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Nuclear Power[1]

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Nuclear power is in trouble. Despite the results of polls, which have shown repeatedly that the majority (about 60 percent) of the public views nuclear power favorably and thinks it safe, there is a sizable and growing opposition to nuclear technology. Public initiatives for a moratorium on nuclear development were recently defeated in California, Arizona, Colorado, Montana, Ohio, Oregon, and Washington. Nevertheless, similar initiatives are being prepared in another 19 states. Within the industry and in government regulatory agencies, there has been a significant defection of middle-level technologists (Burnham 1976a). Many plants have been delayed or canceled, and capital costs will have risen from $300 per installed kilowatt in 1972 to an estimated $1120 by 1985 (Business Week 1975,100). The price of uranium tripled between 1974 and 1976, and the adequacy of the uranium supply after 1985 is in question (Lieberman 1976;Day 1975).

All this is happening at a time when many features of nuclear technology--low average pollution, cost advantages over coal-and oil-fueled plants in many areas, and replacement of foreign oil resources in electric power generation--should encourage rapid adoption of the technology. What causes the malaise?

Delays, cancellations, and rapidly increasing capital costs are not likely to be decisive in the long run. Recent delays and cancellations have been strongly affected by the decreased demand following the sudden doubling in electric energy prices in 1973 and 1974. Rapidly increasing capital costs are a function of the availability of capital, increases in labor costs, and the recent period of high inflation. These problems are shared by large new fossil-fired plants; solar plants would presumably have similar difficulties if they were available.

We attribute most of nuclear power's problems, therefore, to the issue of safety. For the last two years our interdisciplinary group has studied the safety issue, particularly to see how the risk of rare events enters into the energy policy decisions of our society. At first sight, the case for the safety of nuclear power reactors appears impressive. Some frequently cited statistics and examples are as follows.

1. The maximum permitted annual radiation exposure for persons living at the boundary of a nuclear power plant is 5 millirem. Routine population exposure from all nuclear power plants averages

0.003 millirem per person per year (National Research Council 1972). By comparison, natural and medical sources contribute average exposures of 100 and 70 millirem per person per year (National Research Council 1972;UNSCEAR 1972), and individuals living in buildings constructed of volcanic rock (for example, in Rome) may be exposed to twice the natural background, or about 200 millirem per person per year (UNSCEAR 1972).

2. When coal plants are located in large cities, the population exposure from radioactinides in fly ash is 500 manrem per year.[2] This exceeds permitted radiation exposures from reactors of equivalent power (Wilson and Jones 1974).

3. The most complete study to date of catastrophic reactor risk places the probability of a major radioactive release (release of an appreciable fraction of the volatile fission products found in the reactor) at 1 in 100,000 reactor-years;[3] of core meltdown at 1 in 20,000 reactor-years; and of a loss-of-cooling accident at 1 in 2000 reactor-years (Nuclear Regulatory Commission 1975). These probabilities are given credence by the fact that to date, after 300 reactor-years of commercial reactor operation, there has never been a loss-of-cooling accident (Nuclear Regulatory Commission 1975). With these probabilities, the expected number of prompt and delayed fatalities due to 100 reactors in the United States is only four per year; and the population exposed in the unlikely event of a major reactor accident would have a cancer risk only 1 percent greater than its preexposure risk (Nuclear Regulatory Commission 1975).

4. Although plutonium is a potent carcinogen, substantial quantities ($\simeq 10^5$ kilograms) of it have been handled in the past 30 years with no apparent ill effects: there have been no cancers that can definitely be attributed to plutonium in the several thousand workers who have handled the material (Bair, Richmond, and Wachholz 1974).

In early 1976 a committee of the National Academy of Sciences (NAS) began a study of the risks of various electric power technologies. Although a detailed comparison is an extensive task and must await the NAS report, it is not difficult to characterize and compare the risks of the hydroelectric, coal, and nuclear technologies, the three present options for new baseline electric power. We have done this (Table 1) for four classes of hazards: (1) routine occupational hazards, such as those of mining; (2) routine population hazards, such as the inhalation of pollutants; (3) general environmental degradation, such as destruction of cropland, and (4) catastrophic hazards, such as massive release of radioactivity and dam failures. We conclude from Table 1 that the quantified risks, based on available information, are much larger for coal and hydroelectric than for nuclear power.

Considering Table 1, how do we explain the distrust of nuclear power and the continuing doubts about its safety? We submit that the distrust of nuclear power rests in part on its social history; in part on its unique combination of hazards; and in part on the special way it has been managed and regulated. Furthermore, the public distrust of nuclear power is significantly amplified by the rancorous debate in a polarized expert community.

An Intermingling of Issues

Throughout its 30-year history, nuclear power has inspired some of the major hopes and fears of mankind. Although it is difficult to describe this relationship except in terms of influence or anecdote, to ignore the social history of nuclear power is to misunderstand its present predicament. Many new technologies are born in wartime efforts. None have come to symbolize the destructiveness of war as has the atomic bomb. For better or worse, nuclear power was for many years tied to and overshadowed by the course of military developments. To see this, consider the first 20 years of the nuclear age (Baker 1958).

Immediately after World War II, the United States had a monopoly on nuclear technology. All significant U.S. development efforts were in a military direction. Reactors were built to breed weapons materials and to propel submarines and aircraft carriers, and uranium-235 was isotopically separated for military purposes. Commercial nuclear power was seen as something for the distant future and regarded as highly uneconomical (Weinberg 1972). At the same time, the atomic scientists who had built the bomb persuaded the U.S. government to argue at the United Nations that the nuclear enterprise was so dangerous that nothing short of international ownership would suffice to contain it (Baker 1958). They also exerted considerable influence to establish the Atomic Energy Commission (AEC) as a "civilian" umbrella agency to oversee the nuclear enterprise, with the particular charge to promote and develop commercial as well as military aspects of the technology (Rabinowitch 1950).

The idealism implicit in the U.N. efforts and the establishment of the AEC was short-lived, however, and with the first Soviet atomic tests in 1949 faded quickly into the cold war, the McCarthy period, and the arms race. By 1952 this had culminated in the testing of multimegaton thermonuclear devices by both sides in what was later called by AEC commissioner Thomas Murray "a vacuum of military strategy" (Murray 1957). By 1954 most of the public viewed atomic energy as synonymous with military terrorism in a situation in which the "enemy" was seen as a force of unmitigated evil in the world (Rosenberg 1966;Holsti 1967). Public discussion of alternatives uses of nuclear power was almost nonexistent.

The frozen silence finally thawed when the accidental severe exposure of a Japanese fishing vessel to fallout from the 1954 U.S. Bikini atoll test (Lapp 1958) focused public attention on the worldwide hazard of fallout from nuclear weapons testing. In response to this realization, Adlai Stevenson suggested in the 1956 election campaign that atomic testing be halted. President Eisenhower, while against a halt to testing, countered by proposing Atoms for Peace, a program of international sharing of nuclear technology for peaceful purposes (Baker 1958).

In 1956 there was not a single commercial nuclear power plant in the United States. Development efforts had been limited to experiments with alternative, reactor design concepts, and much of this work had, in fact, been cut back by Eisenhower when he took office in 1953 (Mullenbach 1963). At the same time, notable success had been achieved by the AEC-Westinghouse collaboration on submarine and ship propulsion reactors. To launch Atoms for Peace, the United States thus chose a modified naval reactor for a first demonstration

TABLE 1
Risks from three electric-power technologies. Deaths are the number expected per year for a 100-Mwe power plant. In all cases, man-days lost (MDL) are converted to deaths by 6000 MDL/death (AEC 1974a).

HAZARD TYPE	HYDROELECTRIC	COAL	NUCLEAR
Routine occupational hazard	Construction accidents are significant but the risks are not as large as for coal mining	Coal mining accidents and black lung disease constitute a uniquely high risk	Risks from sources not involving radioactivity dominate. Aggregate risks from all stages of the fuel cycle are less than for coal
Deaths	0.1 to 1.0[a]	2.7[b]	0.3 to 0.6[c]
Routine population hazard	Thought to be benign, although specific cases (for example, the Aswan dam) have produced new health hazards	Air pollution produces relatively high, although uncertain risk of respiratory injury. Significant transportation risks	Low-level radioactive emissions are more benign than corresponding risks from coal. Significant transportation risks remain incompletely evaluated
Deaths		1.2 to 50[d]	0.03[e]
General environmental degradation	Permanent loss of free-running streams, agricultural lands, wilderness	Strip mining and acid run-off; acid rainfall with possible effect on nitrogen cycle, atmospheric ozone; eventual need for strip mining on a large scale	Long-term contamination with radioactivity; eventual need for strip mining on a large scale
Catastrophic hazards (excluding occupational)	Major dam failures have occurred, but rarely in modern structures	Acute air pollution episodes with hundreds of deaths are not uncommon. Long-term climatic change induced by CO_2 is conceivable	Risks of reactor accidents are small compared to other quantified catastrophic risks. The problem lies in as yet unquantified risks for the reactors and the remainder of the fuel cycle.
Deaths	1[f]	0.5[g]	0.04[h]

[a] This estimate is based on (1) 10,000 man-years to construct a 1000-Mwe hydroelectric dam and generating station; (2) a heavy construction occupational hazard of 0.34 fatality and 1.34 permanently disabling injuries per 1000 man-years, or about 1 fatality equivalent per 1000 man-years (National Safety Council 1973); (3) distribution of construction fatalities over an assumed 100-year useful life of the project; and (4) hydroelectric generation availability of 10 to 100 percent.

