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AUTHOR Hayes, Denis
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ABSTRACT

This publication is the sixth in a series of papers on global environmental issues. This paper evaluates the future of nuclear power, subjecting it to several tests: (1) economics; (2) safety; (3) adequacy of fuel supplies; (4) environmental impact; and (5) both national and international security. Section headings include: (1) The nuclear fuel cycle; (2) Nuclear economics; (3) Uranium supplies; (4) Safety; (5) Environmental impact; (6) Energy independence; (7) Nuclear terrorism; and (8) Nuclear power and society. This paper suggests that nuclear power may not only be unsafe but uneconomical. Among other examples are several cases of near catastrophic nuclear accidents of which the public was told nothing until the crictical periods had passed. (MR)

This paper is adapted from the author's forthcoming book, *Rays of Hope: The Transition to a Post-Petroleum World* (W. W. Norton, 1977). It may be partially reproduced with acknowledgement to Worldwatch Institute.

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"Nuclear Power: The Fifth Horseman," by Denis Hayes, is the sixth in a series of papers published by Worldwatch Institute in an attempt to identify and analyze emerging global trends and problems. Previous papers in the series are listed inside the back cover.

This paper evaluates the future of nuclear power, subjecting it to several tests—those of economics, safety, adequacy of fuel supplies, environmental impact, and both national and international security. If the world is to "go nuclear," adopting nuclear power as the principal source of energy, each of these criteria should be satisfied. In fact, none may be satisfied.

Nuclear power is being re-examined in many quarters. Local communities throughout the world are concerned over reactor safety. Environmentalists and others are deeply concerned about the lack, or even the prospect, of satisfactory techniques for disposing of radioactive waste. Foreign policy analysts express grave concern over the weapons-proliferation implications of the spread of nuclear power, recognizing that sooner or later an unstable political leader or terrorist group will acquire this awesome weaponry. And, perhaps most damning of all, in 1975 the corporate executives who head electrical utilities in the United States cancelled or deferred 25 times as many new reactors as they ordered. A leading nuclear executive recently described his industry as being sick. The prognosis may be even more serious.

Much of this paper will appear in a forthcoming book, *Rays of Hope: The Transition to a Post-Petroleum World* by Denis Hayes (W. W. Norton, 1977), that examines energy options.

Lester R. Brown
President, Worldwatch Institute

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Arguments against nuclear power are rooted in a simple paradox. Commercial nuclear power is viable only under social conditions of absolute stability and predictability. Yet the mere existence of fissile materials undermines the security that nuclear technology requires.

A commitment to nuclear fission is uncompromising and unending. This power source cannot brook natural disasters or serious mechanical failures, human mistakes or willful malevolence. It demands an unprecedented vigilance of our social institutions and demands it for a quarter million years. At the same time, the use of commercial nuclear power dramatically increases the fragility of human civilization. Acceptance of nuclear technology amounts to acceptance of the inevitable spread of nuclear weapons from nation to nation, and the near-certainty that some nuclear bombs will end up in terrorist hands. The debate is not whether nuclear power will lead to nuclear weapons; that is beyond question. What is unknown is who will control these bombs, how they will be used, and what their use will portend for even the most stable institutions.

The weapons proliferation question ranks above all others. But a swarm of auxillary problems, many of which have received more scrutiny in some countries than in others, deserves attention. If the world is indeed to "go nuclear," all will be legitimate matters of international concern. The entire case against commercial nuclear power deserves broad public scrutiny *before* we become irreversibly committed to a nuclear future.

In the mid-fifties, the United States, the Soviet Union, Britain, and France all began operating nuclear reactors to generate electricity. The Federal Republic of Germany began reactor operations in 1960, Canada and Italy joined the club in 1962, and Japan and Sweden followed in 1963. In the late fifties or early sixties, the People's Republic of China began limited weapons-related reactor operations, exploding its first nuclear bomb in 1964.[1]

By 1970, the list of commercial nuclear nations had lengthened to include Switzerland, the German Democratic Republic, the Netherlands, Spain, Belgium, and India. Since then, Pakistan, Taiwan, Czechoslovakia, Argentina, and Bulgaria have become nuclear powers, bringing the total to twenty-one. Nuclear power now accounts for 17 percent of all electricity used in Switzerland, 15 percent in Belgium, 10 percent in Britain, 9.6 percent in Taiwan, and about 8 percent in the United States.

