and only if the design passes all these tests, then and only then can society have confidence in the design, and proceed to licensing.[2]

Here's a modest proposal that would restore the US to world leadership in nuclear power, and meet the gordian challenges of energy poverty for much of humanity and climate change for all of us.

The Protopark. The Feds designate a portion of some unpopulated federal reserve as a nuclear prototype testing park. Hanford would be my choice, but there may be better locations. The park would be fitted with security, and infrastructure that is a common requirement for all or almost all concepts. This could include a heat sink for rejecting or better using the energy produced by the prototypes.

The test programs will create waste streams. The protopark must have a facility for disposing of Low Level Waste and storing High Level Waste. The LLW facility will need to be able to handle at least Class C material.[3] The HLW facility will look very much like the

[1] 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 steep dive. The test crew recovered and problem was quickly corrected.

[2] 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.

[3] We also need an overhaul of the USA system for classifying nuclear waste which is largely based on the source of the waste rather than its radiotoxicity. This made no sense even for Light Water Reactors and creates major

dry cask storage facilities that are currently handling the spent fuel from some 60 reactors around the country. Typically these pads are less than an acre in size.

Tenant pays. Here's the 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.[4] It would also mean that, if the park is successful, it will cost the taxpayer little or no money.

Liability. Ideally, the tester would be fully responsible for any actual harm associated with a casualty. But under the current USA legal system, the link between a casualty and the alleged harm can be extremely tenuous.[5] This combined with the legal status of the Linear No Threshold hypothesis means that almost any release during testing could lead to essentially unlimited claims.

There is no chance that the USA tort system can be made reasonable, in which case a limitation in liability will be required. In return, 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.[6] 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, it would be a requirement that the insurer have knowledgeable overseer(s) at the tests. The overseer has the authority to yank the bond if she is uncomfortable with how things are going.[7] As soon as the bond is yanked, further tests would be illegal and the prototype would have to shut down.

Potential insurers would have to evaluate the testing risk. But that's what they do for a living. They would turn to the best experts they can find and the relevant professional societies such as the American Nuclear Society. Only after consulting with such people and groups, will they decide whether to write the business and, if so, set the premium, and carefully pick their overseer(s).[8]

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distortions and uncertainties for the new technologies. The system should be based strictly on the level of hazard.

[4] It also avoids the ugly situation where the moocher takes taxpayer money but keeps the IP he developed with our money.

[5] After the Deepwater Horizon blowout, BP paid nearly 200 million dollars to businesses in the Florida Keys. One Key West bar was awarded $600,000 for "lost business". The oil spill never came within 700 miles of the Keys.

[6] The bond could also cover the costs of decommissioning and removal. If not, a second bond covering these costs would be required.

[7] 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.

[8] People who run reactors will tell you insurance inspectors are more knowledgable, tougher, less interested in

Government oversight of the tests would be limited to setting the value of the bond and approving the insurer and the terms of the insurance including the identity of the overseer(s). The candidate prototype would face two major hurdles just to be allowed to enter the protopark:

1. He has to convince the regulators that his technology is safe enough to allow them to set the bond at a reasonable level.
2. He has to convince potential insurers that his technology is safe enough so that they will post the bond at a premium he can afford.

Licensing. After a prototype has completed its tests or been shut down by the insurer, the proponents would still need to apply to the NRC via the "normal" licensing process. But they would do so on the basis of real data, not just computer models.

New technologies require test reactors/prototypes not just so the developers can learn about their design and fix/improve/abort as necessary, but also the regulators can learn about the technology. But this requires a kind of humility on the part of both developers and regulators. We don't know everything we need to know to license this technology for commercial use; so let's learn together.

But regulating such tests requires a step by step approach in which each step is approved based on the results of the tests so far. This is a sequential process that is totally different from normal licensing. And this must be understood by the regulators.

Ongoing Development 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, much of 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.

Multiple Countries. Other countries including Argentina, China and Russia recognize this. The KLT-40S, the HTR-PM, and the CAREM were given permission to begin building

paperwork, more interested in substance than the NRC inspectors.

by their national regulators under special provisions. And in fact ***multiple protoparks in different countries would be a good thing***. If a country sets up a prohibitive regulatory system for a protopark — in our case, this could be done by setting the insurance required at an excessively high level — testers will have the option of moving to a regime which does a better job of balancing risk versus benefit.

Legislation Required. In the US, a protopark will require new legislation.[9] The NRC has 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.

[9] Section 110 of the Atomic Energy Act (1954) contains a blanket exclusion from licensing for facilities built for the account of the AEC (later DOE) and the DOD. But Section 202 of the Energy Reorganization Act of 1974 pulls this back. The DOD exclusion stands. But the DOE exclusion does not hold for demonstration reactors "when operated as part of the power generation facilities of an electric utility system, or when operated in any other manner for the purpose of demonstrating the suitability for commercial operation of such a reactor." This of course is precisely what the prototypes are trying to do.

There has been essentially no technological progress in commercial nuclear reactors in the US in the 40 years since 1974. This is quite remarkable. Section 202 is one of the reasons.

Chapter 10

Replacing the Gold Standard

If the Gold Standard effectively precludes nuclear power and effectively prevents mankind from solving the twin problems of energy poverty and global warming, with what should we replace it? This chaper offers some suggestions.

10.1 Firm, Balanced Limits

ALARA must go 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. 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. The poor need cheap electricity far more than the rich do.

   But it's the longer term implications of ALARA that are the most tragic. Imagine a world 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 almost no 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.[1]

   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.

Firm Dose Rate Limits 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.[2]

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.

[1] 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.[143] Not surprising. The 450 MW Riverbend coal plant in North Carolina operated with a total of 14 people per shift.[43][p 195]. Coal plants are far more maintenance intensive than nuclear plants.

[2] 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.

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 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.[139]

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.[3]

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.[111] 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.