[b] Data are from the Atomic Energy Commission (AEC 1974a). Of the 2.7 deaths, 1.1 are due to mining accidents of all kinds, including major mine disasters, and 1.6 are due to black lung disease and other injuries.

[c] The lower figure is from the AEC (1974a), the higher figure from David Rose (1974).

[d] The lower figure represents transportation accidents only, as given by the AEC (1974a). The higher figure includes an interpretation (National Research Council 1975) of the rather uncertain air pollution epidemiology.

[e] See AEC 1974a. The result is consistent with an average annual exposure of 0.035 millirem per individual per reactor, using a cancer risk of 2 x 10^{-6} cancers per man-rem (National Research Council 1972). The average exposure of 0.035 millirem applies to reactors only. It must therefore be considered as a lower bound for the fuel cycle risk.

[f] The figure represents an estimate for dam failure risk based on all historical incidents, as summarized in the **Reactor Safety Study** (Nuclear Regulatory Commission 1975). The number must be taken as an upper bound since many dam failures will not be connected with hydroelectric generation.

[g] This is based on the occurrence of one 500-death air pollution episode per year, with one-fifth of the pollution attributable to coal power plants.

[h] This estimate is based directly on the **Reactor Safety Study** (Nuclear Regulatory Commission 1975), as discussed in the text, without correction for the incompleteness of the methodology, and must be regarded as a lower bound.

plant. Located in Shippingport, Pennsylvania, this plant went on line in 1958, with a rating of 90 megawatts electric (Mwe). While neither big nor economically competitive, the plant became an important symbol to balance the destructiveness of nuclear weapons in the public's eye.

Meanwhile, the test-ban issue remained the most important public nuclear concern. For seven years (1956 to 1963) it was argued in a context of national security, clean bombs, and dirty bombs, until finally, with the signing of the Moscow treaty, it was literally "driven underground" (Hohenemser and Leitenberg 1967). During this period, despite real doubts about nuclear power economics, extensive plans for commercial nuclear power were developed on a worldwide basis. These plans proved far from realistic and served largely to trigger a new fear that reemphasized the military aspects of nuclear power; that the spread of nuclear power would lead to proliferation of the nuclear weapons capability by making plutonium widely available (see Table 2). Known at the time as the Nth country problem (Davidon, Kalkstein, and Hohenemser 1960;Hohenemser 1962), this fear motivated substantial safeguards in nuclear sharing agreements between the United States and the International Atomic Energy Agency and eventually led to the nuclear nonproliferation treaty in 1968. Proliferation is still feared today and is regarded by some long-time observers, such as Feld (1975), as the single most important hazard of nuclear power.

By 1965, 20 years after the first bombs were dropped, public concern with nuclear policies had subsided to an all-time low. In rejecting President Kennedy's fallout shelter proposals in 1962, the public had shown itself distinctly fatalistic about the prospects for and value of surviving a nuclear war. The first 20 years of the nuclear age thus closed with the balance of terror and nuclear overkill established facts (Lapp 1968). Commercial nuclear power, which had with the start-up of the 500-Mwe plant at Indian Point reached near economic parity with other power sources in 1962 (Mullenbach 1963), made no major impact on a public that now faced news of guerilla war in Vietnam and watched as the number of intercontinental ballistic missiles on both sides increased from the tens to the hundreds to the thousands. In addition, there was no real concern with reactor safety at the time, even though a number of accidents had occurred in experimental reactors (AEC 1971;Zimmerman 1975), and the AEC had outlined rather disturbing conceivable consequences of commercial reactor failure as early as one year before the opening of the Shippingport demonstration plant (AEC 1957).

Since 1965, the public view of nuclear energy has undergone a dramatic and unexpected metamorphosis. Nuclear weapons and nuclear war have disappeared as major issues; the cold war has slowly waned; and although warheads now number in the tens of thousands (SIPRI 1976), threats to the natural environment and a general distrust of high technology have replaced earlier fears. Nuclear power has become controversial, to the bewilderment of nuclear power technologists who for two decades or more have worked on the "peaceful atom" with little doubt about the virtue of the task.

A first attack on commercial nuclear power came late in the 1960s when, as a logical extension of concerns about fallout, the question of routine radioactive emissions from power plants was raised by Sternglass (Boffey 1969), Tamplin (1971), Gofman (1981, 870-871), and others. This issue fit well with growing environmental concerns, which came to a crescendo with Earth Day in 1970. As it turned out, routine emissions were easily shown to be of minor significance compared to other pollutants (see Table 1), and the issue died out soon after Earth Day. But nuclear power had taken on a special status within the environmental movement, and this led in rapid sequence to a whole range of new issues.

TABLE 2
Plutonium production from civilian nuclear power: projection compared to reality. Data are from Davidon, Kalkstein, and Hohenemser (1960) and Willrich (1973). Plutonium production values are estimates for 1975 from Davidon, Kalkstein, and Hohenemser (1960); to obtain the maximum number of nominal weapons, divide these values by 5 (the critical mass of Pu is ≃5 kg).

COUNTRY	PLUTONIUM PRODUCTION FOR 1975 (KG/YEAR)		PERCENTAGE OF PROJECTION ACHIEVED
	ESTIMATED	ACTUAL	
Belgium	1500	200	13
Canada	?	600	
China*	?	?	
Czechoslovakia	5000	200	4
France*	8000	600	7
Germany, East	3000+	100	3
Germany, West	6000	1000	18
India*	?	200	
Italy	500+	200	40
Japan	7000	1000	14
Netherlands	3000	100	3
Norway	?	?	
Poland	1800	?	
Rumania	500	?	
Spain	1800	400	22
Sweden	2000	500	25
Switzerland	?	200	
Soviet Union	?	1000	
United Kingdom*	6000+	2000	33
United States*	?	5000	

*These are countries with nuclear weapons. The United States, Soviet Union, France, and United Kingdom have all produced additional plutonium in military reactors. China and India may have done so.

During 1971 and 1972, the first large environmental coalition, the Consolidated National Intervenors, assembled around the AEC rule-making hearings on emergency core cooling. These hearings exposed serious inadequacies in AEC safety research and regulation. Questions about AEC safety measures had first been raised by the Union of Concerned Scientists (Forbes et al. 1972), a collaboration of scientists from the Massachusetts Institute of Technology, and were reminiscent of earlier public information efforts in the seven-year debate on fallout. In 1973 Ralph Nader and the Sierra Club took up opposition to nuclear power on a variety of grounds, ranging from safety to economics to unsolved problems of waste disposal. Most recently, nuclear power has become, in the view of the environmental movement, a symbol of high technology, unbridled growth, and centralization--all trends that are being increasingly questioned by activists. Thus, Friends of the Earth argues that "U.S. reliance on fission nuclear power to fill the energy needs of an economy characterized by extravagance and waste needlessly mortgages the peace, welfare, and freedom of future generations" (Friends of the Earth 1976). In contrast, the development of various alternative power sources such as the sun and the wind would "counteract the increased concentration of economic and political power in a few giant energy corporations" and "encourage essentially grass roots efforts involving individual and community action and small businesses" (Friends of the Earth 1976).

The critique of nuclear power is today well advanced. A 1975 Harris poll (Louis Harris and Associates 1975) showed the public strongly divided, with environmentalists leading the way (see Table 3). It is doubtful that a consensus of people would agree today that nuclear power is sufficiently safe. Another perspective on the present appears in Figure 1, where media interest, as a surrogate of public concern, is plotted over three decades. Figure 1 clearly shows the two major periods we have sketched. The first upsurge of interest was during the seven-year debate on nuclear weapons testing; the second reflects the environmental and safety concerns about nuclear power that occupy the present.

