Nuclear Energy:

SALVAGING THE ATOMIC AGE

"Before Three Mile Island, I was comfortable with the record of nuclear energy," writes Alvin M. Weinberg, one of the pioneers of atomic power. Yet long before the accident in Pennsylvania last March, Weinberg was worried about the siting, design, management, and operation of the 70 commercial U.S. nuclear power plants that today provide more than 10 percent of the nation's electricity. Short on oil and coal, some countries, notably France and South Korea, are "going nuclear" in a big way. Other countries, such as West Germany and the United States, are increasingly disturbed by the possibility of large-scale radioactive contamination. Weinberg believes that solar energy and other "clean" approaches should be pushed; but none of them, he argues, can fully substitute for the "nuclear enterprise." Here he reviews the history of atomic power and suggests what must be done to ensure its future.

by Alvin M. Weinberg

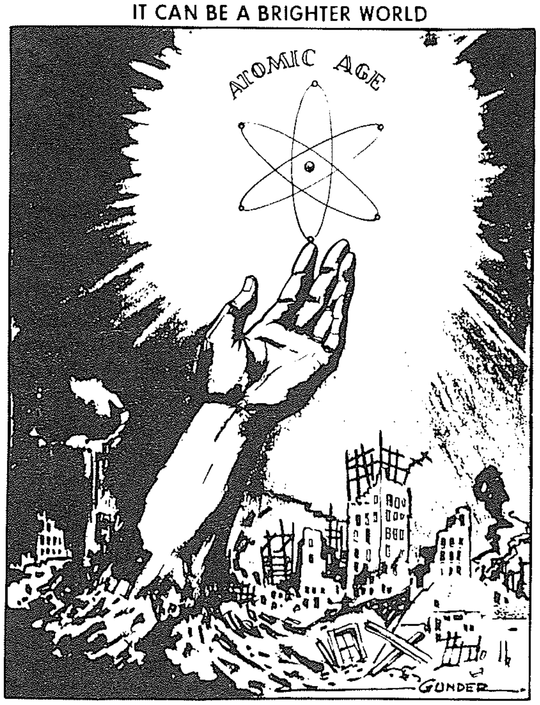
A 1-million-kilowatt, pressurized-water nuclear reactor—the type widely used in the United States today—contains 15 billion curies of radioactivity. This is about equal to the natural radioactivity that accompanies decay of the four billion tons of uranium dissolved in all the oceans. Nothing except time can turn this radioactivity off. The radioactivity in a reactor decays only slowly after the reactor is shut down: it contributes about 200,000 kilowatts of heat while the reactor is running, and, depending upon how long the reactor has been running before shutdown, it is still generating 8,500 kilowatts a week later. Unless a large chain reactor is cooled even after the reaction has ceased, the fuel will melt. If it melts, radioactivity will escape from the fuel and may enter the environment.

From the beginning, all of us at Arthur Compton's wartime Metallurgical Laboratory in Chicago, where the first chain reaction was established in 1942, sensed that man had crossed a threshold when he learned how to create radioactivity at will—and on an enormous scale.

Until then, radioactivity was measured in micro- or millicuries; one gram of radium, costing $50,000, was equal to one curie. (The maximum permissible dose of radium in a human being is one ten-millionth of a gram.) Enrico Fermi, the developer of the chain reactor, and our scientific leader, on occasion would remind us of this. It was not only the Bomb that changed things, he said, it was also the creation of unimaginably large amounts of radioactivity.

The simplest way to ensure that no member of the public was hurt by the release of radioactivity from a malfunctioning nuclear reactor was to put the reactor in a remote place. To be sure, the first chain reaction, on December 2, 1942, took place on

IT CAN BE A BRIGHTER WORLD



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"Out of the devastation caused by the atomic bomb grows the hope for a brighter world," read the caption for this widely distributed 1959 Associated Press cartoon by Ed Gunder. Few cartoons today reflect such optimism over the future of nuclear energy.

57th Street and Ellis Avenue in the heart of Chicago's South Side. This tiny venture into large scale radioactivity gave General Leslie Groves, head of the Manhattan Project, and Arthur Compton plenty of anxiety, but every day counted during the war. To have awaited the completion of the site at Argonne Forest Preserve outside the city would have taken too much time.

But we took it for granted that the large (250,000 kilowatt) plutonium-producing reactors then being planned, as well as a much smaller pilot plant reactor, would be remotely sited—the latter at Oak Ridge in the hills of eastern Tennessee ("site X"), the former on the huge Hanford Reservation in eastern Washington ("site W"). Most of the other reactors built by the Atomic Energy Commission between 1946 and 1974 were confined to these and several other sites: Savannah River, South Carolina; Idaho Falls, Idaho; and Los Alamos, New Mexico.

All of these places were, at the time, far from population centers; and as the supporting towns, such as Richland, Wash., and Oak Ridge, Tenn., developed, they were sprinkled with specialists who had daily experience in the handling of large-scale radioactivity and knew how much was dangerous and how much was but a tiny addition to the earth's all-pervasive natural background radiation.

Had all U.S. power reactors been as secluded as the original Hanford or Idaho Falls or Savannah River reactors, the nuclear enterprise might have avoided many of the problems it has now encountered. We might have had by this time perhaps 25 remote sites, each eventually having as many as 10 or 20 reactors (Hanford at one point had 9 large reactors), each surrounded by a

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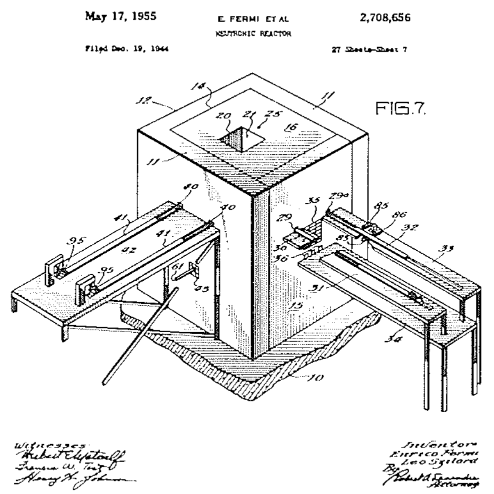


Argonne National Laboratory

The first nuclear chain reaction was established in 1942 in a squash court under the University of Chicago's Stagg Field. Two years later, physicists Enrico Fermi and Leo Szilard applied for a patent on the first nuclear reactor (left). The patent for the two-story-high structure was issued in 1955.

large unpopulated zone, and each ringed at a distance by villages inhabited by people who worked at the plants and for whom the safe handling of radioactivity was a fact of life.

Had the nuclear energy enterprise remained a government monopoly, as originally prescribed under the Atomic Energy Act of 1946, then the siting and generation of nuclear electricity might have evolved along such lines. Power generation would be in the hands of the Atomic Energy Commission, or a successor agency, and the electricity so generated would be distributed by private and public utilities.