[3] There is no limit to how unreasonable an unbridled regulator can be in enforcing As Low As Reasonably Achievable. Theo Richel did an entertaining 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 4.9. 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. Silly, but the lesson for the public is this must be a very dangerous 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.[4] 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.[128] 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.[85]. 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. This was almost certainly Congressional intent, but the result is that NRC legally MUST ignore the 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 possibly the planet.

Define what each limit means 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,

[4] Reducing consumption somewhat may be a viable option for wealthy countries but for poor countries going with less power is far less healthy than coal power.

consider the following hypothetical set of plant boundary rules.

Trigger for corrective action	0.114 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. This is a normal operation requirement based on the 1 mSv/y above background design level recommended by the ICRP for the plant boundary converted to an hourly rate. Has no health implication. 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. This plant shutdown trigger is based on the 50 mSv/y ICRP limit for plant employees converted to an hourly rate. Nil health implications. But something is seriously wrong and must be fixed.
Trigger to warn public to shelter in place	15 μSv/h	15 microsieverts per hour is the IAEA recommended Operational Intervention Level (OIL) for shelter in place. Concern early on is it could go higher. Once rates drop below this level, order can be lifted.
Trigger to recommend evacuation	150 μSv/h	150 microsieverts per hour is the IAEA recommended Operational Intervention Level (OIL) for evacuation.
Trigger to lift evacuation order	35 μSv/h	Per SNT results in LLE of 0.19 days per month. See Section 5.3. ICRP level of 2.3 μSv/h way too low. This is a local level, not plant boundary.

This table 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 levels at which any radiation health effects have been reliably observed, which is at least 100 mSv for an acute dose.

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.[35]

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 un-

	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 10.1: Evolution of General Public Radiation Limits. See also Figure 7.13

> dertaken. This alert level has been set far below — a factor of 100 below — the dose rate at which any radiation health effects have 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.[5][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.

Spread the Good News Table 10.1 shows the evolution of allowable dose rates since the 1930's. Remember when NCRP called for the factor of 30 reduction in the Maximum Permissible Dose in 1957, they admitted, Section 7.8,

> 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[116, page 1]

Table 10.2 shows the SNT Lost Life Expectancy as a function of monthly dose, assuming that dose is received every month in a 70 year life.

According to SNT, 4 mSv/month for an entire life has an LLE of 3 days. This suggests that dose rates below 4 mSv/month (50 mSv/y) should be Below Regulatory Concern in terms

Dose mSv/ month	SNT monthly EAR	Lifetime SNT ERR	Lost Life Expectancy days
0.5	0.12000003	0.00002	0.03
1.0	0.12000011	0.00010	0.14
2.0	0.12000052	0.00043	0.64
3.0	0.12000125	0.00105	1.54
4.0	0.12000234	0.00197	2.89
5.0	0.12000381	0.00320	4.70
10.0	0.12001724	0.01448	21.33

Table 10.2: SNT Lost Life Expectancy for lifetime constant monthly dose

of health effects. This would take us back to the 1948 limits. It is consistent with the lack of any evidence of increased cancer incidence in high background areas such as Kerala. And it's consistent with the nuclear worker limits. The regulator needs to widely promulgate and defend the fact that 4 mSv per month or less dose rates will result in no detectable decrease in life expectancy.

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.[137] 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.

Do not enforce more than the limits 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 should be to enforce the dose rate limits and the corresponding penalties, not dictate how the plant should be operated.

10.2 Encourage incident reporting

Instead of discouraging reporting with blackmark metrics, individuals should be encouraged to report problems. The FAA's Aviation Safety Reporting System (ASRS) allows pilots to voluntarily report near misses and latent hazards. The reports which often involve accidental rule violations are kept confidential. The information is administered by a third party, in this case NASA, which has no enforcement authority. NASA collates and analyses the reports looking for systemic problems. The de-identified reports are published in a monthly news letter and on a web site. Many make fascinating reading. If an individual incident is later investigated by the FAA, the fact that it has been voluntarily reported to ASRS is counted in favor of the reporter.[5] The NRC has no such system. It should.

10.3 Recognize the need for full scale, rigorous, physical testing

It is imprudent to license any new nuke (or any nuclear design) without full scale, rigorous, stress testing, including simulating major failures and proving that the backup safety systems actually

[5] There are actually two systems. ASRS and Aviation Safety Action Program (ASAP). ASAP is an agreement between individual airlines and the FAA. It has stronger protection for the reporter than ASRS. (ASRS reporters get limited immunity from the FAA but not from their employers.) The de-identified reports are not made public. They are distributed only to the airlines in the program. Reporters can only be sanctioned if management, the union, and a third party ASAP team agree. Otherwise, reporting is a get out of jail free card. Serious lapses tend to be reported to ASAP, rather than ASRS.

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.***

Moreover, 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. And a similar system of full scale, uncompromising testing needs to be imposed.

The system for regulating testing must be quite different from that for regulating normal commercial operation The ACRS has questioned NuScale's emergency cooling system, Section 3.2. The solution is simple: build one and test it. But under NRC rules, you cannot build even a test reactor without a licence, and you can't get a license until all such questions are resolved. The Gold Standard sets up an impossible dilemma. Can't prudently license without testing; can't test without a license.

The problem is that the Gold Standard attempts to regulate testing prototype reactors the same way it regulates normal commercial operation. The Atomic Energy Act recognized the need for different rules for test reactors. But over time this distinction has been lost; in part because as long as a "new" design was simply a scale up of an existing design full scale stress testing was deemed unnecessary; but mainly because true full scale, stress testing was regarded as too expensive. Industry opted to rely on computer simulation instead and the NRC went along. The Gold Standard replaced real testing with computer runs.