It is very likely that the link in the public's mind between nuclear power and weapons testing is more deep-seated than is suggested by the correlations given in Figure 1. For example, Pahner (1975), citing a psychoanalytic study of Hiroshima survivors, argues that a substantial part of the public's concern over nuclear power is displaced anxiety rooted in a fear of nuclear war (Lifton 1967). The fading of the ban-the-bomb marches, then, was not a coming to terms with nuclear weapons, but a repression of fear that is destined to resurface elsewhere. In support of this view, Harris poll findings (Louis Harris and Associates 1975) and opinion surveys that we conducted[4] reveal a widespread public concern that "nuclear power plants may explode."

TABLE 3
Perceived safety of nuclear power plants (Louis Harris and Associates 1975). Abbreviations: VS, very safe; SS, somewhat safe; NSS, not so safe; D, dangerous; and NS, not sure.

	PERCENTAGE OF PLANTS				
GROUP	VS	SS	NSS	D	NS
Public	26	38	13	5	18
Environmentalists	10	25	44	19	2

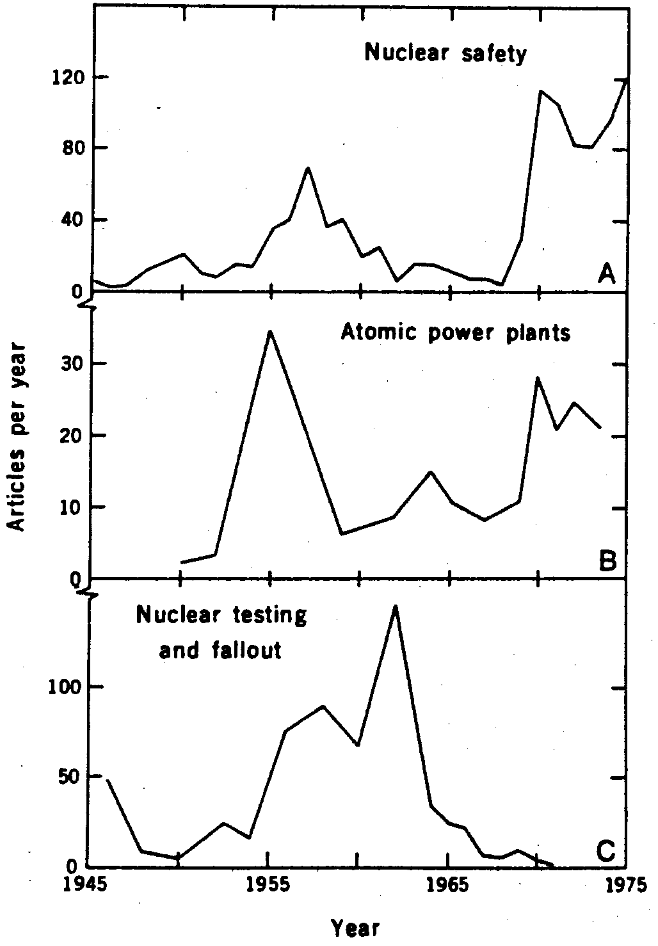

Figure 1. The social history of nuclear power and weapons testing is illustrated by using media interest as a measure of public interest. (A) nuclear safety in the New York Times, (B) atomic power plants in Readers' Guide, and (C) nuclear testing and fallout. Data for (A) were compiled by the authors; the data for (B) and (C) are from Mazur (1975).

The distrust of nuclear power is thus rooted in the fear of nuclear weapons and is augmented by concern about pollution and opposition to high technology and centralization. Is this sufficient to explain all of the distrust? We think not.

Reactor Safety

With the maturing of commercial reactors in the late 1960s, it became clear that nuclear power poses threats that may be unique in their combination of catastrophic potential, duration, and scientific uncertainty[5] (Wilson 1973). To illustrate, we begin with the most studied case: the assessment of catastrophic risk in the light water reactor. Using this assessment as a standard, we examine the state of knowledge for the entire fuel cycle.

The hazards of reactor failure were foreseen at least 19 years ago, when the AEC outlined the consequences of conceivable catastrophic accidents for a 150-Mwe reactor in its report WASH 740 (AEC 1957).

The study was updated in 1965 for the 1000-Mwe plants that were then being planned. The WASH 740 report projected as many as 3,400 deaths and 43,000 injuries; the updated version of the report (Mulvihill et al. 1965) showed as many as 45,000 deaths and a disaster area the size of Pennsylvania. Neither WASH 740 nor its updated version had a major public impact at the time, the former because it was overshadowed by the test-ban debate, the latter because it was suppressed for eight years to "avoid great difficulties in obtaining public acceptance of nuclear energy" (Mulvihill et al. 1965).

As the questions raised in the early 1970s about catastrophic reactor failure escalated, the absence of failure probabilities in WASH 740 and its updated version made for a volatile situation. While the AEC argued that the probability of catastrophic occurrences is very low, critics were free to assume or imply the worst, especially since 300 reactor-years of catastrophe-free commercial reactor operation provided no empirical support for the AEC's low core-meltdown probability (AEC 1973). The AEC therefore commissioned a new study under the direction of Norman Rasmussen of the Massachusetts Institute of Technology. Known as the Reactor Safety Study (RSS), it took into account for the first time both consequences and probabilities of catastrophic accidents (Nuclear Regulatory Commission 1975). The results were not inconsistent with those of earlier studies, although the probability assigned to major accidents turned out to be very small. Specific results of RSS may be summarized as follows:

1. The core meltdown probability is 5×10^{-5} per reactor-year. This is larger than the previous AEC estimate of 1×10^{-6} (AEC 1973) and represents an average for the type of 1000-Mwe boiling water reactor (BWR) and pressurized water reactor (PWR) being built in the United States at present.

2. For each reactor type several categories of radioactive releases following core meltdown are identified, and for each of these a probability is found. This analysis makes clear that core meltdown does not necessarily lead to large releases, although it may do so.

3. For each release class, expected consequences are calculated in six categories: prompt fatalities, prompt injuries, delayed cancers, delayed thyroid nodules, genetic effects, and property damage. Employed in obtaining these results were models of weather patterns population densities, as well as the radiation dose-response methodology discussed in the so-called BEIR Report (National Research Council 1972).

4. The separate results from the BWR and PWR were averaged and presented as risk spectra for the six consequences mentioned above. The uncertainty in these spectra ranges from one-fifth to five times the expected risk, as shown in Figure 2.

5. The risk spectrum for prompt fatalities was compared to the spectra for manmade and natural hazards, as shown in Figure 2A. Delayed deaths due to radiation-induced cancer[6] (American Physical Society 1975) were omitted from this comparison, on the grounds that "predictions of this type are not available for non-nuclear events, and so comparisons cannot easily be made" (Nuclear Regulatory Commission 1975).

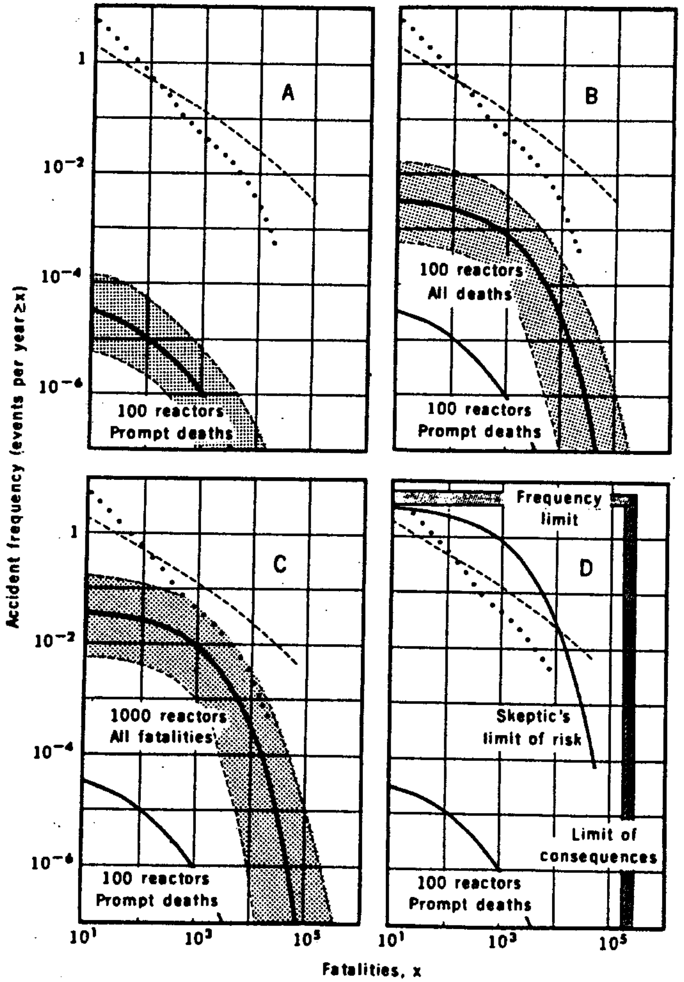

Figure 2. Comparison of the results of the RSS with other catastrophic risk estimates. Natural and nonnuclear manmade catastrophic risks are indicated by dashed and dotted lines, respectively. The RSS results with error bands (shading) are shown as dark, heavy lines. The results in (A) and (B) are from the RSS: those in (C) and (D) are based on increasingly pessimistic interpretations of the RSS, as discussed in the text.