But, in retrospect, this could never have happened. The utilities, perhaps stung by the consequences of their foot-dragging on rural electrification in the 1930s, were anxious to forestall the development of a government-operated nuclear version of the New Deal's Tennessee Valley Authority. And this was not a phantom threat: in the early 1950s, Tennessee's Senator Albert Gore was calling (in vain, as it turned out) for federal construction of six large power reactors in the United States. But the Atomic Energy Act of 1954 put nuclear energy into the private sector: Congress allowed utilities to own and operate nuclear power plants, and indeed, encouraged the private sector to design and develop reactors. Today 41 utilities operate some 70 large nuclear power plants.

Producing electricity in remote sites is also awkward. Utility planners build conventional coal and oil generating plants near cooling water and close to "load centers" (i.e., population centers) to reduce the cost of transmission lines. A conventional plant's impact on the environment has, until very recently, been regarded as a secondary matter. As for fossil fuel plants' possible danger to the public, for a long time this was not an issue, even though their emissions may cause or exacerbate lung disease. It was all but inevitable, therefore, that nuclear generating plants would by and large be sited as conventional plants had been.

Barriers Within Barriers

Thus, during the early 1960s, Consolidated Edison, which traditionally had put its conventional plants close to New York City, proposed building an underground nuclear plant in the borough of Queens; the proposal was withdrawn only when it became clear that the U.S. Atomic Energy Commission would never license a plant in such a densely populated area.

How could nuclear engineers reconcile the intrinsic danger represented by 15 billion curies in the core of an operating reactor with the necessity of placing the reactor fairly close to population centers?

Several strategies evolved. First, reactors were not allowed *too* close to populated areas. The AEC (and now the Nuclear Regulatory Commission) required "exclusion" zones and close-in "controlled" zones around reactors. No one can live in an exclusion zone, which usually extends about one-half mile from the reactor site; the utility controls access to the controlled zone. Of the 90 or so nuclear sites now in operation or being built, only 13 have more than 25,000 people living within a five-mile radius, and only 10 have more than 100,000 within a ten-mile radius. To this extent, the original approach to nuclear safety has prevailed, although only a handful of commercial power plants are sited as remotely as are Hanford and Savannah River.

But this isolation was clearly not enough. Elaborate engineering devices were developed to place barriers between the environment and those 15 billion curies inside the reactor. The AEC used to speak of three approaches to safety: extremely careful design, to minimize the likelihood of a mishap in the first place; various systems, such as shut-off rods and sensors, to abort a mishap before it gets out of control; and back-up devices, such as the emergency core cooling system, to cool the reactor and prevent a meltdown should the regular system fail.

In addition, there are now at least three physical barriers at each reactor between the radioactivity and the world outside: metallic zirconium enveloping the fuel pellets in which the radioactivity is largely generated; the thick steel pressure vessel, along with the pipes that carry the primary cooling water at a pressure of about one ton per square inch; and the now-famous concrete-encased steel dome designed to withstand a pressure of 50 pounds per square inch without leaking. In the event of a core meltdown, should any one of these barriers remain unbreached, little radioactivity would reach the public.

How well had these systems worked before the accident at Three Mile Island, in March, 1979? Pretty much as planned, in American reactors. There were several major accidents, however, as well as many minor incidents:

¶ In 1961 a serious nuclear excursion, apparently initiated by deliberate removal of a control rod, killed three operators in a small experimental reactor in Idaho Falls, Idaho; some radioactivity escaped because this reactor, being located so far from people, had no containment shell.

¶ A loose piece of metal blocked the coolant and caused a partial meltdown at the Fermi fast breeder reactor plant outside Detroit in 1966; both primary system and containment held.

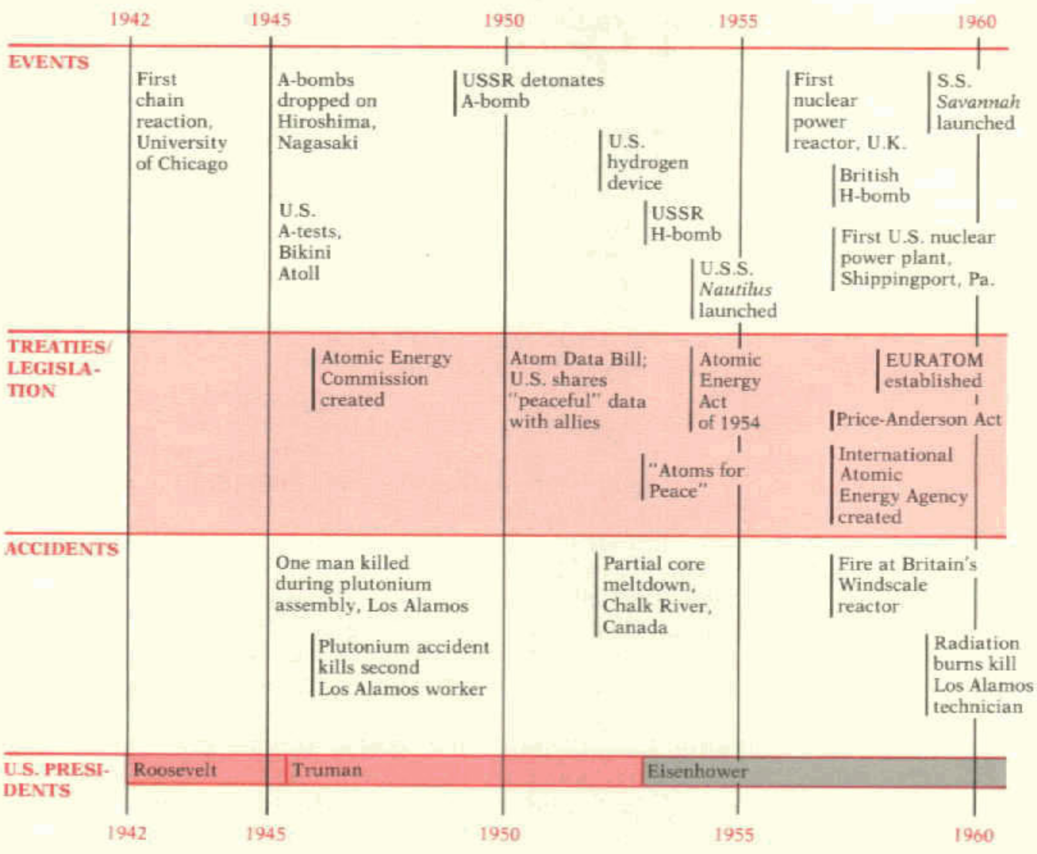
¶ At Browns Ferry, Alabama, in 1975, a fire disabled much of the emergency core cooling system, but enough remained to prevent a core meltdown; no radioactivity leaked to the atmosphere.

Outside the United States, the record, at least in the early days, was not as good. The worst incident was Britain's Windscale fire in 1957. A plutonium-producing reactor made of graphite caught fire; since the reactor was not surrounded by a containment vessel, some 20,000 curies of radioactive iodine were released, several thousand times as much as was released to the outside in the Three Mile Island accident (10–15 curies).