Many of the new technologies being proposed are modular in nature. This means that full scale, rigorous stress testing is economically feasible. But the system for monitoring such testing must be step-by-step where the approval to begin the next test depends of the successful completion of all the prior tests. During this process fixes and improvements will and should be made. Such step-by-step approval is completely different from the current all-or-nothing licensing process which can be described as don't-test-but-eventually-license-anyway.

This does not mean that the rules for testing should be more lenient than those for normal commercial operation. Quite the opposite. A test reactor must operate under the constant monitoring of the regulator whose representative has absolute power to shut the reactor down whenever he feels like it. A test reactor cannot even begin any test without the explicit approval of the regulator. A commercial, base load, nuclear power plant cannot operate under such a set of rules, but a test reactor must.

Allow test reactors to sell electricity These full scale tests properly done will generate quite a bit 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.

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 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).[8][page 205-206] Coal interests complained bitterly about this misuse 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 backdoor way of forcing the commercial plants to license under Section 103. The unintended consequence was to effectively eliminate large scale testing.

Safety Related Design Changes must be Centrally Certified Fixes and improvements are inevitable and proper; but they must be handled in a standardized manner. Any proposed change which affects a design's radiation release resistance — and only such changes — must be tested and certified by the central regulatory body and after approval made mandatory for all plants of that design. To facilitate this, the prototype plants will need to be a continuing operation, but operating under the test approval regime rather than standard commercial rules.

10.4 Require Strong Guarantees

At best QA certificates attest to the process by which a product was manufactured. They say nothing about how well a product performs. Guarantees do the opposite. A strong guarantee is worth more than a thousand certificates. And strong guarantees are self-policing. Strong guarantees come with mandated inspection, maintenance, and operating policies. If the guarantor can show that the maintenance or operations is not per manual, he is off the hook. This puts pressure on the operator to do things by the book. A good example of this process is commercial aircraft engines, Section 8.2.3. Strong guarantees can replace much of the current regulatory apparatus.

10.5 Fixed Compensation Schedule

The system must promulgate and enforce a table of compensation payments for a release. The table can be based on both the dose received from a release and any actions required, e.g mandatory evacuation. Value of Life numbers vary widely, but an upper bound is the US dialysis standard of $129,000 per year or $350 per day. One possibility is to estimate the LLE associated with the dose received, and award that amount plus the actual costs of mandatory evacuation. The table could be quite generous but it has to have reasonable lower limits. And it has to be limited to the direct impact of a release.

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.

10.6 Require liability insurance

The body politic must decide on a reasonable worst case third party casualty cost and require iron clad insurance for this amount. This should be done by elected officials using the table of compensation payments.

The liability insurance requirement is a keystone of the system. It provides money to compensate victims of a casualty. More 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. The latter seem mainly interested in QA paperwork.[6]

10.7 Internalize Reactor Damage Costs

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.[154][Table 3] That's 30 times that of the average gas plant casualty and about 500 times that of the average solar/wind casualty. There are a number of problems with this database, but there is no doubt that a major nuclear power casualty is far more expensive in damage cost than a fossil fuel power plant 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 reactivity.

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

[6] A common trick among American plant operators is to insert a fairly obvious but inconsequential inconsistency in the QA paperwork. When the NRC inspector discovers the error, he writes the plant up proving to his boss he's doing his job. The plant thanks him for pointing out the problem and agrees to take corrective action. The inspector goes away satisfied. Everybody's happy.

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.

Insurance markets tend to work imperfectly when dealing with very rare events. Mutual pools such as that in the American system tend to charge the same premium for all members. The good plants are subsidizing the bad plants so it pays to be a bad plant. Therefore, while we need ironclad liability insurance to compensate third parties in the event of a casualty, I would recommend that nuclear power plants ***not*** be allowed to purchase property damage insurance. Do that and you can be sure that the investor community will carefully scrutinize the design and management of any plant before plunking down the money to build the plant.[7]

10.8 Design Approvals

At this point, we have a system that looks much like that in place for commercial aviation: rigorous full scale testing, tough guarantees, insurance with pre-set compensation, type certification. Air travel is generally regarded as a safe activity, safer than just about any other means of getting from one place to another. We could and probably should stop right here. We don't need design approvals. A license should be based on passing a rigorous set of stress tests, not computer runs. But if in addition to the tests, some sort of separate design approval is deemed necessary, than it must be narrowly focused.

Define Safety Critical Narrowly The reason we have special nuclear regulation is the special hazards associated with radiation. If it is not a radiation hazard, then the standard non-nuclear regulatory system must be relied on. The nuclear regulatory bodies accept this in principle. They distinguish between *safety critical* items and non-safety critical items. Safety critical is this context means essential to controlling radiation hazard. If a component is not essential to this function, then it is not nuclear safety critical, and should not be regulated any differently than it would be if it were in a fossil fuel plant.

But overtime nuclear regulation has expanded its reach to the point where just about everything in the plant is treated as safety critical. So exactly the same functional component in a coal plant is regulated quite differently if it is installed in a nuclear plant. This over-reach is particularly important to some of the new design concepts. In these designs, any increase in reactor temperature automatically decreases power. A big enough temperature jump shuts the fission process down. This is inherent in the reactor physics. There is nothing a malfunctioning control system or confused operator can do to avoid this shutdown. Such designs also remove the decay heat in a totally passive matter, requiring no power, no control system action, and no

[7] The system should include coverage of decommissioning costs in the event of a total loss, so that the investors cannot walk away and leave that cost to the public. But none of this money should go to the plant's investors/lenders.

operator intervention. In fact the control system or the operator can do exactly the wrong thing, and the decay heat will still be safely handled.

It's the designer's responsibility to prove to the regulator that his design does indeed control the reactor and cool the decay heat in such a manner. (The best and really the only way to do it is by testing including creating the casualties that the design claims it can handle.) But once he has done that, any component that is not essential to these functions is not safety critical. It is none of the nuclear regulator's business. That includes the operators, and the plant control system and its software.