The widely publicized comparison given in Figure 2A appears to settle the nuclear debate as far as accidents are concerned. Yet we know that this is an illusion. Below we explore several issues that transcend the RSS.

Delayed Cancer Deaths. Excluding delayed cancer deaths from the comparison in Figure 2A on the grounds stated above begs an important value question. Alternative characterizations of delayed cancer deaths are as follows:

1. Delayed cancers appear as a $\simeq$ 1 percent annual contribution to a preexisting nonnuclear cancer risk. This is statistically an undetectable effect; thus for one rather high-consequence nuclear accident, 170 additional cancers are expected, for an annual total incidence of 17,000.

2. Delayed cancers exceed prompt fatalities in number by a factor of 100 or more. Since there is no acceptable way of discounting future deaths--as we discount future income in economic analysis--we must attribute all deaths, prompt or delayed, to the accident frequency in question, as shown in Figure 2B.

Both of these interpretations are technically correct, although they are based on different crucial value judgments. The dilemma is reminiscent of the fallout debate, in which one side quoted "small" percentage effects and the other "large" absolute numbers. In that case, the perception of large eventual fatalities evidently won out and led the politicians to sign a test-ban treaty.

Genetic Effects. From a value point of view, the treatment of genetic effects is even more problematic than that of cancer deaths. Like cancer deaths, genetic effects are delayed, but unlike cancer deaths, the delay may extend indefinitely. Alternative characterizations of genetic effects are similar to those for cancer risk and may be stated as follows.

1. The risk of genetic effects is a small, undetectable percentage of a preexisting background for nonnuclear effects. Even if all genetic effects lead to death--and they certainly do not--the calculated annual incidence is only one-sixth of the increment of cancer deaths.

2. The absolute number of genetic defects may be larger than the number of cancer deaths since genetic defects propagate for many generations, especially since modern medicine makes possible the survival of those with what would otherwise be fatal mutations. Under future, possibly less favorable medical conditions, an increased genetic load may have drastic effects on individual chances of survival. This cannot be stated as an increment of risk per year (Muller 1955).

Extrapolation to 1000 Reactors. The RSS gives results for 100 light water reactors. Plans for the nation call for the installation of as many as 1000 reactors in the next 30 years. This raises the question of extrapolation. There are at least two alternative views of this problem.

1. It is improper to extrapolate linearly from 100 to 1000 reactors since this does not take into account probable improvements in management and technology with increasing experience (Nuclear Regulatory Commission 1975).

2. One might as well extrapolate, since learning may in whole or in part be canceled by increasing human carelessness as nuclear power proliferates. In addition, learning is strongly attenuated by present lack of standardization and the fact that an appreciable number of future reactors will be breeders, for which the RSS is irrelevant.

Neither view 1 nor view 2 can be supported or refuted by any available quantitative analysis. Therefore, it is reasonable to plot conservatively both prompt and delayed consequences, as in Figure 2B, and then extrapolate linearly to 1000 reactors, as in Figure 2C. Thus, a reinterpretation of the RSS results (without challenging the methodology of the study) indicates that the risks of catastrophic reactor failure approach the risks of a variety of manmade and natural catastrophic hazards.

A Skeptic's View. A final set of issues deals with a challenge to the methodology of the RSS. A number of critics have stated that the RSS analysis leading to the core meltdown probability is inadequate on the following grounds.

1. Completeness. It is impossible to know whether fault-tree analysis has identified all failure modes, particularly of the common mode variety (Kendall et al. 1974). The RSS agrees, but it is argued that the most important modes, including common ones, have been included.

2. Design Adequacy. Probability and fault-tree analysis cannot deal with inadequacy in reactor design as distinct from statistical failure of components (Kendall et al. 1974;Weatherwax 1975). Experience in the aircraft industry shows that unsuspected design inadequacy is responsible for most early crashes (Hohenemser 1975). The same may be true of reactors.

3. Human failure. As used in the RSS, probability and fault-tree analysis do not deal with certain types of human error, such as willful acts and sabotage. The RSS is, in effect, a statistical study of a perfectly designed machine, with the only sources of failure lying in the statistical malfunction of components and statistically quantifiable operator errors.

None of these criticisms is directed at the quality of analysis done in the RSS within the framework of probability and fault-tree analysis. They are warnings that a skeptical view of the methodology demands that the results be viewed as reasonable lower bounds on accident risk. One may, as some have suggested (Kendall et al. 1974), patch up the methodology or introduce more conservative error limits. Alternatively, one may bypass the RSS analysis for defining risk absolutely and rely instead on bounds defined in part by experience.[7] Two such bounds are (1) the empirical upper bound on accident risk arising from the current 300 reactor-years of catastrophe-free commercial reactor operation and (2) the high-consequence asymptote of the RSS risk spectra, which coincides more or less with the results obtained in the updated version of WASH 740. These bounds of skepticism appear as shaded bands in Figure 2D. Also shown is a risk spectrum of the RSS shape that conforms to these bounds and shows how a rational skeptic might assess reactor risk. The space between this curve and the RSS curve for prompt deaths from 100 reactors is a measure of the gap that currently exists between the strongly skeptical view of nuclear power and the views of a nuclear proponent who accepts the RSS executive summary at face value.

Individual risks calculated from Figure 1 are presented in Table 4, where they may be compared to individual risks from other

TABLE 4
Individual fatality risks (from Nuclear Regulatory Commission 1975)

CAUSE OF ACCIDENT	ACCIDENT RISK PER YEAR (DEATHS PER MILLION)
Principal noncatastrophic risks	
Motor vehicle	300
Falls	90
Fires and hot substances	40
Drowning	30
Poison	20
Firearms	10
Machinery	10
Water transport	9
Falling objects	6
Electrocution	6
Railway	4
Lightning	0.5
Principal nonnuclear catastrophic risks	
Air travel	9
Tornadoes	0.4
Hurricanes	0.4
Fires	0.5
Nuclear reactor risks	
100 reactors, prompt deaths (Fig. 2A)	0.0002*
100 reactors, all deaths except genetic (Fig. 2B)	0.02
1000 reactors, all deaths except genetic (Fig. 2C)	0.2
1000 reactors, rational skeptic's limit (Fig. 2D)	20

*Risks are based on the 15 million people who live within 25 miles of 100 nuclear plants and are candidates for prompt death. All other nuclear risks are based on 200 million people.

hazards, both catastrophic and noncatastrophic. (The individual risk for Figure 2A has been used to characterize catastrophic nuclear risk in Table 1.)

Conclusion. Whether seen through Figure 2 or Table 4, the assessment of catastrophic reactor risk can vary widely, from a point far below other risks to a point that exceeds a number of risks that many consider significant. The assessment of reactor accident risk depends on how we value the future, including the next generation; how we project the future safety of an evolving technology; and how much confidence we have in risk estimation that is based on no direct experience with the event for which risk is assessed. In the end, our answer will depend on whether we are technological optimists or pessimists.

The Rest of the Fuel Cycle

Aside from reactor failure, the light water reactor fuel cycle, shown in Figure 3, is susceptible to several other catastrophic risks. As a first step in characterizing them, we have constructed an exhaustive typology of risks, shown in Table 5. Here, conceivable catastrophic risks are symbolized by initiating events for each hazard and fuel-cycle stage. Below we discuss briefly the present state of knowledge about each of the columns in Table 5.

Nuclear Explosions. The risk of nuclear explosions derives from the possibility that weapons-grade material is illegally diverted from various stages of the fuel cycle. In an international context, this risk was widely discussed 20 years ago and was the principal motivation for the nuclear nonproliferation treaty. More recently, Willrich and Taylor (1974) have emphasized the relative ease of bomb construction and the lack of security against theft from domestic fuel-enrichment and reprocessing plants, as well as plutonium storage facilities. No attempt has, to our knowledge, been made, in a manner that is compatible with the units of Table 1 (expected deaths per reactor year), to evaluate the risk of theft. The prospect of the plutonium economy with annual inventories of 30,000 to 200,000 kilograms (Willrich and Taylor 1974) makes the diversion of a critical mass of ~5 kg plausible. At the same time, as far as we know, the military have successfully guarded for 30 years a stockpile of ~100,000 kg of weapons-grade material, much of it in the form of weapons.

