Comparing nuclear and fossil-fuel energy risks

Risks to workers

As we have previously stated, the most important point in any decision to choose or to eschew nuclear energy is fair comparison of the real costs of nuclear energy and of the alternatives to it. We know that working in any heavy industry is likely to exact some toll on life and limb.

Suppose you are injured in working to produce nuclear electricity, either extracting the uranium or working at the reactor. It will cost money in two ways—because you need medical attention and must pay the doctor and the emergency room for their medical services, and because your work must be replaced while you’re gone. Table E20.12.1 gives the costs (in 1970 dollars) of industrial accident injury to individuals, both the persons injured, and the cost averaged over the entire population.[42]

TABLE E20.12.1

Injury Costs to Individuals per Year

Activity	Persons Involved (number)	Injury Cost ($)	Annual Cost per Person ($)
Uranium mining, milling	620	463,200	747.09
Manufacturing	33,724	1,519,300	45.00
Reactor operations	1290	81,800	63.00
Reprocessing	800	91,720	115.00
Public near reactor	33,841,000	19,410	0.0004
Total U.S.	200,000,000	2,175,520	0.10

Note that the Table E20.12.1 does not mention radioactivity at all. Surely there are such costs, even if many of these accidents do not land the injured party in the hospital. Table E20.12.2 attempts to estimate the risks and costs to workers of both typical accidents and radiation exposures.[42] Apparently, the risk from ordinary accidents is twice as great as the risks from radiation.

TABLE E20.12.2

Risks to Individual Workers per GWyr of Nuclear Energy

Activity	Accidents (not Radiation Related)	Radiation Related (Cancers and Genetic)	Injuries Total	(Days Off)
Uranium mining, milling	0.173	0.001	0.174	330.5
Fuel processing, reprocessing	0.048	0.040	0.088	5.6
Design, manufacture of reactors, instruments, etc.	0.040		0.040	24.4
Reactor operation, maintenance	0.037	0.107	0.144	158
Waste disposal		0.0003	0.0003	
Transport of nuclear fuel	0.036	0.010	0.046	
Totals	0.334	0.158	0.492	518

TABLE E20.12.3

Summary of Nuclear Health Risks per GWyr of Nuclear Energy

Source	Fatalities	Days Lost
Sagan	0.390	1022
Rose	0.492	513
Hub et al.	0.952	373
AEC	0.161-0.364	

A summary table, Table E20.12.3,[237,252] also makes this comparison in an overall fashion and also takes into account fatal accidents, most of which occur in mining or traffic accidents. The individual estimates vary widely, but we can see that the human cost is less than one fatality a GWyr, and perhaps a year of time off work summed over all workers.

TABLE E20.12.4

Fossil Fuel and Nuclear Occupational Fatalities due to Accidents[a]

(Fatalities per GW-plant-yr[b])

	Fossil Fuel		
	Coal	Oil	Gas
Mining/pumping	0.96	0.06	0.02
Fuel Processing	0.02	0.04	—
Transportation	0.05	0.03	0.02
Power Plant Operation	0.03	0.03	0.03
Total	1.1	0.16	0.07

	Nuclear Reactors	
	PWR	BWR
Mining	0.09	0.09
Milling	0.005	0.005
Conversion	0.0003	0.0002
Enrichment	0.001	0.001
Fabrication	0.0004	0.0005
Reprocessing	0.0001	0.0001
Transportation	0.002	0.002
Power Plant Operation	0.01	0.01
Total	0.1	0.1

[a] From 1965-1970 injury rates and production data.

[b] Basis is a 1 GW_e plant generating 6.6 TWh at a 75% capacity factor.

Of course, nuclear workers are not the only ones to suffer accidents. If we looked just at the costs of nuclear energy without looking at the alternatives, we would be misstating the case. It is reasonable to compare worker safety in the nuclear utility industry to that in the coal utility industry. Table E20.12.4 shows the costs of coal mining and coal use in coal-fired utilities and in nuclear energy in utilities, respectively.[4] The comparisons are for exactly comparable plants.