Mandatory Inspections and Tests Vendors who produce essentially the same component for both nuclear and non-nuclear applications tell us that one of the biggest differences is they can't be sure when the NRC inspector will show up for a scheduled test. Therefore, they either have to assume a worst case delay in their pricing or claim they can only proceed on a cost plus basis.

Where ever the regulatory system requires the regulator to inspect an assembly or component or witness and approve tests, then given adequate notification, the regulator's representative must show up at the scheduled inspection/test time. If he does not, then the inspection/test is deemed passed. If he does, then he must declare whether or not the inspection/test has been successfully completed with 24 hours after the end of the inspection/test. If he decides that it has not, he must state why not within the same time frame.

To compete, nuclear must be based on assembly line production. There is nothing more disruptive to this process than stopping everything, sitting around, and waiting for an inspector. It is not just that this job is delayed for an indefinite period, but all the other jobs up and down the line are affected. Production scheduling, a crucial key to assembly line manufacture becomes impossible. And along the way worker morale is destroyed.

The flip side of this issue is, if the builder can reliably do production scheduling, the cost of a failed inspection or test is very high. The builder has an extremely strong incentive to ensure that his quality is such that the inspections and tests go smoothly.

Fixed Approval Period The regulator must be required to approve or disapprove an application within a reasonable but fixed amount of time specified by the legislative branch. Failure to do so results in dismissal, and the application is deemed approved.

In the US, we have exactly the opposite situation. Not only is the NRC strongly incentivized to prolong an application review as long as possible, each application must also be reviewed by the Advisory Committee on Reactor Safeguards (ACRS). The ACRS is an independent group of knowledgeable people who are charged with reviewing license applications separately from the NRC. However, the results of an ACRS review can be ignored by the NRC. So the ACRS's only real weapon is delay. If the ACRS is concerned about something for whatever reason, it will refuse to complete its review. There are no rules governing ACRS behavior. The ACRS is answerable to no one. There is no way of appealing an ACRS decision to not complete its review.

Two Sided Arbitration If an applicant believes his application or an inspection/test has been disapproved in manner that is inconsistent with legislative intent, then he can take his case to arbitration. One arbitrator chosen by the applicant, one by the regulator, and one by the two arbitrators.[8] If the arbitrators rule in favor of the regulator, then the applicant pays a substantial fine. If the arbitrators rule in favor of the applicant, the regulators responsible for the disapproval are dismissed. Strong time limits should apply to this process.

We have given nuclear regulators absolute power. With that absolute power comes an equally heavy responsibility. If the regulator fails to carry out those responsibilities in a manner consistent with society's welfare, he must pay a price.

Policemen have been given special privileges and powers. Policemen who abuse those privileges can and should be fired. The same thing should be true for nuclear regulators, whose actions have resulted in hundreds of thousands of premature deaths and imperiled the planet.

Design Approval Cost Design approval and production inspection need not be costly. In ocean transportation, the Classification societies review every major drawing, redo all of the critical design calculations, and attend all scheduled tests during building and trials. Their fee is about 2% of the price of the ship.

10.9 Fund the regulator via user fees

The regulator should be funded by a per kilowatt-hour tax on electricity actually generated by nuclear power. This will give the regulator a tiny share of the benefits of his regulation, partially aligning his incentives with society's. For countries new to nuclear, this will require the government to put some money up front which will be repaid by a successful nuclear program.

The worst way to fund the regulator is by application review fees. This is an excellent way of suppressing new technology. Worse, it an irresistible incentive to prolong the application process as long as possible. This system is in essence a payment to the regulator by the applicant to obtain approval of his design without the need for testing. In other contexts, such payments are called bribes.

[8] The panel of arbitrators can be chosen a number of ways. Perhaps a system similar to that used for federal judges: nomination by the administrative branch, confirmation by the Senate.

10.10 Summary

To recap, the requirements for an efficient, effective nuclear regulatory regime are:

1. Firm dose rate limits.
2. Limits that recognize the hazards associated with alternative sources of base load power.
3. Consequences of violating the limits clearly defined.
4. Enforce only the limits and their consequences.
5. Make clear to the public the meaning and purpose of each limit.
6. Replace blackmark metrics with voluntary incident reporting.
7. Test then License.
8. Step by step control of testing.
9. Centralized design changes and fixes.
10. Require strong guarantees.
11. Fixed compensation payments for a release.
12. Require iron clad liability insurance.
13. Internalize property damage costs.
14. Any nuclear plant design approval must focus only on what's critical to radiation hazard.
15. Limited approval periods.
16. Two sided arbitration.
17. Regulator funded by user fees.

Chapter 11

The Nuclear Power Complex

The American nuclear power complex 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 complex move easily back and forth between the complex's components. See Section 11.8.

In Chapter 10, we came up with a sizable list of regulatory changes required if nuclear power is to be allowed to solve the Gordian knot. But it is not just regulatory rules that must be changed. We must impose competition on a industrial complex that embraces lack of competition. 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 complex. 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

[1] For another example, see Toomer's Creek, Section 10.1.

[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.[104] In practice, it guaranteed that military thinking would strongly influence nuclear electricity.

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 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.[167] 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.[122][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.

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 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. 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.[4] Far more importantly, once you tell that lie, any sizable release of radioactive material from a nuclear power plant becomes unthinkable.

[3] Trying and failing. The 2012 numbers in Table 11.2 on average are 7% higher than 2011. Overall the numbers 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] 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.

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

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.[150] To do this, they assume that the waste must be separated into "high" level and "low" level despite the fact that due to decay over the last 60 years, there is now little difference in the dose rates. The categorization is based on the origin, not the current radioactive activity. This separation is required, 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.

In this context, *high level waste* is defined to be the waste from the initial separation of the fission products from the uranium and transuranics. Fission products tend to decay fairly rapidly. 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.[150][page 766]

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 already has a large number of million gallon, stainless steel tanks; so many that, 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.