Massive Fission-Product Release. After the reactor, fission product hazards occur in the "back end" of the fuel cycle: in reprocessing, waste disposal, and transport to and from these facilities. These processes are not currently operational in the commercial U.S. fuel cycle. The only commercial reprocessing plant, in

TABLE 5
Typology of catastrophic nuclear risks.

FUEL CYCLE STAGE	HAZARD TYPE: NUCLEAR EXPLOSION	HAZARD TYPE: FISSION PRODUCT RELEASE	HAZARD TYPE: PU DISPERSAL
Mining, milling, and refining			
Enrichment and fuel fabrication	T		S, A
Light water reactor		S, A	S, A
Fuel reprocessing	T	S, A	S, A
Plutonium storage	T		S, A
Waste disposal		S, A	S, A

Key: T, theft; S, Sabotage; and A, accident.

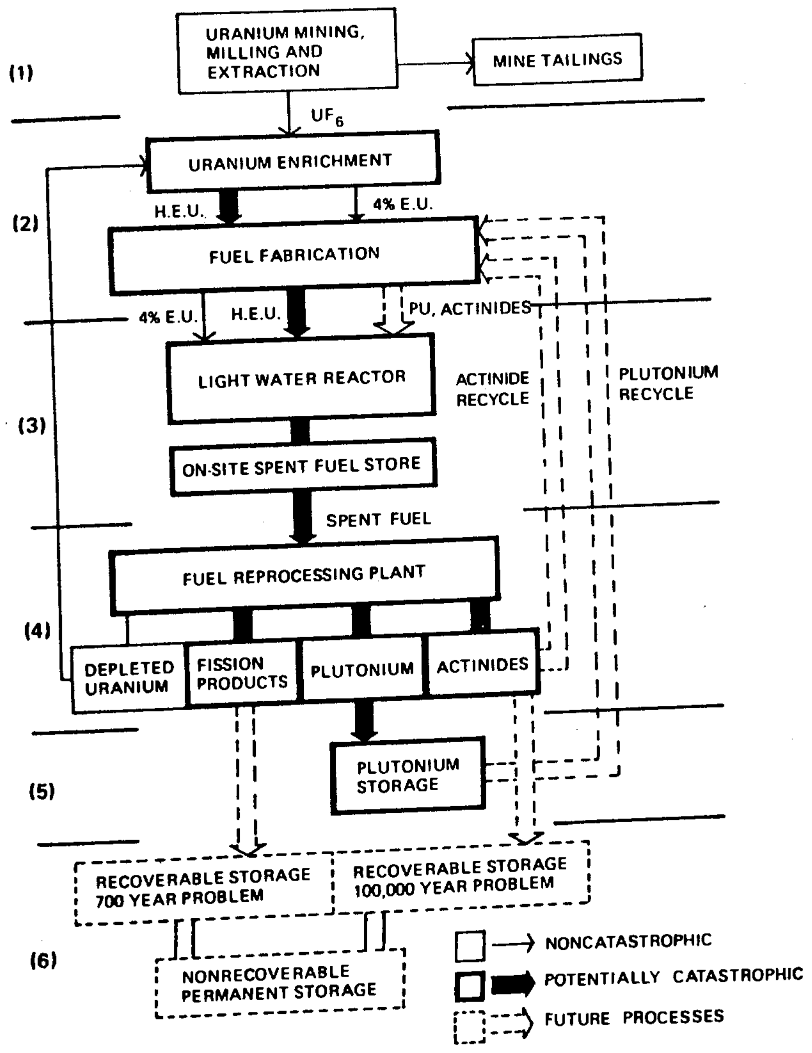

Figure 3. The light water fuel cycle, showing portions currently operational and nonoperational in the United States. The abbreviations E.U. and H.E.U. stand for enriched and highly enriched uranium, respectively.

West Valley, New York, closed in 1972 after six years of operation and is being redesigned and enlarged. A second plant, at Morris, Illinois, has been scrapped because of technical problems that would, among other things, have led to unacceptable occupational exposures. A third plant, at Barnwell, South Carolina, is under construction and is scheduled to open soon. As to the disposal of solid waste, it is still not clear what the product, and therefore the process, will be and where it will be stored (Colby 1976). Most spent fuel is now stored at reactor sites in cooling ponds. Failure to resolve the waste-disposal questions may delay opening and operation of reprocessing plants under construction, even if they are otherwise functional.

In view of the immature state of the back end of the fuel cycle, it is perhaps not surprising that little effort has been spent on risk assessment. What has been done may be summarized as follows.

1. Cohen (1976), in an effort to show that wastes do not pose a significant threat, obtained an upper limit of 0.01 death per reactor-year for random deep burial of solidified wastes. His result depends on treating as equivalent the risk from naturally occurring uranium in rock and the solid waste at the bottom of a deep disposal hole.

2. The AEC (1972) analyzed risks associated with the transportation of spent fuel and waste and estimated accidental fatalities from nonradiological and radiological causes as 0.01 and 10^{-7} per reactor-year, respectively. Ross (1975) challenged this on the grounds that not only volatile fission products (as assumed by the AEC) but also semivolatile fission products can be released in truck accidents accompanied by fires. Our interpretation of his analysis leads to a fatality rate of 0.01 per reactor-year.

Risks not assessed may be more important: consider two cases.

1. If present plans materialize, by the year 2000 there will be 50,000 annual shipments of spent fuel and waste, containing 2 to 3 megacuries each and covering a total of 50 million truck miles (AEC 1972). This would appear to pose a significant sabotage risk.

2. If and when operational, fuel reprocessing plants will handle the fission-product inventories of several reactors. They are potential sources of radiological risk an order of magnitude greater than the risk from reactor accidents. Considering the lack of experience with commercial reprocessing, it is doubtful that even if a study like the RSS were undertaken, meaningful results could be obtained.

Plutonium. A third category of risk involves dispersal of plutonium. In a fully developed fuel cycle this can occur nearly anywhere after the mining of uranium (see Table 5). Plutonium toxicity is based on its alpha activity and, like fission product toxicity, at low doses manifests itself through cancers with a latent period of 15 to 45 years. Although fission-product effects are fairly well defined, however, numerical estimates of plutonium toxicity vary and are controversial.

On some things, however, there is general agreement (Bair and Thompson 1974). Ingested plutonium is almost entirely excreted, and the dominant risk to humans is from inhaled particles. If insoluble, the particles stay in the lung with a half-life of 1000 days; if soluble, they are transported by the blood to the bone and liver and cause cancer at these locations. Plutonium accidents are likely to release insoluble PuO_2; therefore, lung cancer is the dominant risk to humans, and it is reasonable to characterize the toxicity of plutonium by the lung cancer dose. (On the assumption of the linear hypothesis, this is the population dose capable of producing one lung cancer on the average.)

On the basis of a few accidental exposures (Cohen 1975), it is possible to express the lung cancer dose in micrograms of inhaled or deposited plutonium. Table 6 shows a variety of estimates for lung cancer doses. In regard to Table 6, we make the following observations.

1. There have been no cases of lung cancer in 26 plutonium workers who received serious lung doses in 1954 and another 25 who were exposed in 1965 (Bair, Richmond, and Wachholz 1974). Therefore, animal experiments with PuO_2 inhalation (Bair and Thompson 1974) and the experience of underground miners with dust containing natural alpha emitters (National Research Council 1972) constitute the only direct link between lung cancer and internal alpha activity. The nonoccurrence of human lung cancers in the 50 serious plutonium exposures is nevertheless helpful in setting a lower bound on the lung cancer dose.

2. In consensus documents on the biological effects of radiation (National Research Council 1972;UNSCEAR 1972), it is assumed that the effect of internal alpha activity may be predicted on average doses to affected organs. The first four lines of Table 6 are based on this assumption. Either an absolute or relative risk model may be employed. In the first, the expected number of cancers is proportional to the dose; in the second, it is also proportional to the spontaneous cancer rate. This leads to a smaller estimated plutonium lung cancer dose for smokers than for nonsmokers (Gofman 1975a).

3. Despite average dose assumptions made in consensus documents, it is widely agreed that internal alpha doses are almost never evenly distributed (Bair, Richmond, and Wachholz 1974;Bair and Thompson 1974). The effect of dose localization on particle size is illustrated in Table 7. Consequently, Geesaman (1968), Martell (1975), Morgan (1975), and others expect that toxicity depends on particle activity. With large particles of PuO_2 very few cells are exposed, most receive lethal doses, and little if any dose is effective in cancer induction; with small particles the dose structure becomes indistinguishable from an average dose; with intermediate particles, high but nonlethal doses may produce a "resonant" cancer response in a relatively small number of cells. While this model is consistent with available experimental information, no clear-cut evidence of resonant response has yet been found.