Figure E20.12.1 [4] shows another perspective on the risks of coal, the number of days lost. Figure E20.12.1 presents a perspective very similar to that of Table E20.12.4.

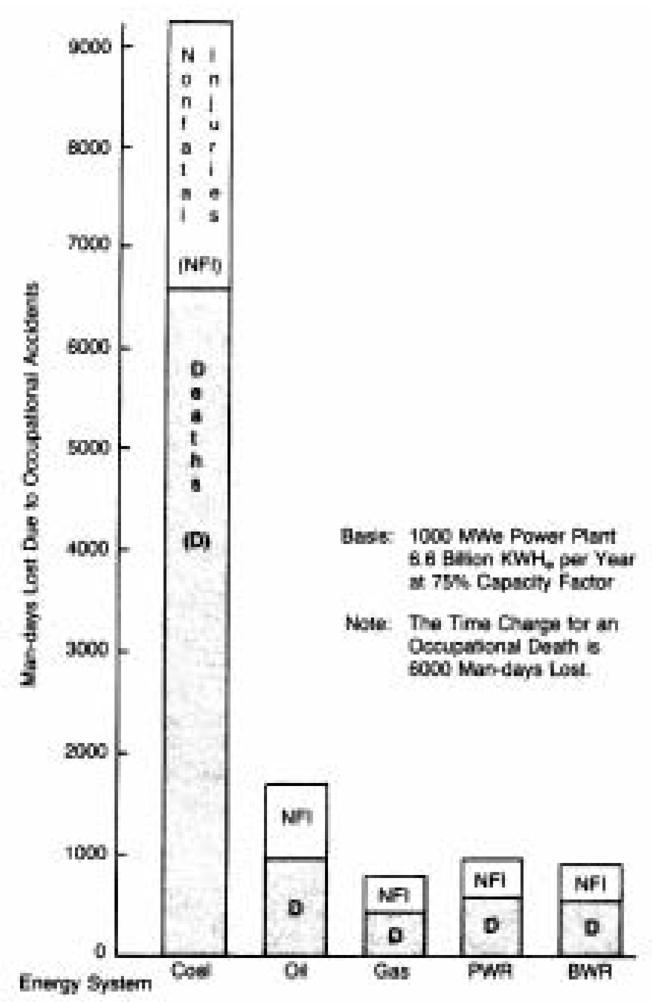

Fig. E20.12.1 Person-days lost per MWyr over the lifetime of various energy generating system. (U.S. Atomic Energy Commission)