At the end of 1975, commercial reactors totaled 158 worldwide with a combined capacity of 66,995 megawatts of electricity—up tenfold in 10 years. Planned additions would quickly multiply that capacity another eightfold to 526,822 megawatts, derived from 660 reactors. Commercial nuclear power plants are currently under construction in Austria, Brazil, Finland, South Korea, and Yugoslavia. Australia, Denmark, Egypt, Hungary, Iran, Israel, Mexico, the Philippines, Poland, Romania, South Africa, and Thailand are actively courting the idea of going nuclear. By the end of the century, 40 or more countries could have a combined generating capacity of more than two million megawatts.[2]

Global nuclear development was initially spurred by the belief that fission would provide a cheap, clean, safe source of power for rich and poor alike. However, the dream of "electricity too cheap to meter" has foundered under a heavy burden of technical, economic, and moral problems—some of which appear to be inherently unsolvable. A growing body of analysis suggests that the total costs of nuclear power far outweigh the total benefits.

In much of the western world, the future of "the peaceful atom" has grown cloudy. In the spring of 1973, the Swedish Parliament called a halt to nuclear power development while the government initiated a public education program around the motto "learn more and you will influence more." Public opinion polls over the next two years showed a steady erosion of support for nuclear power, and, by the time of the final governmental decision on May 29, 1975, a majority of Swedes opposed the construction of more reactors. A parliamentary coalition voted to limit future nuclear construction to two reactors beyond those already planned at the time of the moratorium.[3]

Annual United States reactor orders, which reached a peak of 36 in 1973, declined to 27 in 1974, and plummeted to 4 in 1975. Cancella-

"Global nuclear development was initially spurred by the belief that fission would provide a cheap, clean, safe source of power for rich and poor alike."

tions and deferrals outpaced new reactor orders in the U.S. by more than 25 to one in 1975. Even as numerous states debate nuclear moratoria and other restraints, a *de facto* national moratorium appears to be developing.

Nuclear development in Japan has been snagged by a series of lawsuits and by widespread protest rallies. The government, worried about the nation's heavy reliance on foreign oil and coal, desires to implement a program of rapid nuclear development. But nuclear opposition in Japan traces back to Hiroshima and Nagasaki, and to years of street demonstrations protesting the arrival of U.S. nuclear-powered naval vessels. Japan's first nuclear-driven ship, the Mutsu, developed a widely-publicized radiation leak during a trial run in September of 1974. The vessel was forced to remain at sea for seven weeks before its home port would allow it to be towed in. For more than a year, no ship-building community was willing to undertake the needed repairs. An offer by the port city of Sasebo in early 1976 provoked protests by the Harbor Workers Union, the Sasebo City Employees Union, the Fisheries Federation, and 11 other organizations. The Struggle Committee Against the Mutsu has recently announced plans for a sea blockade to prevent the ship from entering the port.

In early 1975, twenty thousand people from the Baden-Württemberg area of West Germany staged a prolonged sit-in protesting a proposed 2700-megawatt complex in Wyhl. More than 8000 Swiss citizens participated in a similar sit-in protesting a planned 932-megawatt reactor near Basel.

In May of 1975, a convocation of nuclear opponents was held in Canberra, the Australian capital. The critics (who all arrived on bicycles) pitched a tent city, sang protest songs, created a street theater, and boiled a symbolic pot of tea on a solar cooker in front of Hifar, the country's only nuclear reactor. A coalition of trade unions, environmental groups, and peace organizations subsequently asked the Australian government to establish nuclear-free zones in the South Pacific, the Indian Ocean, and Antarctica.