It is clear, therefore, that plutonium toxicity poses problems significantly more intractable than those addressed by the RSS. To reach a useful conclusion, it is necessary not only to calculate dispersal probabilities but also to consider the large uncertainties in toxicity. We are therefore unable to report on an assessment of plutonium dispersal that represents a degree of scientific consensus.

A possible useful perspective has been suggested by Gofman (1975b). The amount of ^{239}Pu deposited in the lungs of humans in the United States totals 0.034 gram and results from the dispersal

TABLE 6
Plutonium lung cancer doses as estimated by various authors.

SOURCE	DEPOSITED CANCER DOSE (μg) ^{239}PU	REACTOR GRADE PU
Cohen-BEIR absolute risk model[a]	204	38
Gofman-BEIR relative risk model[b]	43	8
Gofman relative risk model		
Smokers[c]	0.058	0.011
Nonsmokers[c]	7.3	1.4
Tamplin-Cochran hot-particle model[d]	0.002	0.0004
Bair-Thompson beagle dog experiments[e]	27	

[a] Estimates based on calculations by Cohen (1975), using the BEIR absolute risk model (National Research Council 1972). The result applies to adults 20 to 30 years of age.

[b] Estimates given by Gofman (1975a), using the BEIR relative risk model (National Research Council 1972) with a lung cancer risk of 0.5 percent of the spontaneous lung cancer risk per man-rem of exposure. The results differ from the preceding ones because current spontaneous rates are used instead of 1945 rates, on which the absolute risk model is based.

[c] Estimates by Gofman (1975a), using the BEIR relative risk model (National Research Council 1972) with modified assumptions: (i) a relative risk of 2 percent of the spontaneous risk per man-rem is used, and (ii) a distinction between smokers and nonsmokers is made, and the much higher "spontaneous" cancer risk of smokers is used. The higher relative risk conversion is justified by previous work of Gofman and Tamplin (see Gofman 1981, 870-871 for a list of references). Although the estimated lung cancer dose for smokers is very small, Gofman argues that it is not consistent with the nonoccurrence of lung cancers in 25 Los Alamos and 25 Dow Chemical workers accidentally exposed in 1944 and 1965, respectively.

[d] Estimates based on the work of Tamplin and Cochran (1974). These authors have considered 1- to 10-μm "hot" particles and have argued that locally high doses must be used in calculating the cancer risk. The results quoted here are based on the Tamplin-Cochran "dose distribution factor" of 10^5 (average dose multiplied by 10^5 to estimate locally high doses near hot particles) and the BEIR absolute risk model. Lung cancer doses as small as those given here are inconsistent with the nonoccurrence of human cancers in the Los Alamos and Dow Chemical exposures, and also with recent hot-particle experiments on animals (Bair, Richmond, and Wachholz 1974).

[e] Estimates based on the work of Bair and Thompson (1974) with beagle dogs (Bair, Richmond, and Wachholz 1974), as suggested by Gofman (1975a). The lowest dose at which all dogs die of lung cancer has been taken as the upper limit for the dog lung cancer dose. The human lung cancer dose was obtained by multiplying by the ratio of the lung mass in humans to that in dogs.

TABLE 7
Relationship of particle size to number of cells at risk for a static lung burden of 0.016 μc of $^{239}PuO_2$ (AEC 1974a). Static particles are assumed in a structureless human lung of uniform density $0.2 gcm^{-3}$ with an average cell volume of 10^3 μm^3. Cells at risk are taken to be those in a sphere of radius equal to the alpha-particle range (200 μm at the assumed density).

PARTICLE DIAMETER (m)	NUMBER OF PARTICLES	ACTIVITY PER PARTICLE (PC)	CELLS AT RISK	FRACTION OF LUNG (%)
0.1	5.4×10^7	3×10^{-4}	3×10^{11}	30
0.3	2.0×10^6	0.01	1.3×10^{10}	1
0.7	1.8×10^5	0.08	1.2×10^9	0.1
1.0	5.4×10^4	0.3	3.6×10^8	0.03

of ≈400 kg through weapons testing (Bennett 1974). If uptake of accidentally dispersed reactor grade plutonium is not to exceed the effects of fallout, dispersal in a future plutonium economy must be limited to ≈80 kg, assuming equal uptake fractions for the two cases. (Reactor-grade plutonium is about five times more toxic than weapons-grade plutonium.) Cumulative production by the year 2000 may be 10^7 kg (Willrich and Taylor 1974); hence, independent of toxicity, containment will have to be at the 99.999 percent level. The social cost of the ≈0.001 percent escaped plutonium will be 160 to 116,000 lung cancers, depending on which toxicity estimate in Table 6 is used.

Management of Safety

The properties of nuclear power--high technology, large capital investment, rapid growth, abbreviated experience, and low probability-high consequence risks--pose unprecedented regulatory problems. Until recently, these have been compounded by an unhappy marriage between development and regulation in the AEC (Metzger 1972;Primack and von Hippel 1974), an arrangement that dates back to the struggle for civilian control of atomic energy at the end of World War II. In this situation, the overriding priorities for development gave short shrift to pressing safety needs (Gillette 1974a-d). Thus safety research funds have been diverted to support the development of the breeder; quality assurance objectives replaced safety research objectives in the Loss of Fluid Test (LOFT) Program; the safety research budget of the regulatory staff before 1970 remained quite small (see Figure 4); and the regulatory staff was denied access to research findings from national laboratories. Because of the increasing public criticism of nuclear safety in the 1970s and continuing underestimation of the regulatory task, AEC regulatory managers became crisis managers. The recent establishment of the Nuclear Regulatory Commission (NRC) as a regulatory agency and

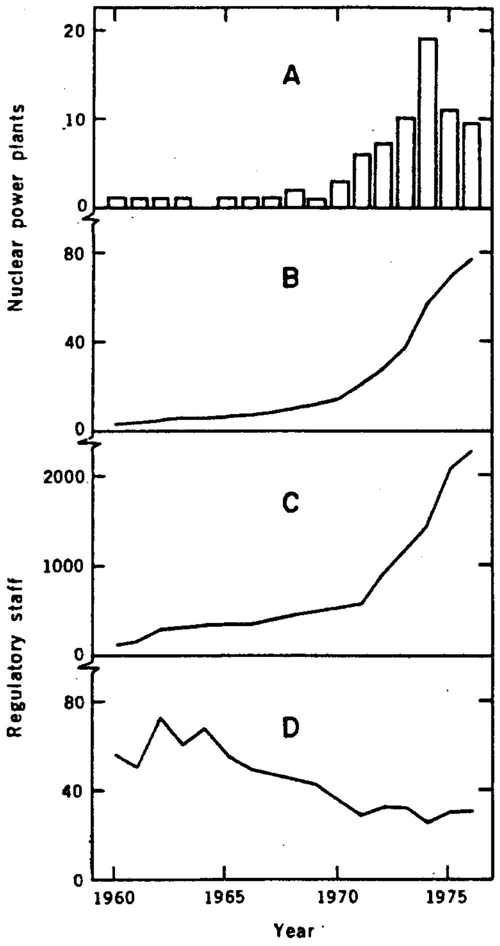

Figure 4. Growth of nuclear power and its regulatory staff. (A) Number of nuclear power plants achieving commercial operation each year. (B) Total number of nuclear power plants in commercial operation. (C) Total regulatory staff per nuclear plant in commercial operation. (D) Regulatory staff per nuclear power plant in commercial operation. Note that as nuclear power grew rapidly in the 1970s, the regulatory staff per power plant declined. The rulemaking hearings on emergency core-cooling systems (ECCS) did not have an effect on the regulatory staff per plant.

increased funding of regulatory work may eventually solve this problem. Yet change will be slow, since below the commissioner level the NRC is staffed largely by former AEC personnel carrying with them a bureaucratic ethos built over a period of 30 years.

In the present furor over safety, it is well to remember that for years the AEC and the Joint Congressional Committee on Atomic Energy agreed that regulation was in the public domain, while responsibility for safety lay primarily with private industry. Quite independent of the confusion between development and safety goals, this model of regulation and safety appears, in retrospect, inadequate. The unhappy history of emergency core-cooling systems (ECCS) serves as an apt example (Cottrell 1974).