A properly operating reactor is generally a benign source of energy. It emits no carbon dioxide or sulfur dioxide or particulates. Its radioactive emissions during routine operation are rather less than those from a coal plant of the same output.* The main hazard comes from the 200 tons of uranium that is mined to keep it fueled each year. The mine tailings—leftover material after uranium ore is processed—contain about 1,000 curies, but they are usually stored in remote places and much of the

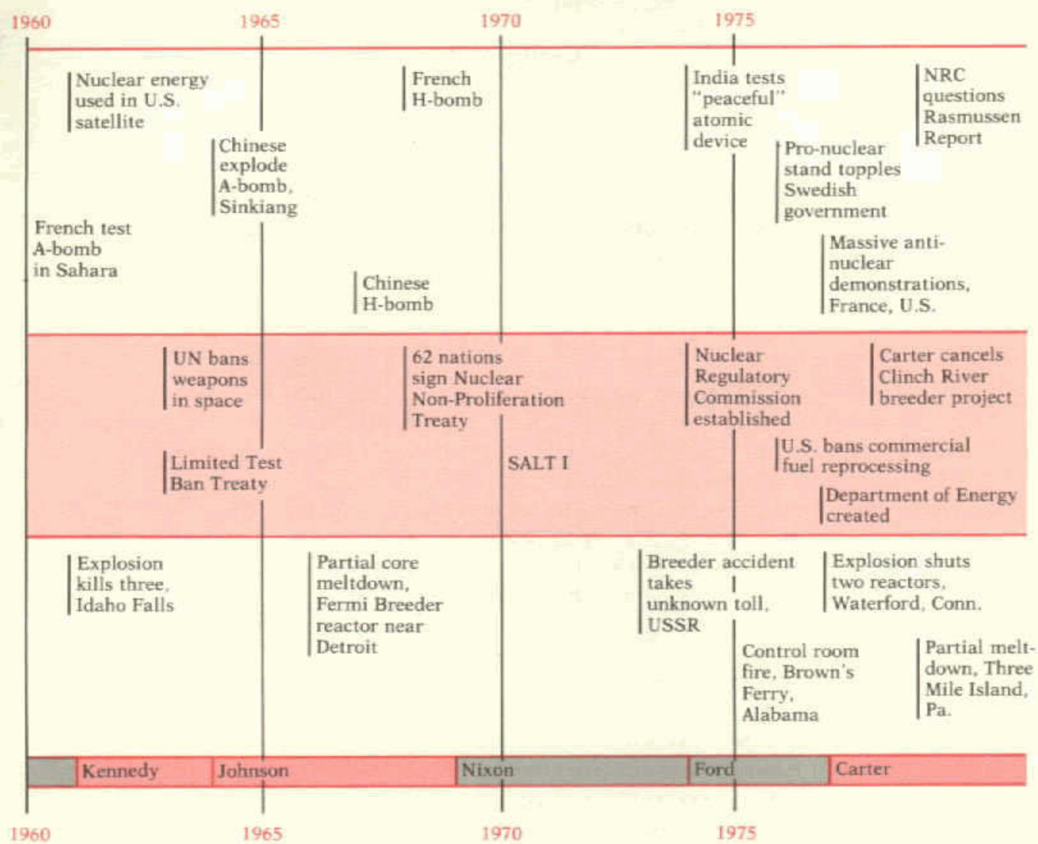
*A 1-million-kilowatt coal plant burns 2.5 million tons of coal per year. This coal may have some 10 tons of uranium in it, and this represents about 50 curies of radioactivity in the coal ash and in gases released in the air near the coal plant.

THE ATOMIC ERA: KEY EVENTS



radioactivity decays before it is dispersed. Covering the tailings with a foot of earth would reduce even these emissions.

Unlike many critics, I would put disposal of toxic radioactive wastes in the category of lesser problems. This is largely because the high level, potentially dangerous wastes occupy so little space (two cubic meters per reactor per year) and because, after about 1,000 years, the wastes are no more hazardous than the original uranium from which the wastes were formed. (This uranium is part of nature, and it seems unreasonable to require the sequestered wastes to be less hazardous than the original uranium.) To sequester wastes for 1,000 years simply does not



strike me as being beyond reason. After all, cave paintings by Cro-Magnon man have survived for 12,000 years. In Oklo, Gabon, there are ancient underground natural chain reactors that operated for 500,000 years: Many of the fission products and essentially all of the plutonium created in these remarkable phenomena have remained in place, unattended, for almost 2 billion years! Despite the great public concern and political passion generated over nuclear wastes, I view them as a nuisance for which there are many solutions.

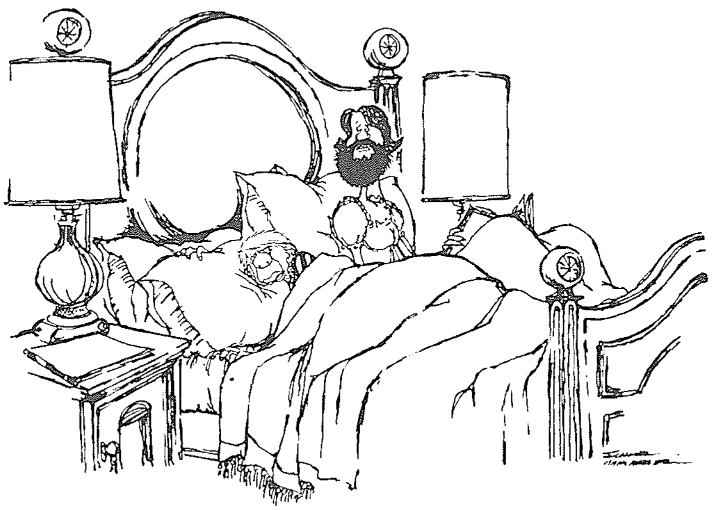
Nor do I consider nuclear proliferation, the issue on which so much discussion hinges today, the principal problem of nuclear energy. Most, if not all, of the world's atomic bombs have come from reactors built expressly to make bombs, not from power reactors. Should a country want to make bombs badly enough, it can do so without troubling to build or buy a commercial power reactor. Indeed, I believe nuclear power is rather peripheral to the proliferation issue; our attempts to devise technical fixes for that problem tend to be "allusive and sentimental" (to quote Robert Oppenheimer) rather than "substantive and functional." We can *not* prevent Pakistan or South Africa from making bombs if they are intent on so doing and if their leaders place the manufacture of bombs above other national aims.

The Probability Paradox

The 15 billion curies in an operating reactor, and the possibility of its release, has long struck me as the primary issue, the one on which nuclear energy will stand or fall. Since a serious reactor malfunction is a matter of probability, the issue becomes more and more important as more reactors are built. To illustrate: If the probability of a serious malfunction, in which significant amounts of radioactivity are released, is, say, 1 in 20,000 per reactor per year, then when there are 100 reactors operating, one might expect one such accident every 200 years; but if there are eventually throughout the world 10,000 reactors—as could happen were nuclear energy to become the world's primary energy source—then, unless the probability of an accident for *each* reactor is reduced, one could expect one such accident every two years.

I do not believe the public in the United States or elsewhere would retain much confidence in an energy system that caused even relatively modest radioactive contamination every two years. Nor does it make much difference where accidents happen: TV converts an accident anywhere into an accident everywhere. For nuclear energy to grow in usefulness, the accident probability *per reactor* will simply have to diminish; the public will have to be prepared to cope with the radiation risk such infrequent accidents might entail; and the media will have to deal with nuclear malfunctions in the same way it deals with other industrial accidents that have comparable impact on health.