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 complex itself has created.

The clean up efforts at the Idaho National Lab 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.[150] This does not mean that the complex 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."[120] Niebuhr wasn't talking about the nuclear complex. 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 m 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.[5] 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

[5] 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.[37][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 far 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 IFR breeder reactor 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.
>
> 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.
>
> 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 Windsor 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. And those states that are being asked to accept the nuclear waste can legitimately be concerned about that. 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 for 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.

The sad fact is that nobody in the nuclear complex 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 dangerous. Once the nuclear complex promulgated and promoted ALARA, they had to expect the public to take them at their word. And they have. Here are a couple of examples.

11.5.1 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.[6] 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.[146][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 complex, but it is a consequence of adopting ALARA.

11.5.2 The Fukushima Tritium

Perhaps the most extreme example of the unnecessary problems the nuclear complex has created for itself is hydrogen-3 or *tritium*. It is hard to imagine a less dangerous radioactive material 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. 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 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.[161]

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).

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[6] If he doubles the distance from the plate, the dose rate will drop by about a factor of 4.

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.[121] 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.[7] To get any response from mice, they had to be fed 37,000,000 Bq/L water.[48] 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.[52] 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.[98][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.[8]

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.

Fish normally have a natural radioactivity of about 350 Bq/kg, mostly from Potassium-40.[98][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 complex's embrace of LNT and promulgation of ALARA has paralyzed us.

11.5.3 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

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[7] Tritium emits a slow moving electron whose average energy is 5.6 keV. Most of this energy gets dispersed in the electron clouds of other molecules before it can get to a critical molecule like DNA. At these low energies, the assumption of a linear relationship between energy and damage is highly suspect.

[8] 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.

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. For a public which has been taught by the nuclear complex to fear any release, this could well be unacceptable.

11.6 The nuclear power complex is nuclear power's worst enemy

Anti-nuclear groups like to take full credit for making nuclear power uneconomic. But we have seen (Section 7.8), they were very late to the party. In all fairness, they should at least acknowledge the help they have had from the nuclear power complex itself. Consider:

1. It was the nuclear power complex 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 complex that attempted to suppress its own ten million dollar study of shipyard workers which contradicted LNT, Section 4.6.7.
3. It was the nuclear power complex that squashed the Low Dose Radiation Research Program that was producing results which invalidated LNT.
4. Table 11.3 shows how consistently and stubbornly the complex has defended LNT.

Table 11.3: The Complex's Defense of LNT

Low Dose Bomb Survivors	Ignored	Own fruit fly data	Ignored
Dial Painters	Outlawed	Own Shipyard workers	Ignored
Berkeley, etc results	Squashed	Taipei Apartments	Ignored
Own Animal studies	Ignored	Yangiang Results	Ignored
Nuclear worker studies	Outlawed	Kerala Results	Ignored

5. It was the nuclear power complex 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 complex 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 complex 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 complex that happily accepted 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 complex 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 complex that happily accepted 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 complex 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 complex 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 complex 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 complex 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.[9] 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

[9] 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%.

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 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. Urenco was prepared to quote a fixed price for whatever amount of LEU19 DOE wanted to buy with delivery starting in 2021.[10] 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

[10] 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.

nuclear in the USA and is now stomping on its grave. This is how the nuclear power complex self destructs.

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.[11] There was no spectacular technical breakthrough. Just incremental improvement on top of incremental improvement. Yards unable to make these improvements did not survive.[12]

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.

[11] 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.

[12] For another example of the power of competition, check out solar panel prices over the last 30 years.

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 and adherence to the system that produced those results. The nuclear power complex 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. To do that ***we must ruthlessly eliminate barriers to entry.***

Organizationally how would we do that? This will vary from country to country. While I believe it is unrealistic to expect the USA to change the way it regulates nuclear electricity, I will use the US as an example.

1. Separate nuclear weapons development and nuclear power development. Nuclear weapons development should be a Department of Defense function. The DOE facilities and the parts of the national labs which are involved in military functions should be transferred to DoD and the military budget.
2. The portions of the labs dealing with nuclear electricity should be privatized or disbanded, releasing all that talent to the market.
3. Stop wasting money on attempting to reduce near background levels of radioactive contamination. Any contamination resulting in dose rates below 4 mSv/month is insignificant medically and better left where it is.
4. Do not try to pick winners with other people's money.[13] Stop spending taxpayer money on specific nuclear (or any other) power technologies. The DOE no longer has any real function and disappears.
5. Massively downsize the NRC and make it part of the Federal Energy Regulatory Commission. This division of FERC would be responsible for testing and certifying new designs. It would look a lot like the Federal Aviation Authority, focused on test results rather than process.
6. Operational nuclear plants would become the responsibility of the state in which the plant is located. Let each state decide whether it wants nuclear electricity or not. The states that opt for nuclear power would impose the regulatory regime outlined in Chapter 10.
7. Set up an independent body to investigate nuclear (and other) power plant mishaps and casualties. The entity would function like the National Transportation Safety Board.

In short, stop throwing taxpayer money at the nuclear power complex. Turn the job of regulating nuclear power plants over to the same people who regulate fossil fuel plants.

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[13] And for God's sake, don't mandate monopolies as we did with Yucca Mountain, Section 2.4, and Centrus, Section 11.8.

11.10 Nuclear Power versus Commercial Aircraft Fatalities

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, about 50 people were killed and perhaps another 1500 will have their lives shortened in an observable manner.[14] ***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.[133] 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.[15]

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.

In contrast, the nuclear power complex promulgates two ugly falsehoods:

1. By accepting LNT and enforcing ALARA — in part to extract billions of taxpayer dollars per year in clean up money — the health hazards of near background dose rates are exaggerated by multiple orders of magnitude. Any release becomes a catastrophe.

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[14] This estimate is based on SNT. But even if we accept the 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.