In 1966, when the AEC identified the loss-of-coolant accident leading to core meltdown as its highest safety priority, it initiated a major research effort and instituted a series of regulatory changes that were designed to ensure the safety of the larger reactors then being developed (Kouts 1975a;Ford and Kendall 1972). Yet in 1969, there were still only three members of the regulatory staff working directly on evaluation of ECCS. In the 1971 ECCS rule-making hearings, Morris Rosen, then chief of the Systems Performance Branch of the AEC's Division of Reactor Standards, testified that the regulatory staff simply did not have adequate knowledge to make licensing decisions on 100 reactors then pending (Ford and Kendall 1972). It was clear by then that the ECCS problem transcended the capability of any single industry and must, contrary to earlier expectations, be taken over by the government. By 1975, at least 10 years after the initial recognition of the ECCS problem and at a time when the number of commercial reactors stood at about 50, no solution appeared in sight, 90 percent of all current light water research funding was committed to the problem, and in the words of the new director of safety research (Kouts 1975b): "the future program in reactor safety research is largely . . . the future of the ECCS program."

Yet, as we have tried to make clear, there are other significant safety issues in the nuclear fuel cycle. Some, such as waste disposal, may be moving to an early solution. Others such as plutonium dispersal hazards, may never be fully understood, since they involve issues that have been called trans-scientific (Weinberg 1972)--they can be stated in the language of science, but appear for practical purposes to be unanswerable by science.

Finally, it is now becoming clear that the regulation of nuclear safety is impeded by the large capital investments required. These investments go beyond the initial capital (which approaches $1 billion per plant). For example, the official investigative report on a fire in the plant at Browns Ferry, Alabama, called for improved fire prevention designs and noted that retrofitting would cost between $100 and $300 million per plant, with another $500 to $1300 million needed to buy coal for lost electric generating capability (Burnham 1976b). The Indian Point 1 plant on the Hudson River stands idle because of the costs involved in the NRC decision to require ECCS retrofitting. The safety problems involved in "grandfathering" (exempting from retrofitting) can be significant, but because they pose major cost implications, they have emerged as an element in the heated debate among experts.

Rancorous Conflict

Resolution of regulatory problems becomes doubly difficult in a polarized environment. Doubts about credibility and accusations are quick to surface when regulators, by force of circumstance, must obfuscate or risk exposing ignorance. Evidence of the escalating conflict over nuclear energy policy is particularly abundant in the

scientific community. In 1975, the Ford Foundation funded a "blue-ribbon panel" to study nuclear energy in the United States. A prime consideration in choosing the panelists was lack of a strong previous position on the problem. A similar NAS study of nuclear risk ran into recruitment difficulties because of the lack of highly qualified "disinterested scholars." A leading journal recently rejected an article by nuclear critics because of its advocacy tone and later accepted one by a proponent of nuclear power, which provoked a stinging rebuttal by the rejected authors (Boffey 1976a). Meanwhile, both sides compete in the number of Nobel laureates and other scientists they can enlist (Boffey 1976b;Walske 1976).

Supporters of nuclear power tend to perceive its opponents as an undifferentiated mass, somewhat irrational and hysterical, committed to the destruction of a technology that is often the lifework of its supporters. The rancorous conflict promotes a "besieged camp" mentality. In the view of some proponents, new issues arise not because genuine new problems have been found, but because outstanding questions have been put to rest and the critics are forced to shift ground.

For critics of nuclear power, the enemy includes the regulators, industry representatives, and supporting scientists who combine in foisting an unsafe technology onto an unknowing and trusting public. Influenced by past cases of censorship and cover-up (Gillette 1972a-d), opponents take at face value no one who speaks in favor of nuclear energy but look immediately for hidden motivations.

The rancorous conflict that feeds on the inadequacies of the regulatory process in turn undermines this process. On strictly human terms, the U.S. regulatory official has a nearly impossible task. Thanks to the Freedom of Information Act, memoranda, letters, and reports are under continuing public scrutiny, and decisions must be made in a "goldfish bowl." The effect is to discourage candor, and when candor survives to blunt its positive impact. For example, when a regulatory task force reported critically on the performance of safety systems during the fire at the Browns Ferry plant (Burnham 1976b), instead of lauding the frankness and openness of the report, nuclear opponents such as Ralph Nader have used it as evidence of everything that is wrong with nuclear reactors and the regulatory process (Walske 1976).

Perhaps the most striking products of the rancorous conflict among experts are current voter referenda that attempt to force a decision despite an apparent lack of public information and understanding on the technical issues that warring factions of scientists and regulators have been unable to resolve (Atomic Industrial Forum 1976). Thus, the California initiative called for a public decison on the effectiveness of all safety systems, the adequacy of waste disposal and storage systems, and improved nuclear accident and liability insurance protection (California 1976).

Conclusion

Weinberg (1972) described the adoption of nuclear power in the following terms: "We nuclear people have made a Faustian bargain with society. On the one hand we offer--in the catalytic nuclear burner [breeder]--an inexhaustible source of energy. . . . But the price we demand of society for this magical energy source is both a vigilance and a longevity of our social institutions that we are quite unaccustomed to." We see the issue of nuclear safety as a Hydra, or many-headed monster--no sooner is one head severed than two others spring up to take its place, and the central head is immortal or nearly so.

Our immediate prognosis is for extension rather than diminution of the opposition to nuclear technology. Public opinion, which has consistently supported nuclear power, is nonetheless deeply divided, much as it was during the war in Vietnam. There is some evidence that wider public exposure to rancorous debate on nuclear power may well stiffen the opposition, as in the Swedish experiment in mass education (Grafström 1975) or in the persistence of opposition despite the initiative defeats.

Our own bias is to keep the nuclear option open, but to proceed cautiously; to press vigorously for solutions to immediate problems; but to forego at this time the implementation of plutonium recycle and the breeder. Time is needed to complete the risk assessment of the light water reactor fuel cycle, to validate experimentally computer codes that serve as substitutes for experience, to resolve such problems as spent fuel transport and waste disposal. Time is also needed to learn to live with or avoid trans-scientific issues such as plutonium toxicity, and intractable social risks such as sabotage, theft, and nuclear weapons proliferation. Finally, time is needed to evaluate long-term energy alternatives not described in Table 1, alternatives that may yet prove to have more favorable characteristics than currently available energy technologies.

Summary

Society seems content to strike a more moderate or uncertain balance with other technologies than with nuclear power. This attitude is traced to the social history of nuclear power, the genuine uncertainty and complexity of safety issues, underestimation of the regulatory task, and the rancorous nature of the debate. Nuclear power is not just another problem of technology, of environment, or of health. It is unique in our time. To be more demanding of nuclear safety may be to apply a double standard, but not necessarily an irrational one.

Our best course appears to be to keep the nuclear option open, work toward the rapid resolution of problems such as waste disposal, but postpone recycling and the breeder reactor. Time is needed to resolve immediate problems such as transport and disposal of nuclear wastes; to come to terms with trans-scientific issues such as plutonium toxicity, sabotage, and weapons proliferation; and to evaluate long-term energy alternatives.

EPILOGUE (JANUARY, 1985)

Nuclear power is still in trouble. More than seven years after the foregoing paper was written the de facto moratorium on nuclear power persists and will almost certainly continue to do so, at least for the near term, despite resuscitation efforts by the Reagan

administration. A new chapter entitled "Three Mile Island" and an important addition to the chapter on nuclear proliferation have appeared in the social history of nuclear power. Genuine uncertainty over safety issues continues in their wake; an antiregulatory administration threatens to undermine the massive regulatory effort sparked by the accident at Three Mile Island (TMI); a searching review of the Reactor Safety Study found an underestimate of the error bars on accident probabilities and led the Nuclear Regulatory Commission to withdraw its endorsement of the study's estimate of the overall risk of reactor accidents; assumptions concerning the source term for radioactive releases in a major accident are under reconsideration (Payne 1985); emergency response has become a new source of contention, and the rancorous scientific debate has not diminished. Meanwhile, the public distrust of nuclear power appears to have diminished somewhat in intensity but not in substance. Added to these factors of distrust in nuclear power is a powerful economic reality, the deterioration of this energy source's market viability in the face of declining energy consumption and high interest rates.

Continuing scientific debate over nuclear power is quite evident in the response to the accident at Three Mile Island. Since nearly all the radioactivity was contained within the plant, proponents of nuclear power claimed that the accident sequence fell well within the predictions of existing risk assessments (specifically the Reactor Safety Study) and that the success in containing radioactivity illustrated the inherent resiliency of "defense-in-depth" principles of reactor safety assurance. Opponents, pointing to the interaction between technical and human error, see the accident as an indictment of the technlogy and the industry and a harbinger of greater accidents to come. Meanwhile, the Presidential commission appointed to investigate the accident concluded that "fundamental changes" in safety management were required if "risks are to be kept within tolerable limits" (U.S. President's Commission on the Accident at Three Mile Island 1979,7-8).