Bo Lindstrom, the Swedish aeronautical engineer, pointed out some 20 years ago that air travel faced exactly this dilemma. He argued that if air travel continued to expand, and the accident rate *per passenger mile* held constant, then by around the



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"Relax Rosalynn . . . The Nuclear Regulatory Commission said it was safe to go into that plant. . . ." Bill Schorr's cartoon appeared shortly after President Carter and the First Lady toured Three Mile Island.

year 2000 there would be several serious accidents every day around the world. For the individual passenger, air travel would remain as good a risk in 2000 as it was in 1960. But, he argued, the public's *confidence* in air travel would collapse. Air transport has, of course, become much safer, per passenger mile, than it was at the time Lindstrom made his observations; and, I suppose, the public and the media have become somewhat inured to occasional air crashes. Both changes were necessary for air transport to survive.

What are the actual probabilities of malfunction in reactors? Before the Three Mile Island accident, all of us in the nuclear enterprise were fairly comfortable with the estimates made by Norman C. Rasmussen of M.I.T. in his famous 1975 study on the probabilities and consequences of a reactor accident.* He estimated that for a light-water reactor the probability of a core meltdown that would release at least a few thousand curies of radioactivity was 1 in 20,000 per reactor per year.

*United States Nuclear Regulatory Commission, Reactor Safety Study: *An Assessment of Risks in U.S. Commercial Nuclear Power Plants,* October 1975, WASH-1400 (NUREG-75/014).

Most of these incidents would not cause physical damage to the public. A few would, and a very few, estimated at one in a billion reactor years, might be a major catastrophe—3,300 immediate radiation deaths, 45,000 extra cancers, $17 billion in property damage.

Gripping Dramas

Rasmussen himself has set the uncertainty in his estimate of probability at about 10 either way (although the report puts the uncertainty at half this), his estimate of consequences perhaps at three. That is, the probability of an accident causing significant property damage might be as high as one in 2,000 per reactor per year; the probability of the very worst accident 1 in 100 million reactor years. A recent NRC review of the Rasmussen report led by University of California physicist Harold W. Lewis has set even greater uncertainties on the probabilities, although it generally praised Rasmussen's methodology.

Before Three Mile Island, I was comfortable with the record of nuclear energy. The non-communist world's light-water reactors had amassed 500 reactor years without a meltdown; if one added the U.S. nuclear navy's record, one could roughly triple this—no meltdowns in about 1,500 reactor years. Rasmussen's upper limit of meltdown, about 1 in 2,000 reactor years, was close to being vindicated.

Though I write this before all the returns are in, I believe it is fair to say that Three Mile Island suggests that the probability of accidents that release a few thousand curies may have been underestimated, not so much because of possible engineering deficiencies, but because of human error. Closure of two valves, thus incapacitating the auxiliary feedwater system, followed by various other malfunctions and operator errors, was not, as far as I can deduce, contemplated in the Rasmussen study.

Yet containment for the most part held. The iodine released was perhaps a dozen curies; the maximum total whole body exposure to any member of the public was probably less than what we used to accept *every day* as the allowable dose in the early days of the atomic energy project. No member of the public has suffered bodily harm from Three Mile Island.

Chauncey Starr, vice chairman of the Electric Power Research Institute (the research arm of the utilities), has estimated that an incident like Three Mile Island has a 50-50 chance of occurring every 400 reactor years. Can nuclear energy survive if such incidents have a 50 percent chance of happening that of-

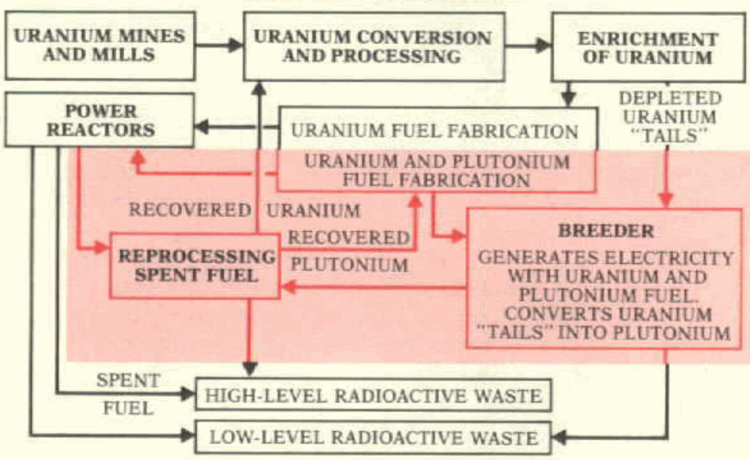
THE CHAIN REACTION

Uranium-235 undergoes fission when it is bombarded with neutrons. For nuclear energy to be possible, the same agent, the neutron, which splits the ^{235}U nucleus and releases energy, must itself be released during fission. In this way, a "chain" reaction can be propagated: A single ^{235}U nucleus splits and in splitting gives off roughly two neutrons; this in turn causes two other ^{235}U nuclei to split, four neutrons are given off; and so on.

In most reactors of current design, the ^{235}U is diluted with ^{238}U, just as it is in nature. Uranium-238 usually does not undergo fission but competes for neutrons with the ^{235}U. To establish a chain reaction in such a mixture, it is necessary to slow or "moderate" the neutrons. This is accomplished by mixing the uranium with a substance (e.g., water) containing "light" elements, such as hydrogen. The neutrons lose energy in colliding with protons, much as a billiard ball loses energy when it strikes another, stationary ball.

The ^{238}U, though it does not directly engage in the chain reaction, does absorb some of the neutrons given off in fission. Upon absorbing a neutron, ^{238}U is converted to plutonium-239. This isotope *can* support a chain reaction; ^{239}Pu was used as the bomb material at Alamogordo and at Nagasaki.

NUCLEAR FUELS CYCLE



Nuclear fission is the heart of the nuclear-fuel cycle; the unshaded area shows the other existing elements. Shaded areas show how fuel cycle would expand to accommodate fuel reprocessing and breeder reactors. Fear of nuclear proliferation prompted the Carter administration in 1977 to halt U.S. commercial fuel reprocessing and slow commercial breeder development.

ten? I do not think it can. It is not that people will actually be hurt; it is that people will be scared out of their wits. The drama of the hydrogen bubble in the pressure vessel at Three Mile Island has rarely been matched on TV. And with 200 reactors operating in the United States alone by the 1990s, one might expect a new, gripping TV serial once every few years.

Six Suggestions

Can the nuclear enterprise be redesigned so as to make it acceptable? Can the probability of an incident like Three Mile Island be significantly reduced? And is it likely that the public's (and the media's) reaction to future Three Mile Islands will be more commensurate with the actual damage rather than with their perception of the potential hazard?