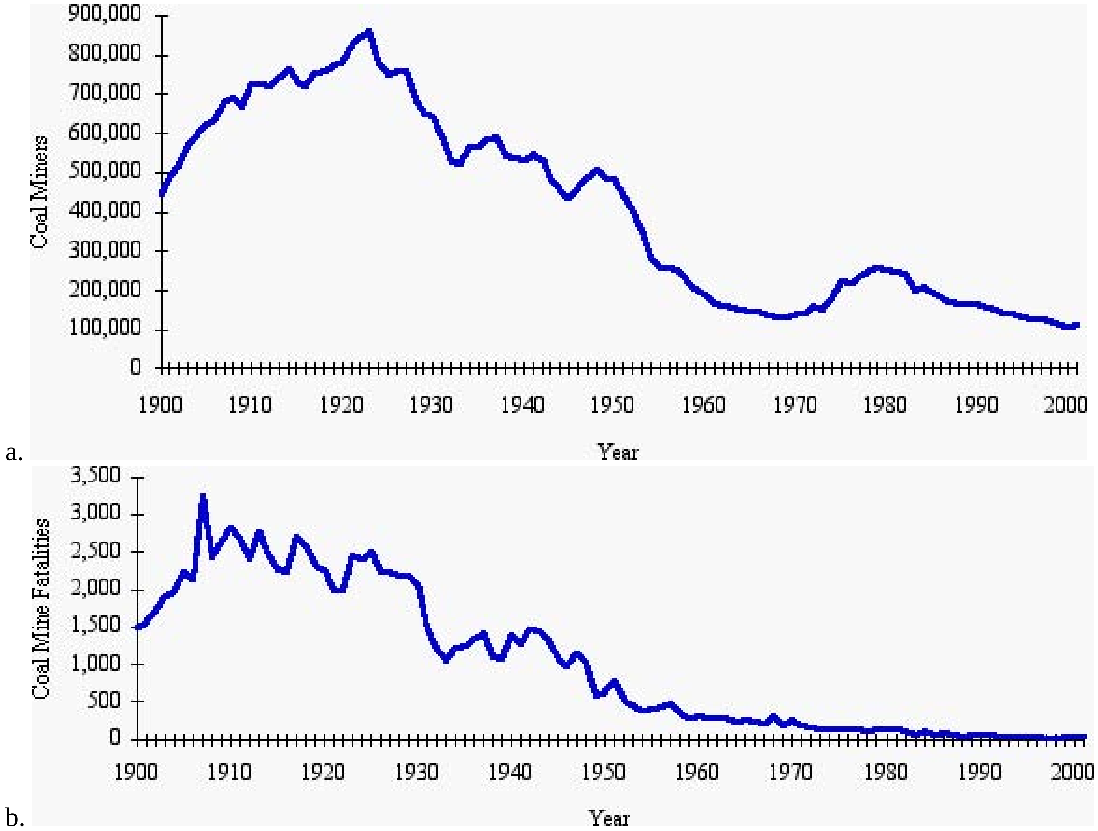

Fig. E20.12.2 a. Annual number of coal miners, 1900-2001. b. Coal miner annual fatalities, 1900-2001. (U.S. Department of Labor, Mine Safety and Health Administration)

Another way of looking at this is to examine just the number of deaths per year due to coal or uranium mining. Figure E20.12.2 shows statistics for coal miners from 1900 to 2001. Note that the death rate from coal mining is 4×10^{-4} per miner per year (67 deaths per year averaged from 1980 to 2001 out of the average number of miners, 166,000; see also Fig. E10.12.3) according to the Mine Safety and Health Administration of the U.S. Department of Labor.

For uranium miners, as we have discussed, there are both the accidents and the fatal cancers that ensure from extended breathing of dust. Between 1995 and 2001, just 3 American uranium miners died in accidents, compared to 260 coal miners.[253] The expected number of fatal cancers is 44 per year worldwide, out of 260,000 miners (assuming all work 40 years in uranium mining), or 1.7×10^{-4} per miner per year.[8] The uranium miners' overall risk is about 2×10^{-4} per miner per year, half that of the coal miners. Of course, most coal gas continues to be burned in utilities' boilers, while most uranium goes to the Federal Government for the weapons programs, not to the nuclear electricity industry. That is the reason that the per-utility plant comparisons above are so starkly different.