The many recommendations emerging from at least nine major post-Three Mile Island appraisals have produced an extensive effort to upgrade the safety of nuclear power plants. The most important changes include (1) greater regulatory attention to operating reactors and an increased willingness to order shutdowns and levy fines, (2) a more balanced approach to risk management, with increased attention to slowly developing accident events, to consequence mitigation and emergency response, and to human factors, (3) greatly increased use of probabilistic risk assessment in designing and operating plants, in licensing, and in regulating plants (Nuclear Regulatory Commission 1984), (4) a substantially increased industry effort to upgrade safety assurance at individual plants and to improve its own technical capabilities and training programs, particularly through the work of the Institute for Nuclear Power Operations (INPO), and (5) internal changes within the Nuclear Regulatory Commission aimed at enhancing its inspection and regulatory functions and emergency-response capabilities.

Despite general agreement that safety has been upgraded, the extent of improvement remains uncertain. The spate of new regulations mandated by the NRC, though clearly upgrading safety in some areas (for example, emergency response), may have resulted in a formalism in industry response and a diversion from more imaginative approaches to risk control. On the other hand, the extensive analysis of plants by probabilistic risk assessment (Nuclear Regulatory Commission 1984), intensive effort on improved training of operators, and increased security measures have probably served to lower (perhaps significantly) the risk of major reactor accidents. Open to question is the extent to which either industry or the regulators have achieved the fundamental changes in attitudes and "mindsets" that many post-accident assessments believed central to substantial improvement in safety performance.

Unsettling also is the prospect of future Three Mile Island accidents. If one accepts the recurrence probability of such accidents as falling between one in several hundred thousand to one in several thousand reactor years (as indicated by a probabilistic risk analysis of a particular plant), then one should expect such an accident every five to ten years (assuming 125-150 Gwe installed capacity) and every two to five years somewhere in the world. With current costs for the TMI cleanup projected at over $1 billion, it is increasingly evident that even near misses of major reactor accidents are socially unacceptable.

The past five years have also witnessed continued scientific dispute over the health effects of low level radiation, despite the fact that it is perhaps the best understood of all carcinogenic hazards. Consider, for example, that

> the majority of a scientific committee of the National Academy of Sciences accepted a linear-quadratic extrapolation as the best expression of predicted effects of low-level radiation, with dissenting reports arguing for the linear extrapolation on the one hand and the quadratic extrapolation on the other,

while

> a series of studies have emerged purporting to find higher occupational or therapeutic incidence of cancer than would be predicted by either the linear or the linear-quadratic extrapolation.

Meanwhile, the only significant additional data are those emerging from the new studies of neutron and gamma ray doses and cancer mortality at Hiroshima and Nagasaki, yet these results have been subjected to varying interpretation and appear only to have fueled the debate. The controversy highlights the continuing absence of data that could provide confirmation or rejection of the various interpretations and undoubtedly contributes to a public perception that science is really deeply divided.

Underlying the public distrust of nuclear power has been the continuing concern over waste disposal, an issue that now consistently tops the list of worries over the technology. The public response reflects, at least in part, the inadequate historical performance on radioactive waste disposal. Significant legislative progress, however, has been made on radioactive wastes, as embodied in the Low-Level Waste Policy Act of 1980 and the Nuclear Waste Policy Act of 1982. The extent to which the acts will be implemented in a timely manner remains to be seen; site selection remains a problem for both high-level and low-level wastes and the schedules demarcated for the former appear overly optimistic. Although the Reagan administration has lifted the indefinite deferral of reprocessing, subsidies to support private initiatives have not been forthcoming. Allied Chemical has written off its half share in the Barnwell reprocessing plant, and increasing public concern over nuclear weapons (as well as economic realities), and particularly the plentiful supply of uranium, may reverberate on the long-term prospects for reprocessing.

In regard to this last issue, a significant event for public concern was the Israeli strike in 1981, allegedly for "preemptive" objectives, on the experimental Iraqi reactor. Although subsequent discussion suggests that political considerations may have provided the motivation, the action mobilized the latent public fears over the links between nuclear weapons and nuclear power plants. Similarly, the statement by President Reagan that accumulating spent fuel may be used in the planned expansion of nuclear weapons provoked concern in industry no less than the public (Graham 1981).

As important as these safety issues is the deterioration of nuclear power in the marketplace. The worldwide decline in electric power demand and higher interest rates have resulted in no new domestic orders for nuclear power plants (while dozens of coal plants have been ordered) over the past six years and an overall cumulative cancellation or postponement of over 80 earlier nuclear plant orders. In 1977, our prognosis for nuclear power development was that "increasing capital costs would not be decisive in the long run." A combination of factors--high interest rates, substantial regulatory uncertainty, and saturation of electricity demand--interacted, however, to produce fewer energy plant orders and to deepen utility reluctance to invest in nuclear when plants are added. Given a steady decline over the past decade of projected energy use by the United States, this situation is unlikely to change quickly.

Thus, intentionally or not, time is available to deal with the Hydra-headed issues of nuclear power and to work to regain the public trust in this technology. The mid-1980s offer a clear fork in the road--whether to take advantage of an antiregulatory administration to press ahead in spite of the unresolved safety problems or to pause in order to put in place needed changes, to explore new (and perhaps inherently safer) reactor designs, and to strike the compromises required if nuclear power is again to prosper in the United States.

NOTES

1. This article appeared originally as "The Distrust of Nuclear Power," Science 196 (1 April 1977):25-34 (Copyright 1977 by the American Association for the Advancement of Science) and reflects the authors' views at that point in time. The epilogue reexamines the issue of public attitudes toward nuclear power in 1985.

2. A rem is a unit describing radiation dose in man. It measures the number of ion pairs per unit volume of tissue. A man-rem refers to the accumulation of 1 rem in a single human, or fractions of a rem in several humans such that total dose is 1 rem.

3. A reactor-year is a unit describing the amount of reactor operating experience. For example, 1 reactor-year's experience may be accumulated by one reactor's operating for one year or 12 reactors operating for one month.

4. The surveys involved 100 person-in-the-street interviews in Boston, London (England), and Toronto in 1975, between 200 and 250 similar interviews in each of the three cities in 1976, and 100 lenghthier residential interviews (by random cluster sample) at two reactor sites each in Britain and Canada and at three reactor sites in the United States.

5. R. Wilson, among others, has argued that transportation of liquefied natural gas in ships represents threats comparable to those of nuclear power (see, for example, Wilson 1973). We agree in part, but we would argue that long-term effects of radioactivity set nuclear power apart.

6. The existence of delayed deaths in significant numbers was first recognized by the American Physical Society (1975). Delayed death estimates not very different from these were subsequently incorporated in the final version of the RSS (Nuclear Regulatory Commission 1975). The issue of delayed deaths was not recognized in the draft version (AEC 1974b).

7. For interesting discussion in this connection, the authors are indebted to Jan Beyea.

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11

Hazard Assessment: Art, Science, and Ideology[1]

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Human beings appear to become increasingly adept at creating, discovering, or rediscovering threats to themselves and to their environment. A new professional interest, hazard assessment, has developed in assessing these threats. Hazard assessors are becoming more numerous and their products in the form of risk assessments, risk/benefit analyses, environmental impact statements, and technology assessments are widely diffused.

The task is not one for specialists alone; people have always assessed environmental threat: storm, drought, fire, or disease. But for the new and newly discovered hazards, there is strong perception of risk but little experience with consequences. With such uncertainty it is not surprising that hazard-assessment practice is still more art than science and that distinctive, contrasting ideologies flourish.

Hazard Assessment Methods

Hazard assessment is the prime component of the intelligence function of hazard management (chapter 3). For descriptive convenience, Figure 1 separates the overall process into three overlapping elements, but it is important to recognize that in practice the distinctions are blurred. **Hazard identification** is the recognition of a hazard, the answer to the question: what constitutes a threat? Its methods are the methods of research and of screening, monitoring, and diagnosis. **Risk estimation** is the measurement of the threat potential of the hazard, an answer to the questions: how great are the consequences, how often do they occur? Its methods are methods of knowing: revelation, intuition, and extrapolation from experience. **Social evaluation** is the meaning of the measurement of threat potential, an answer to the question: how important is the estimated risk? Its methods are methods of comparison: aversion, balance, and cost/benefit analysis.

Hazard Identification

For much of human history, the identification of environmental hazards arose from the direct human experience of harmful events and consequences or from the application of ritual or magic. Technological hazards too often manifest themselves experientially as