In my view, all of this is possible. Indeed, Three Mile Island could be the salvation of nuclear energy. Before the incident, the possibility of a core meltdown was, by and large, the private knowledge of the nuclear and the antinuclear communities. Today, every newspaper reader and TV viewer knows about cooling systems and their malfunction. Best of all, the managers of the electric utilities that operate nuclear plants are now acutely aware that the responsibility entailed in operating a nuclear power plant is far greater than that entailed in operating a fossil-fuel plant.

But "consciousness raising" is not enough. I believe an acceptable nuclear future should have six characteristics: increased physical isolation of reactors, further technical improvements, separation of generation and distribution, professionalization of the nuclear cadre, heightened security, and public education about the hazards of radiation.

Physical isolation. It is unfortunately too late to return to the original siting policy that confined nuclear activities to very remote places. But we can achieve a good deal by confining the enterprise, forever, to those existing nuclear sites that have few people near them. About 80 nuclear sites (operating or being built) currently meet that criterion. Evacuation in an emergency would be relatively easy. More important, everyone living within five miles could be educated about radiation, and each household might be equipped with a radiation detector, much like smoke detectors.

Moreover, the size of the future population within five miles ought to be restricted. This could be accomplished if the area (75 square miles) around each site were properly zoned. If we eventually had 100 isolated nuclear sites in all, this would amount to

THE FEDERAL ROLE

At the end of World War II, the United States had a $2 billion atomic industry on its hands, with major laboratories, research reactors, and hundreds of scientists and other personnel. The question in Washington: What to do with it all?

One group, led by General Leslie Groves, head of the wartime Manhattan Project, sought to keep the atom under military supervision. Another, led by Connecticut's freshman Democratic Senator, Brien McMahon, pushed for civilian control. The latter prevailed with passage of the McMahon Act in 1946, which created the five-member Atomic Energy Commission (AEC). Congress charged the Commission (chaired by David E. Lilienthal, former head of the Tennessee Valley Authority) with both weapons development and research into possible peaceful applications of the atom.

Initially, the AEC's budget was modest. In 1952, for example, Congress gave the agency $753 million, of which only $67 million was for nuclear reactor development. More than $400 million was devoted to weapons and the manufacture of fissionable materials.

The Atomic Energy Act of 1954, passed by a Republican Congress in the wake of President Eisenhower's "Atoms for Peace" speech to the United Nations, was designed to turn nuclear energy over to private industry. It allowed electric utility companies to own and operate nuclear power plants (though none were yet in existence) subject to AEC licensing. The act prohibited the government from selling nuclear-generated electricity, but did not set out any master plan for siting and development of private power reactors. The utilities were given further incentives under the 1957 Price-Anderson Act, whereby the federal government itself insured nuclear utilities against damage claims. The first U.S. power reactor began operating that year in Shippingport, Pennsylvania. With massive government subsidies, the commercial nuclear industry began to thrive.

In 1974, the AEC was reorganized. Its watchdog functions passed to the new Nuclear Regulatory Commission, while its research arm became the Energy Research and Development Agency (ERDA). ERDA was absorbed by President Carter's new Department of Energy (DOE) in 1977.

The current (fiscal year 1979) DOE budget is $10.7 billion. As in the old AEC, a substantial portion of this total—about $2.5 billion—goes for defense-related activities. Research on nuclear power claims $1.1 billion. Other energy research categories: solar, $559 million; fusion, $356 million; coal, oil, and gas, $759 million. The department also spends $485 million annually on nuclear waste management. Most of this waste is generated by weapons programs, not by electric utilities.

committing 7,500 square miles to the enterprise in perpetuity. Only a small part of this area, perhaps 200 square miles, would be exclusively reserved for nuclear operations; the rest could be devoted to farming.

Since the number of sites is limited, the generating capacity of each will increase as the nuclear enterprise grows. Eventually each site may have as many as 10 reactors, compared to an average of less than 2 per site now. Such clustering ought to bring in its wake other improvements. Large sites are likely to have more able people in charge than are small sites. There will develop an organizational memory: Small mishaps on Unit 2 five years ago are not likely to be repeated on Unit 4 today. I speak of this from my experience at Oak Ridge, a large, powerful, nuclear center which has always had the logistical strength and organizational memory to contain the damage when accidents have happened.

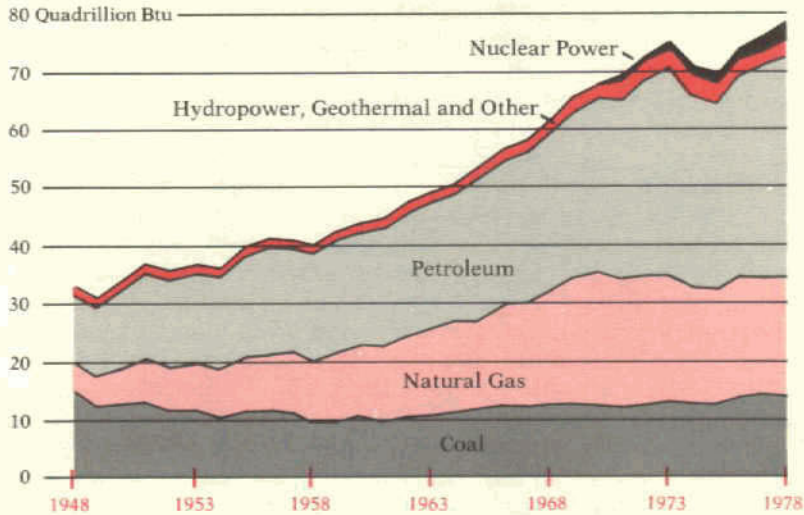
A Question of Nerve

The sites, like dams, also ought to be invested with an imputation of permanence. If one concedes that the sites are permanent, then one can simply leave the voluminous low-level radioactive wastes (as well as the old reactors) in place until their radioactivity has largely decayed. After 100 years or so, the bulk of the low-level wastes, as well as the old reactors, will be fairly innocuous. Dismantling old reactors after that should be relatively easy. During the decay period, the old reactor buildings might be used to store the other nuclear wastes. In an active, self-contained nuclear complex, maintenance should pose little difficulty.

Technical improvements. As Three Mile Island has shown, the nuclear establishment is still learning. Is it learning fast enough? Will improved back-up systems reduce the probability of failure faster than the number of reactors grows? Surely Three Mile Island will lead to corrections of certain faults in existing pressurized-water reactors. It will also lead to even tougher government regulations. This combination of tougher regulation and improved technology will certainly lessen the likelihood of future Three Mile Islands.

Beyond this is a more fundamental question: Are there types of reactors inherently safer than the common pressurized-water reactor (PWR)? After all, the PWR was conceived as a compact reactor capable of being stuffed into a submarine; its evolution into the mainstay of huge central nuclear power plants on land is still a source of wonder to its original

U.S. CONSUMPTION OF ENERGY FOR ALL PURPOSES



Source: Energy Information Administration, *Annual Report to Congress*, 1978, vol. 2.