[15] This is based on the Markandya and Wilkinson estimate of 0.07 deaths per TWh, the 2019 consumption of 22,300 TWh, and a world population of 7 billion.[101] Sovacool et al put the nuclear power fatality rate at 0.01 deaths per TWh.[154] Of course, the shift to nuclear power would materially increase your life expectancy relative to any other dispatchable source of electricity.

2. To counter this lie, they gin up bogus probabilities of a release; and then ask us to assume a release will never happen. It did not take long for this second lie to be exposed. Based on past experience, in an all nuclear grid, we will have a significant release every few years.

The public knows it is dealing with an exposed liar and assumes the worst. It is hard to imagine a more suicidal posture. Unless there is a fundamental change in this self-destructive policy, nuclear power is doomed.

Chapter 12

Metanoeite

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.

- 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.
- 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. Nuclear power cannot be safer than perfection.
- 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.
- The nuclear power complex has to stop thinking that the public is too stupid to evaluate risk. The nuclear power complex 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 radiation protection establishment must abandon LNT for a model which is consistent with the facts. Sigmoid No Threshold is an obvious candidate.
- We all need to understand that radiation dose rates 20 times higher than average background are not a health hazard in any meaningful sense.[1] Such dose rates will rarely be exceeded outside the plant boundary even in a Fukushima style 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 and leadership 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.

[1] Average background is about 2 mSv/y. Dose rates of 42 mSv/y for 15 years in Kerala were associated with slightly depressed cancer incidence, Section 4.9.

Postscript 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, [97][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 complex 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.

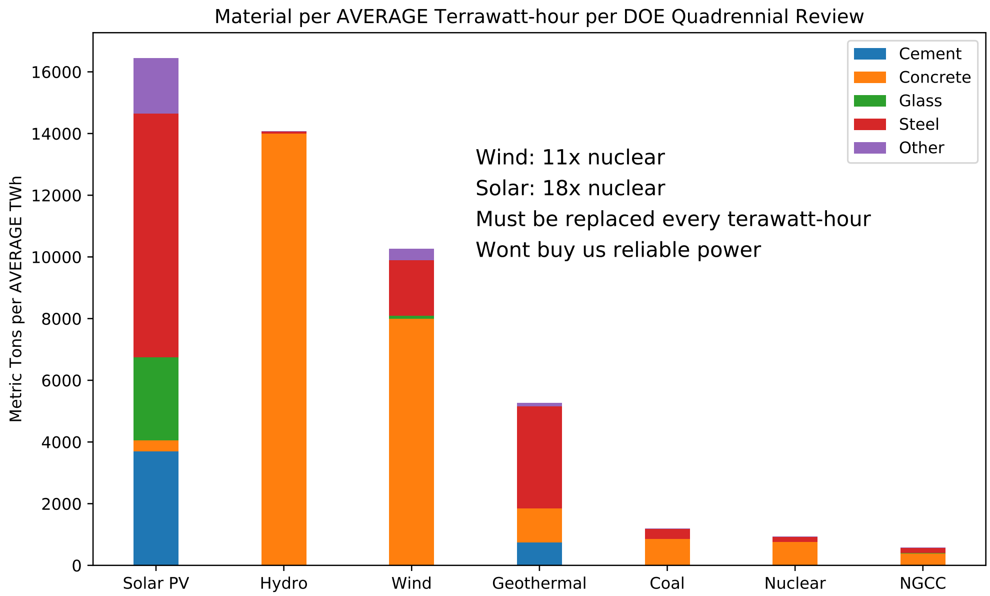

Figure A.1: DOE Estimate of Resources per Terrawatt-hour.[123][Table 10.4]

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."[87]

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.

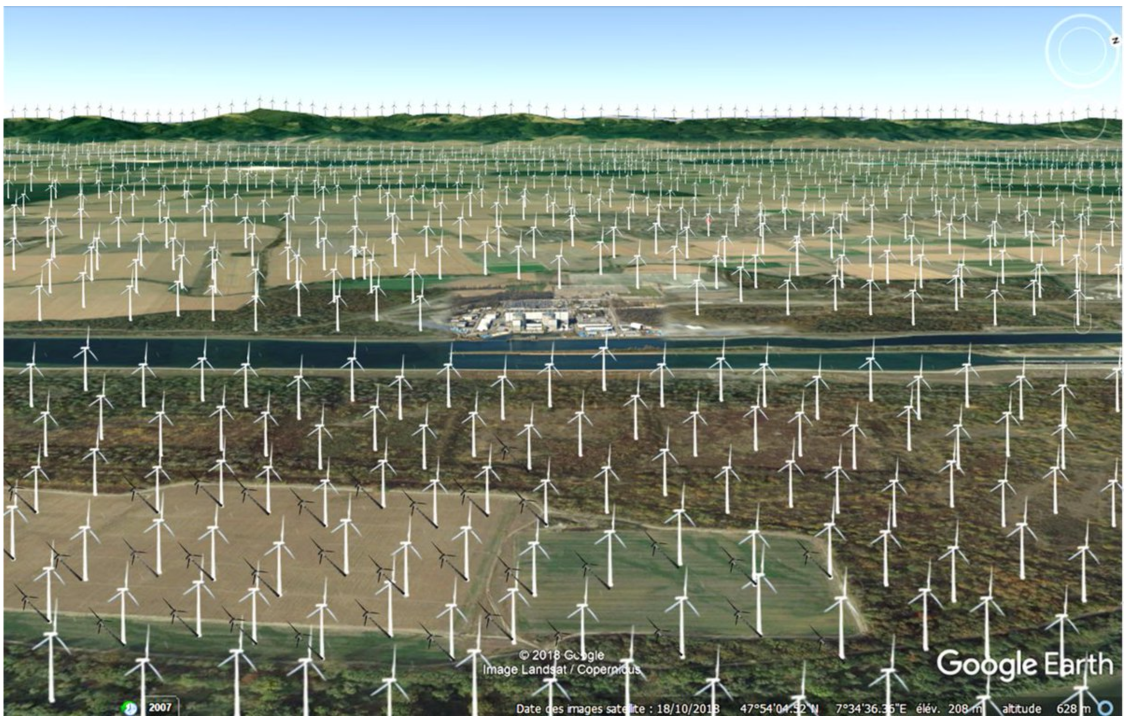

Figure A.2: The 850 3 MW nameplate wind turbines shown will produce on average about one-third the electricity of the 1.8 GW Fessenheim plant in the center of the graphic. And when the Fessenheim plant is shutdown, we will also need to replace nearly 1.8 GW's of dispatchable capacity to ensure reliability. 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.