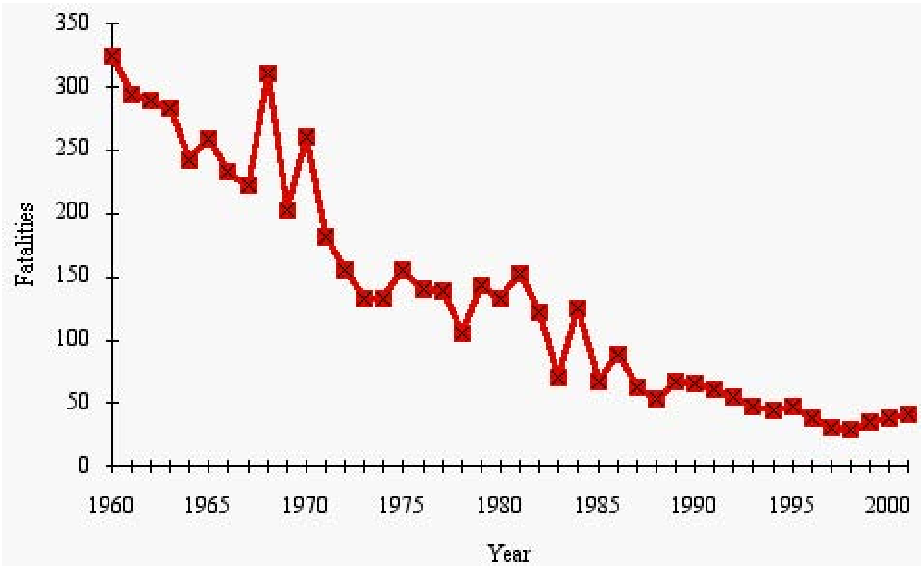

Fig. E20.12.3 Larger-scale annual coal miner fatalities, 1960-2001, enlarged from Fig. E20.12.2 b. (U.S. Department of Labor, Mine Safety and Health Administration)

Clearly, coal-fired fossil fuel is much more dangerous to workers than any other way of producing electricity. Gas-fired and nuclear electricity are of comparable cost, and oil is roughly twice as costly. Coal-fired energy is over 5 times more costly in life than nuclear energy.

As of the 1970s, the numbers of deaths and injuries associated with coal mining and processing had decreased from those of Tables 18.13 and 18.14:[(254)] coal mining claimed 0.33 deaths per Mt and coal processing 0.019 deaths per Mt; the number of disabling injuries is 25 per Mt in mining and 1.2 per Mt in processing. Still, coal-fired electricity is the most costly for its workers.

The health costs to bystanders from coal and nuclear electricity

From Ch. 13, we are aware that burning coal produces huge volumes of waste gases, some part of which, still a huge volume, power plants then emit. Included among these gases is carbon dioxide, which we learned appears to be changing our climate. Climate change will have effects on health, but these are more subtle than the effects on buildings and people from particulates and sulfur and nitrogen oxides. Table E14.5.3 from **Extension E14.5, *The 1990 CAAA, NO_x, particulates, and the EPA*** and Table 13.5 from Ch. 13 indicate the scope of the cost to individuals in terms of their health and to their property.

Nuclear plants under normal operation emit very small quantities of a few gases. None of the gases pose a direct threat to health or property of the sort that is attributable to coal-fired plants. Of course, nuclear plant gases may contain small amounts of radioactivity. How does this differ from coal plants?

Several analyses show that coal-fired plants can release substantial radioactivity.(255-263) How can that be? All fossil fuel contains radioisotopes.(83) Radiation comes with all deep-Earth minerals, and the radioactive decay chains exist in secular equilibrium in the rock—including coal. The amount of uranium and thorium isotopes in coal is greatly variable, but the analysis of Ref. 256 suggests that 1 ppm and 2 ppm, respectively, for these is representative. Since the coal fired plant (operating at 80% capacity) produces electricity from 674,000 tonnes of coal, they find 2.32 million kg/MWyr, and calculate that 2.32 kg/MWyr of uranium and 4.64 kg/MWyr of thorium will be released, even assuming only 1% coal ash in the smoke (10% was more typical at the time of the study).(256) Their conclusion was that Americans living near coal-fired power plants are exposed to higher radiation doses, particularly bone doses, than those living near nuclear power plants that meet government regulations.

The EPA found slightly higher average coal concentrations than used by McBride et al. of 1.3 ppm and 3.2 ppm, respectively.[262] Gabbard (Ref. 262) finds that American releases from each typical 1 GW_e coal plant in 1982 were 4.7 tonnes of uranium and 11.6 tonnes of thorium, for a total national release of 727 tonnes of uranium and 1788 tonnes of thorium. The total release of radioactivity from coal-fired fossil fuel was 97.3 TBq (9.73×10^{13} Bq) that year. This compares to the total release of 0.63 TBq (6.3×10^{11} Bq) from the notorious TMI accident, 155 times smaller.