Nuclear power currently provides only about 4 percent of total U.S. energy needs, far less than coal, natural gas, or oil. The nuclear share of U.S. electric generating capacity, however, is more than 10 percent, and rising. Americans today use twice as much total energy as they did in 1950.

designers. The British, without quite saying so, suggest that their large graphite reactors cooled with gas are less prone to mishaps than is the PWR.*

The Russians continue to build large graphite, water-cooled reactors, as well as reactors like that at Three Mile Island; the Canadians use heavy-water systems. I was a long-time proponent of a completely different reactor type that used fuel that was already in the liquid state, the molten-salt reactor. Is it impossible to return to Square One and try to design a reactor that is more resistant to the so-called China Syndrome? Does the technical community have the nerve, and do the other actors (utilities, government, manufacturers) have the money and the will to design and commercialize a completely new system? Perhaps when the furor over Three Mile Island subsides, we will embark on this uncertain, but possibly rewarding, new path.

*Three reactors other than PWRs are used commercially: *gas-cooled-graphite*, in which the uranium rods are embedded in a huge block of graphite and are cooled by flowing gas; *water-cooled-graphite*, in which water is used as coolant; and *heavy-water*, in which the graphite is replaced by a tank of heavy water—i.e., water in which the ordinary hydrogen is replaced by heavy hydrogen (deuterium).

Generation and Distribution. The nuclear system requires a powerful organization if it is to be operated properly. We have in this country about 200 electricity-generating utility companies. Nuclear electricity does not lend itself very well to such fragmentation, nor to small operators. A 1-million-kilowatt power plant often represents a large fraction of the total output of a smaller utility. Twenty-seven of the 41 "nuclear" utilities have but a single reactor. It seems to me that such small nuclear utilities are less likely to maintain the organizational strength and memory necessary to operate a nuclear reactor properly than is an organization that owns and operates many reactors.

If the siting policy that I espouse becomes a reality, it seems natural that the large, clustered sites will be operated by powerful organizations whose main job is operating nuclear facilities. Presumably, most of the sites would serve more than a single utility. Thus, one could envisage the gradual separation of generation from distribution of nuclear electricity, the former being in the hands of powerful organizations—public or private—that *do nothing but generate nuclear electricity.* Such nuclear generating entities would have the technical capacity to supervise every element of the design and construction of their plants. They would be much less at the mercy of the reactor and equipment suppliers than they now are.

Clearing the Brain

It is a delicate, and not very clear, question as to whether the operating consortia should be public or private, whether one would get better (and safer) operation from private organizations policed by the Nuclear Regulatory Commission or from a public Nuclear Energy Authority. There is an inherent tension between *safe as possible* and *cheap as possible.* The conflict manifests itself when a pilot decides to cancel a flight because the weather is bad, even though this costs his company money. Many would argue that a public operator is more likely to weigh his decisions on the side of safety. But public authorities seem to me to be harder to regulate than private ones.

After Three Mile Island, every nuclear utility, not to mention reactor manufacturer, must realize that its very existence may depend on avoiding incidents of this sort. This must be powerful medicine for clearing one's brain of a possible confusion as to which comes first, safety or continuity of electricity supply.

Professionalization of the nuclear cadre. The pilot of a transatlantic Boeing 747 is paid about $100,000 per year, perhaps 50 percent of what the president of his airline gets. The superintendent of a nuclear plant gets $40,000 per year, about 20 percent of what his president gets. The pilot and the operator bear a heavier burden of direct responsibility for people's lives than do their respective bosses. In the case of the pilots, this is more or less acknowledged in their pay; in the case of a plant superintendent, it is not. Why?

I believe the answer is to be found again in the mistaken belief among utility executives that a nuclear plant was just another generating station. The pay scales, indeed, the whole conception of training and expertise, tended to be strongly influenced by this perception. Moreover, a utility manager found it awkward to pay operators of one kind of plant much more than he paid operators of another.

But the responsibility borne by the nuclear operator is so great that he and his staff must be regarded—and trained—as an elite. They must constitute a cadre with tradition, competence, and confidence. Is it possible to get people of such quality for jobs that are essentially very boring? This is the same problem faced, say, by the pilots on the Eastern Airline shuttle between Washington and New York or by the anesthesiologist during a routine operation. We deal with this ennui with money, with status in the community, with shorter work schedules. This is the very least we can do with nuclear operators.

That is why I have so strongly urged cluster siting and separate generating entities: Both would be more conducive to creation of the professionalized corps necessary to keep the nuclear enterprise out of trouble. At a nuclear center, there will be *many* people to choose from when vacancies arise. There will be a general ambience of expertise. And an independent generating entity can pay its employees salaries that are not bound by the locked-in traditions of coal-fired utilities.

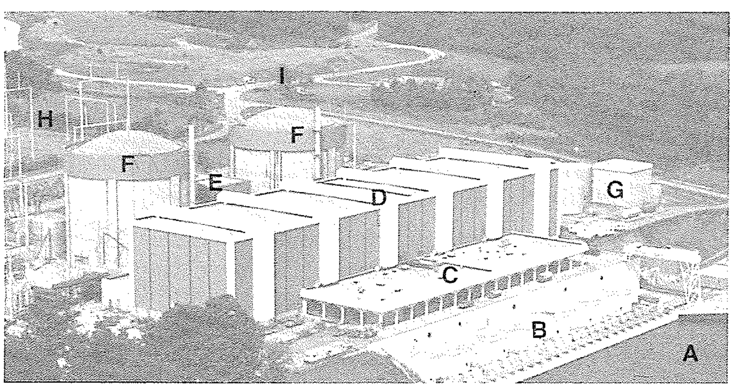
Heavy security. The nuclear enterprise will always demand far greater security than the fossil-fueled enterprise. Terrorists and saboteurs can merely incapacitate a fossil plant; in nuclear plants, they can, albeit with some difficulty, produce serious accidents. This is another reason why cluster siting is important. It is easier to guard 10 reactors on a single site than 10 reactors on separate sites.

Public education about radiation. None of the above measures will ensure the survival of nuclear energy unless the public and the media come to accept the risk of radiation as no different from the risk of other noxious substances that are products of our technology, particularly agents such as mercury or

CALVERT CLIFFS, A TYPICAL PLANT

The idea behind nuclear power—creating heat to boil water to make steam to drive turbines—is simple. But operating a commercial reactor is a complicated business. The Calvert Cliffs plant, comprising two pressurized-water reactors in Maryland on the Chesapeake Bay, is typical. Owned by the Baltimore Gas & Electric Company, it began operating in 1975; construction costs totaled $766 million. A profile:

Designer: Combustion Engineering, Inc.
Builder: Bechtel Power Corp.
Personnel: Over 200, including chief engineer, section engineers, nuclear plant operators, secretaries, guards.
Capacity: About 1,620 megawatts. Electricity produced in 1978 was the equivalent of 16 million barrels of oil.
Site: The plant itself covers 126 acres of a 1,135 acre tract. A high wire fence surrounds the entire property. Housing begins beyond the perimeter; 150,000 people live within 30 miles of the reactor.
Security: Number of guards not disclosed.
Environmental effects: As a coolant, the plant uses 2.4 million gallons of water from the Chesapeake Bay every minute; the water is returned to the bay 10 degrees warmer. According to a company statement: "The plant has no significant effect on the environment." According to a Nuclear Regulatory Commission statement: "Emphasis [at Calvert Cliffs] is upon commercial operation; attitude toward safety is that meeting N.R.C. requirements literally is sufficient."
Service Area: Calvert Cliffs serves 800,000 residential, industrial, and commercial customers in Baltimore and eight nearby counties.