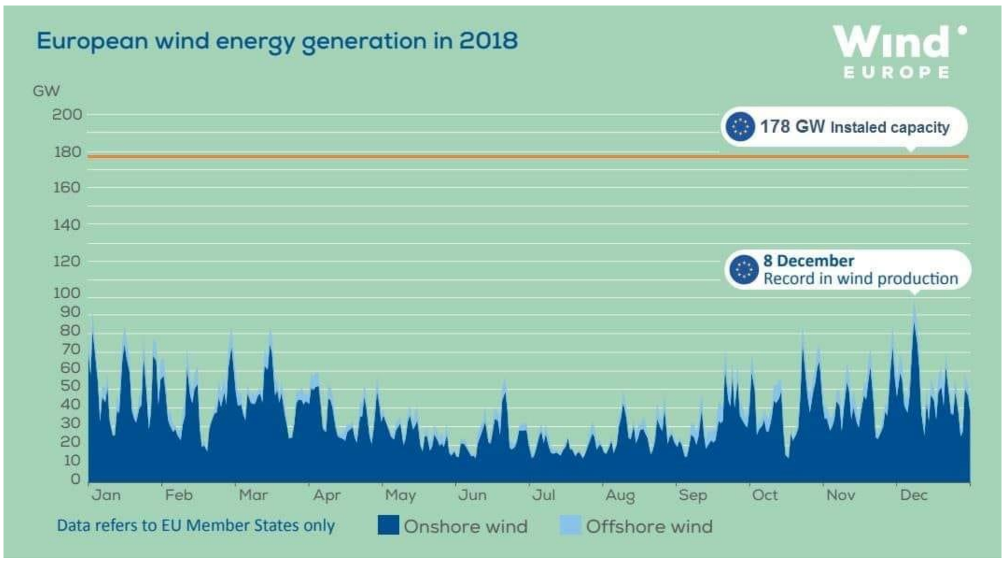

Figure A.3: European wind performance, 2018

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 less than 10% capacity. 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.

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

[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.[169]

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.4, is that they are bearing the cost of maintaining two systems: the intermittent, and the dispatchable. Perhaps Denmark and Germany can afford a doubling in price to obtain about 20% of their electricity from wind and solar; but the developing world (and the planet) cannot.

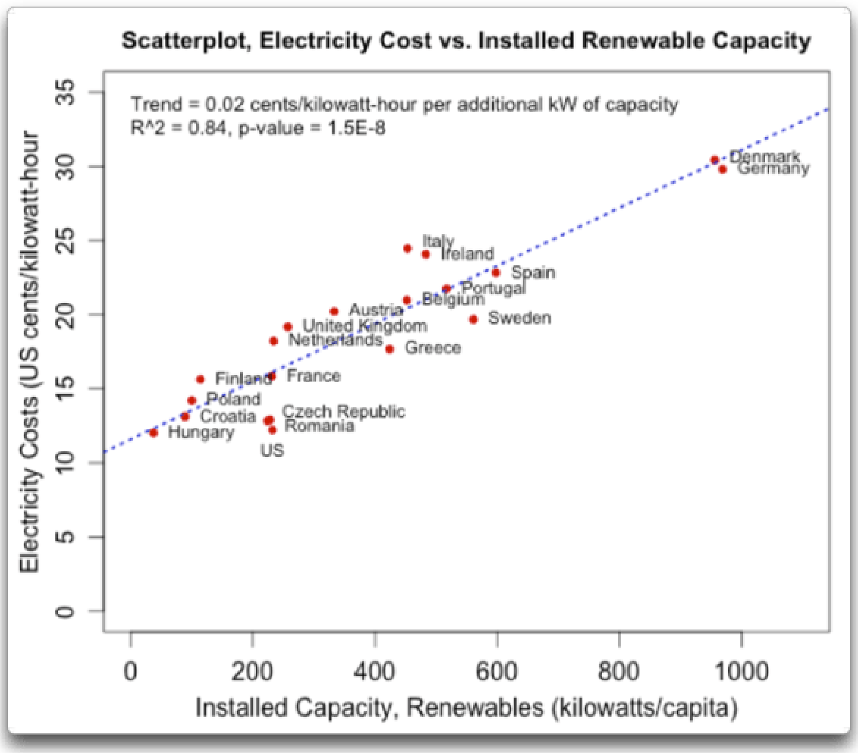

Figure A.4: Retail price versus W/S capacity per capita

[4] If society were to enact a CO_2 tax, replacing subsidies and mandates, then W/S would correctly be competing with the fuel cost plus the tax.

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.[79] Figure A.5 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.