The National Council on Radiation Protection and Measurements (NCRP) similarly found that population exposure from operation of comparable (1 GW_e) nuclear and coal-fired power plants was 4.9 person-Sv/yr for coal plants and 4.8×10^{-2} person-Sv/yr for nuclear plants, a factor of ~100 greater for the coal-fired plants.[264]

An unsettling thing is that waste fly ash from coal-fired electricity is often turned into building material such as cinder block, which can then be used in homes.[261,265] According to Corbett's analysis, the major exposure pathway for activity is building materials made out of wastes from coal burning: he estimates a maximum individual dose at 120 μSv/yr.[261] Recall that the average yearly dose is 3.6 mSv, so this is small, but if the linear no-threshold dose relation is correct, causes additional health consequences.

Nuclear proliferation

Gabbard (Ref. 262) also points out that the fly ash collected at coal-fired plants is low-level waste that would be strictly regulated at a nuclear reactor. If a nuclear reactor released the same quantity of radioactive waste in fly ash, there would likely be national protests. This waste stream contains so much activity that "[i]n a few year's time, the recovery of the uranium-235 released by coal combustion from a typical utility anywhere in the world could provide the equivalent of several World War II-type uranium-fueled weapons."(262) The popular press has also noticed this point: "A coal plant releases about 74 pounds of uranium-235 each year, enough for two or more nuclear bombs."(210)

Indeed, Gabbard also mentions that neutrons in air can breed plutonium-239 and thorium-233 from uranium-238 and thorium-232. This is worrisome both because extremely small amounts of plutonium-239 and plutonium-240 are extremely toxic and because it offers the opportunity for rogue nations to mine the wastes for fissionable uranium, plutonium, and thorium that could then be turned into bombs. And, because coal fly ash is so ubiquitous, no one would know it was happening until too late.

"Cleansing Earth"?

B. L. Cohen, a nuclear energy expert, pointed out in the mid-1980s that a single 1 GW_e coal-fired plant causes 25 fatalities, 60,000 cases of respiratory disease, and $12 million in property damage, as well as emitting an amount of NO_x equivalent to 20,000 cars per year.(125) It also produces ashes and sludge. In Cohen's view, nuclear energy is a means of cleansing Earth, since the net activity of the planet declines as the uranium-235 is used up.

In later work, Cohen went further in analyzing probabilistically the risks of coal-fired and nuclear plants.(258) Examples of non-radioactive carcinogens include beryllium (as an example, EPA death risk estimate ~ 5.3×10^{-6}/kg ingested), arsenic, cadmium, chromium, and nickel (all discussed in **Extension 13.2, *"Heavy metals"***).

Cohen calculates the effect of their release by following the chain that leads to deaths: transfer from ground to stomach,

$$\sim 1000 \text{ kg/yr} = 1.2 \times 10^{-5} \text{ g/d} \times 365 \text{ d/yr} \times 2.6 \times 10^{8} \text{ people;}$$

transfer from ground to oceans,

$$\sim 1.9 \times 10^{6} \text{ kg/yr} = 1 \times 10^{12} \text{ soil kg/yr} \times 1.9 \times 10^{-6} \text{ kg of Be per kg of soil.}$$

This takes place over a period of about 100,000 yr, assuming the soil is the top 5 meters and it takes about 22,000 yr to erode a meter of soil. Now, the probability that a beryllium atom in the ground enters the stomach before reaching the oceans is just 1000 kg/yr/(1.9×10^{6} kg/yr) = 5.4×10^{-4}. Therefore, the number of deaths per tonne of beryllium released that get into the top 5 meters of soil is

$$\text{Deaths} = (5.3 \times 10^{-6}/\text{kg}) \times (1000 \text{ kg/t}) \times (5.4 \times 10^{-4}) = 2.9 \text{ deaths/t Be.}$$

So, given that there is a release of 4.5 tonnes of Be/GWyr, Cohen finds

Deaths from beryllium = (2.9 deaths/t Be) (4.5 t Be/GWyr) = 13 /GWyr.