(A) *Water intake basin;* (B) *pump house;* (C) *administration building;* (D) *turbine room;* (E) *control room;* (F) *reactor containment buildings, constructed to withstand earthquakes, tornadoes, and the direct impact of a 747 jetliner;* (G) *water tanks;* (H) *plant switchyard;* (I) *first security clearance checkpoint.*

polychlorinated biphenyls that persist and sometimes (as at Seveso, Italy) interdict land.

Why, after all, did Three Mile Island create such extreme concern, especially since not one member of the public has been harmed by it or, for that matter, by the operation of any other commercial nuclear reactor? Why was Three Mile Island the biggest story of the year when the collapse of the Grand Teton Dam in 1976, or even the collision of the jumbo jets in Tenerife in 1977, vanished from the front pages in a few days?

Invisible Hazard

I see several reasons for this seeming double standard. The potential for a disaster was there, though exactly how close we came will have to await the outcome of the current investigations. Since its dimensions could not be gauged and the whole situation was so completely novel, the crisis provided the classic ingredients of high media drama. The fear of possible radiation-induced death goes deep. Radiation *is* mysterious: It cannot be sensed, you can't see it, yet it can kill you.

The estimate of the hazard of radiation is clouded by bitter scientific dispute. In particular, there is the strongest kind of disagreement among scientists as to the effect of very low levels of radiation, even levels as low as our natural radiation background. Most of the estimated delayed cancer deaths associated with so-called hypothetical accidents are supposed to be caused by exposures well below the occupational limits. If one assumes that any extra radiation, however small, causes cancer, then if millions of people are exposed, some extra cancers will result. But if, as I believe, low-level radiation is nowhere near as dangerous as, for example, television newsmen seem to think, then the public's (and, perhaps more important, the media's) reaction to the possibility of such irradiation may be far more restrained.*

The whole question of low-level radiation is so critical to public acceptance of nuclear energy that I consider this a leading, if not *the* leading, scientific issue underlying the nuclear controversy. Unfortunately, since the effects (if any) are so rarely seen because the exposures are so small, the issue may be beyond the ability of science to decipher. Fortunately, we do have a standard—natural background radiation—with which to

*The controversy over low-level radiation is examined in *The Effects on Populations of Exposure to Low Levels of Ionizing Radiations,* the report of the Committee on the Biological Effects of Ionizing Radiations, National Academy of Sciences (1979). The committee divided sharply on the issue, a dissenting report is appended.

compare additional exposures. At Three Mile Island, the total dose to the population was about 1 percent of natural background—a level where no effects can be seen.

Unless changes are made that restore the public confidence, the Nuclear Age will come to a halt as the present reactors run their course. And we shall have to revert to the energy strategies that were available before fission was discovered. What are the alternatives to fission? Aside from conservation, which has its limits, there are only four: geothermal, fusion, fossil, and the various forms of solar energy.

The potential of geothermal energy—from natural steam or hot dry rocks—is relatively small; if we are to contemplate a world that has many more people, and that uses, say, three times as much energy as we now use, geothermal can hardly help.

Pricing a Moratorium

As for fusion, despite the optimism that prevails among scientists working in the field, it seems to me that the possibility still remains just that—a possibility. The fuel, deuterium and tritium (isotopes of hydrogen), is all but inexhaustible, yet the engineering remains formidable. Moreover, fusion is not devoid of radioactivity. To be sure, there is 100 times less in a fusion reactor than in a fission reactor. But, as Three Mile Island suggests, if fusion is to be acceptable, it too will require a public that understands the relative hazards of radioactivity. Thus, my view about fusion is agnostic—let's work on it, but let's not count on it.*

Fossil fuel is, of course, what we shall turn to in increasing amounts whether or not we have fission. But if we had a moratorium on new fission plants beginning in 1985, we might, in the United States, have to burn about a billion tons more of coal by the year 2000 than if we had no such moratorium. And as for oil, the political pressures might become quite intolerable should our need for the world's oil increase drastically.

Nor is fossil fuel a benign source of energy. Even a *properly operating* coal plant emits noxious fumes. The dangers from burning fossil fuels are undramatic—deaths from coal mine accidents, black lung disease among miners, bronchial troubles downwind of a coal-burning plant. By contrast, the dangers of a nuclear plant are localized and dramatic, even though, as Three Mile Island has shown, a nuclear plant can suffer an extraordi-

*For a comprehensive overview of fusion, and the obstacles it faces, see David A. Dingee's "Fusion Power," in *Chemical & Engineering News*, April 2, 1979.

nary amount of damage without anyone being hurt. Fossil fuels also pose a large-scale worldwide threat comparable to that of proliferation. I refer to the accumulation of carbon dioxide (CO_2) in the atmosphere. Most climatologists (though not all) believe that doubling the CO_2 may increase the average surface temperature of the earth by about 2°C, and would diminish the equatorial-polar temperature gradient, which drives the wind system, by about 10°C.

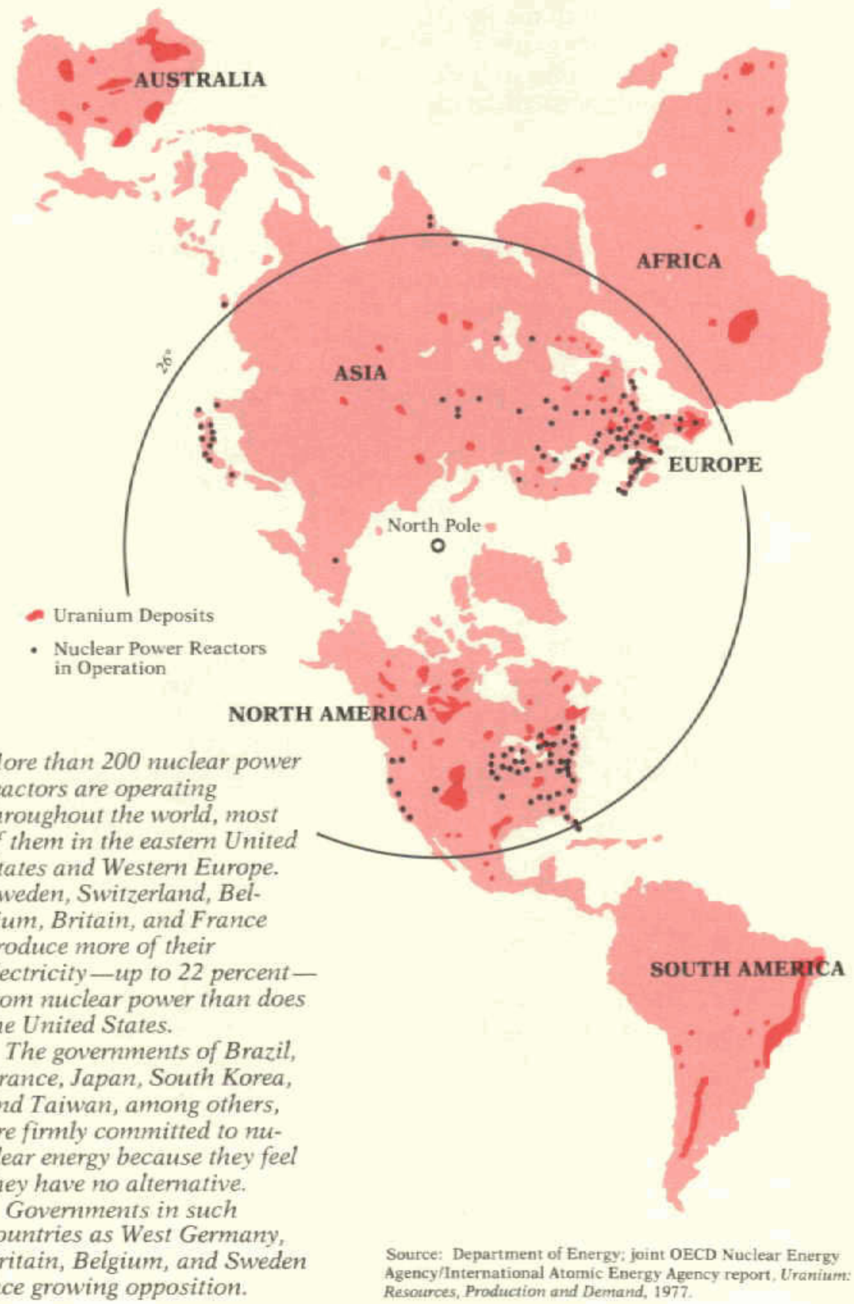
Not all the ensuing changes need be bad. But the doubling of CO_2 in the atmosphere, which could happen by, say, the year 2050, represents an unprecedented climatological experiment by man. It might cause the seas to rise, turn deserts into grasslands, grasslands into deserts. If this is a real possibility, then would continued burning of fossil fuel be a responsible course, even if fossil fuels were inexhaustible (which they aren't)?