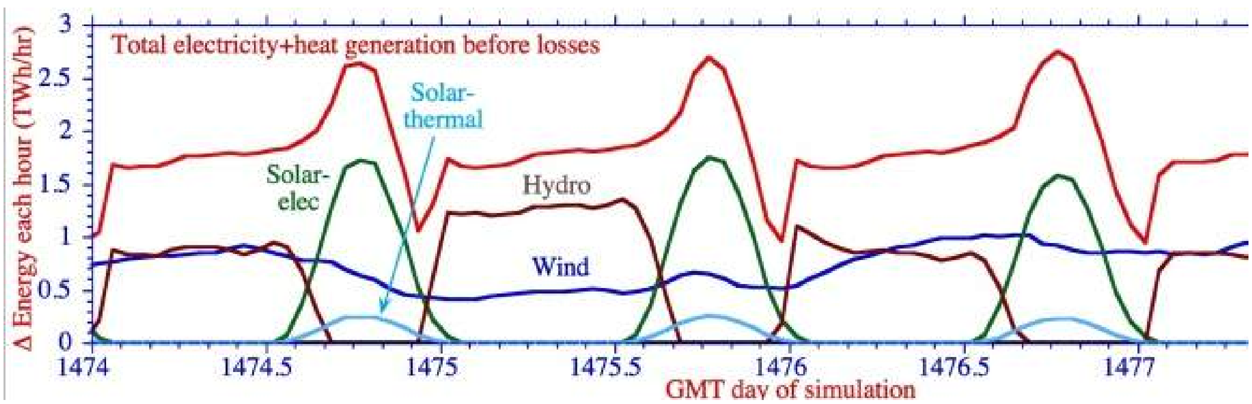

Figure A.5: Simulation of Jabcobson grid, reference [33][Figure 1].

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, probably 2. 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.[5]

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 renewables 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 of wind capacity installed in the state, and zero from the states 4.3 GW 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 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. 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.

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 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.[147] 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.

[5] 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.

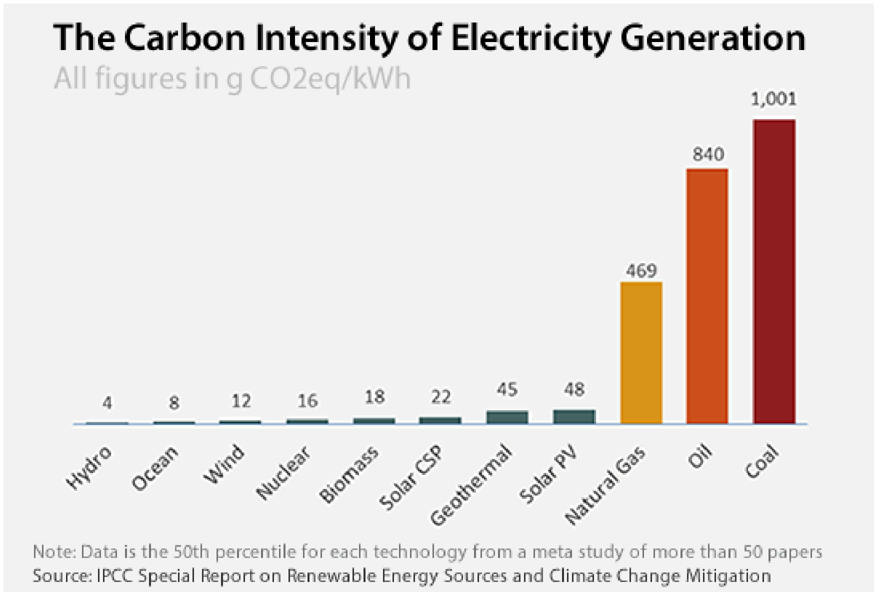

Figure A.6: IPCC Life Cycle CO2 intensity

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 obviously not 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.6 shows the IPCC estimates for life cycle CO2 intensity. For wind it is 12; for nuclear, 16; and for PV solar, 48 gCO2/kWh.[6]

According to the M.I.T. paper, solar is cheaper than wind. So solar dominates their 'zero' carbon solutions, especially in their low cost scenarios. 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 IPCC numbers, life cycle this grid will produce 180 g/CO2 per kWh.[7]

They also need 350 GWh of lithium-ion battery storage which will add 60 million tons of CO2 to the mix.[141][p 24] This 3 million tons of batteries, 26 million Tesla Powerwalls costing

[6] The US National Renewable Energy Laboratory came up with essentially the same number for PV solar.

[7] Buried in any CO2 intensity number is a capacity factor. IPCC does not tell us the capacity factors assumed in Figure A.6. 180 g/kWh assumes 0.3 for both wind and solar. The combined actual capacity factor for the Sepulveda grid is just under 0.1. Adjusting for the difference in capacity factor $(0.3/0.1) \cdot 48 + (0.3/0.1) \cdot 12 = 180$.

$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.

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.[127][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 130 g/kWh. An acceptably reliable system might be designed to a 10 day lull which for Germany has a return period of 20 years.[8]

A portion of the CO2 intensity of these low carbon technologies is due to the electricity required in mining, manufacturing, etc. The IPCC 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.[61][Figure 6]. Using the IPCC numbers, this drops PV solar's intensity to 24. 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.[141][Table 17][9]

With these adjustments, the CO2 intensity for the paper's 'zero' carbon New England grid is roughly 101 gCO2 per kWh. 142 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 16 g/kWh, perhaps half this in an almost all nuclear grid.[11] ***And we***

[8] 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. This table 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 nickle to store that much power for about a half hour.

	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

[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 101/142 gCO2/kWh grid, then the electricity is not as clean as we have assumed. This leads to a multiplier.

[11] The IPCC median number for nuclear may be high by a factor of three or more. See Section 7.2. Much future uranium mining will be In Situ Leaching (ISL), which will cut this further. ISL is about the most benign mineral

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.***

A.5 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.[12] 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. 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.

Despite the fact that nuclear and W/S are in mortal combat, the nuclear complex 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.

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extraction process imaginable. Treated water is injected into and drawn through a uranium bearing sandstone, dissolving the uranium into the water, which is pumped to the surface. No surface disturbance. No mine tailings. Regulations require that the water quality in the sandstone be restored to its pre-mining use.

[12] 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.

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 to that level. Lather and repeat.
2. Much more fundamentally, 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 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 that 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.

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