Similarly, he is able calculate the risks for each of the carcinogens, finding

Deaths from arsenic = 10 /GWyr,

Deaths from cadmium = 20 /GWyr,

Deaths from chromium = 7 /GWyr,

Deaths from nickel = 1.4 /GWyr.

Overall, then, Cohen identified roughly 50 deaths per GWyr from non-radioactive carcinogens in the effluent of coal-fired plants.

The release of low-level wastes from nuclear reactors leads, by a similar chain of reasoning, to 0.0004 deaths per GWyr.[(258)] Of course, there are about one hundred GW nuclear reactors generating electricity, so the overall risk of nuclear energy is about 0.04 deaths. How much would it cost to reduce the risk further?

The EPA has also studied the effects of metals and radioactivity release from fossil-fueled utility generating facilities.[266] Some plants emit more radioactivity than others, because of variations in the proportions of uranium and thorium in the coal used. Only 17 of the 684 plants that were studied posed risks greater than 1×10^{-5}. According to Ref. 266, "[t]he highest estimated multipathway radiation exposure . . . due to radionuclide emissions from utilities was predicted to be 1.5 mrem [15 μSv] per year, which is estimated to pose an increased cancer risk of 3×10^{-5}. Seventeen plants (13 coal-[fired] and 4 oil-fired plants) were estimated to pose multipathway risks between 1×10^{-5} and 3×10^{-5}. The estimated cancer incidence in the U.S., due to emissions and dispersion of radionuclides within 50 km of each utility, is estimated to be 0.3 cancer deaths/yr."

The risks due to exposure to radionuclides from utilities are substantially lower than the risks due to natural background radiation. The average exposure to natural background radiation (excluding radon) for the U.S. population has been estimated to be roughly about 1 Sv (100 mrem) per year, which is about 67 times higher than the highest exposure due to utility radionuclide emissions.

Should we worry?

Should we worry about the nuclear releases from nuclear plants? Well, the number 4.0×10^{-4} seems pretty small. Even 0.04, the risk from 100 reactors, which is equal to the risk from one coal-fired power plant, seems small.

Given that coal-fired plants emit roughly 100 times more radioactivity, even ignoring the overwhelming effects of air pollution, coal represents a much greater risk than nuclear electricity. Even the coal number, one hundred times greater, a risk of 0.04 per plant seems pretty small in the grand scheme of things. However, this means that there would be about 6 deaths (there are about 150 coal-fired GW plants) every year from coal radioactivity. This is in addition to the aforementioned 50 deaths from other carcinogens and many more deaths related to air pollution. How much would it cost to reduce the risk further? Would it be better to spend money to reduce the risk of coal-related deaths or nuclear-related deaths?

What method of generating electricity is the best? What do we have to include in the accounting to decide? How much are we willing to pay to reduce the risk—from coal or nuclear? Are there better places to put that money? These are the tradeoffs that must be made, and need to be discussed.

The cost of the photovoltaic alternative

We tend to think of solar energy as “green energy,” or clean energy. Figure E20.12.4 shows cost comparisons of various energy strategies.[(267)] Solar energy appears a worse choice than nuclear energy. Nuclear energy appears to be one of the least dangerous ways to generate energy.

Solar energy generating facilities are almost as dangerous as coal- or oil-fired generating facilities.[(267)] Much of the cost of the unconventional sources comes from the cost of the backup systems that are necessary.

In the study, the backup for times that solar energy is offline was assumed to be a coal-fired power plant, which is the most hazardous of the alternatives. This contributes much of the hazard risk for photovoltaic energy. If nuclear energy or gas were used instead, the risk would be significantly lower.

It also should be noted that if cadmium is used in the solar cells, the risk increased dramatically. Cohen estimates that the risk is 1.4 deaths in the first 500 years after installation—higher than nuclear, less than from coal. However, if a total perspective (hundreds of thousands of years), there would be 80 deaths from solar cells as against 70 from coal.[257]