Which leaves us with solar energy, including hydro, wind, waves, biomass, and ocean thermal gradients as well as direct solar. Solar energy is immense, environmentally benign, the darling of the people (no one is against solar energy). But it is also intermittent and, insofar as one can tell, expensive. If what we contemplate is an all-solar world, not one in which small household solar water heaters are backed up by electricity from the local utility, then we must come to terms with the intermittency of solar energy. Either we adjust our lives to a sun that does not always shine, or else we arrange for storage—perhaps with auxiliary engines operated on alcohol, or electric batteries, or perhaps by hydrogen-generated photoelectrically. Overcoming intermittency seems to be very expensive, though how expensive I cannot say. What seems clear is that an all-solar society is almost surely a low-energy society, and one in which energy will be a good deal costlier than it is now.

The Faustian Bargain

To my mind, the only alternative (or perhaps adjunct) to a solar society is the one based on fission—at least if one concedes that fossil fuels are limited, or that the CO_2 danger must be taken seriously, or that fusion will forever evade us. But such a fission future might involve several thousand U.S. reactors, and one must then come to terms with the problem I alluded to earlier: Even though the probability per reactor of a serious accident is small, when the system becomes large the number of accidents may become too frequent for the public to tolerate.

Thus, if a solar society can be made to work, by all means let us work hard to achieve it. I favor pushing solar technology as



More than 200 nuclear power reactors are operating throughout the world, most of them in the eastern United States and Western Europe. Sweden, Switzerland, Belgium, Britain, and France produce more of their electricity—up to 22 percent—from nuclear power than does the United States.

The governments of Brazil, France, Japan, South Korea, and Taiwan, among others, are firmly committed to nuclear energy because they feel they have no alternative.

Governments in such countries as West Germany, Britain, Belgium, and Sweden face growing opposition.

Source: Department of Energy; joint OECD Nuclear Energy Agency/International Atomic Energy Agency report, *Uranium: Resources, Production and Demand*, 1977.

hard as we can. But let us not mislead ourselves. Solar cannot take over very much of the load for a long time, if ever; and a solar society will not be the utopia many advocates perceive it to be, even if some very major improvements in energy storage and photoelectric conversion are achieved.

But suppose we do not achieve these technological breakthroughs, can we put a price on solar energy at which we would prefer it over nuclear because nuclear is handicapped by its radioactivity? There are many who would abolish nuclear in favor of solar *whatever* the cost. This I cannot view as a rational response. But neither can I say how much extra one should pay for solar to avoid the disadvantages of nuclear. And it is not impossible that the price one must pay for an acceptable nuclear system—with its better technology, higher-paid personnel, and tighter security—conceivably could price nuclear out of the market.

About eight years have passed since I first referred to nuclear energy as a Faustian Bargain. I have since been corrected both by nuclear advocates (who prefer Prometheus to Faust) and by scholars (who say that Goethe's Faust didn't really make a bargain at all). Nevertheless, what I meant was clear: nuclear energy, that miraculous and quite unsuspected source of energy, demands an unprecedented degree of expertise, attention to detail, and social stability. In return, man has, in the breeder reactor, an inexhaustible energy source.*

Three Mile Island has undoubtedly turned many away from nuclear energy, has reinforced their belief that nuclear energy is simply too hazardous. Three Mile Island for me has a rather different significance. I have often said that Goethe's Faust was redeemed:

> 'Who e'er aspiring, struggles on,
> For him there is salvation.'

and that man, in his striving, will finally master this complex and unforgiving technology.

My antinuclear colleagues retort that this is foolish technological optimism—that man is imperfect, and that anything that

*A breeder, which creates more nuclear fuel than it consumes, requires only 1/60th as much uranium as do present-day "burner" (e.g., pressurized-water) reactors. Unless we are badly underestimating our uranium reserves, Phase I, the age of burners, will necessarily be transitory. Phase II will rely on breeders. The Carter administration supports development of an advanced, sodium-cooled breeder, but it is strongly opposed to completion of the Clinch River Breeder, a sodium-cooled pilot plant that was to be built in Oak Ridge, Tennessee. As of this writing, Congress continues to fund the project despite administration attempts to kill it.

can go wrong will go wrong. But man is also ingenious, and the history of the two worst American reactor accidents—Browns Ferry and Three Mile Island—demonstrates this. In both cases, the accident was precipitated, or at least exacerbated, by human error: a lighted candle at Browns Ferry, closed valves at Three Mile Island. In both cases, the operators used their ingenuity to contain a nasty situation. And in *neither* case was anyone harmed by excess radioactivity. It is their cynical denial of human ingenuity and uncompromising acceptance of human fallibility that is the main weakness of the more strident nuclear opponents.

I am not an uncritical advocate of nuclear energy. I believe the enterprise needs fixing if it is to survive. Nor can the nuclear enterprise wait too long before its managers demonstrate to the public that they recognize this fact. I hope those of us who believe that nuclear energy cannot be lightly cast aside will do more than simply restate our faith in the technology. We must come up with positive and convincing initiatives that prove to the public that the lessons of Three Mile Island have been learned. To do less will commit us to energy options whose inherent difficulties, though not as dramatic as those of nuclear energy, could in the long run be even more serious.