The Canadian government continues to laud the virtues of its CANDU reactor, but the Canadian Coalition for Nuclear Responsibility has begun mobilizing public opposition. Partly because India constructed a nuclear explosive out of material from a Canadiansupplied reactor, Canada's anti-nuclear forces have grown rapidly during the past two years.

Early in 1975, more than 400 French scientists signed a manifesto protesting the 50 nuclear power plants France then planned to build.
10 In the spring of the same year, *L'Express*, a weekly French news magazine, drew 25,000 responses to a printed questionnaire on nuclear power. Eighty percent of those responding felt that terrorists would have little trouble obtaining bomb-grade materials; 72 percent feared for the environment; and only 25 percent felt that current security precautions were sufficient. That fall French President Valéry Giscard d'Estaing announced that the French domestic reactor program would be reduced, while new emphasis would be placed on exporting nuclear technology.

This French shift has been mirrored in the other nuclear nations. As nuclear interest has ebbed in the developed world, reactor vendors have turned to less industrialized countries. For most poor nations, a capital-intensive, highly centralized, and technically complicated source of electricity is a tragically inappropriate investment. But the nuclear vendors, and their home governments, which often guarantee attractive financing, are not primarily concerned with optimizing the use of the world's capital. They seek, rather, to recoup their own multi-billion dollar research investments and to improve their balance-of-trade positions. Hence fierce competition has evolved for the nuclear market provided by the developing nations. The long-term consequences of this sales race may be catastrophic.[4]

Early nuclear critics tended to be gadflies, pointing out flaws in reactor designs and calling for immediate remedies. With the passage of years, many of these reformers became outright opponents, convinced that the problems with nuclear technology were so intractable that commercial fission should be bypassed as a major energy source. In early 1976, three high-level officials resigned from the U.S. General Electric Company in order to work full-time on behalf of the Nuclear Safeguards Initiative in California. Anti-nuclear sentiment is now coalescing into an international movement with a rapidly growing base of political support.

The Nuclear Fuel Cycle

Although the nuclear reactor has been the focus of most of the nuclear controversy to date, it is but one component in the nuclear fuel cycle.[5] Fuel is mined, milled, enriched, fabricated into fuel elements, used in a reactor, and reprocessed to recover valuable materials. Then the radioactive wastes must be contained—some of them for hundreds of thousands of years. Risks surround every step.

Uranium miners are exposed to radiation, particularly in accumulations of radon gas. This has led to hundreds of serious health problems, and such problems will increase substantially as the volume of mined uranium grows, and as more inaccessible deposits are worked.[6]

The milling process (which isolates the four pounds or less of uranium oxide in each ton of ore) produces residues called tailings that contain radium. In the past, these radioactive tailings have contaminated drinking water and have been used to construct buildings. In Grand Junction, Colorado, homes and schools were built of tailings, and were inhabited for years before their radiation levels were recognized as dangerous.[7]

Fuel enrichment poses another set of problems. The most common reactors—light water reactors—require "enriched" uranium, fuel that is 3 to 4 percent U-235. Yet the few pounds of uranium in each ton of ore contain only 0.7 percent fissionable U-235. Further, this isotope is chemically identical to the far more common form, U-238, and cannot be separated by simple chemical reactions. Elaborate physical enrichment processes that can distinguish between atoms on the basis of weight are needed to separate U-238 atoms, which constitute 99.3 percent of all natural uranium, from the infinitesimally lighter U-235 atoms.[8]

For the past two decades the United States has dominated the world market for enriched uranium, with production from three large gaseous diffusion plants at Oak Ridge, Tennessee; Paducah, Kentucky; and Portsmouth, Ohio. But now numerous other countries are experimenting with several new enrichment technologies. Four general enrichment processes are in differing stages of development: gaseous diffusion, centrifuge, nozzle, and laser.

Gaseous diffusion is the process with which the nuclear industry has had the most extensive experience. Though this process has a long, successful history, beginning with weapons production, it is slow, energy-intensive, and extremely expensive. The two other mechanical enrichment processes, centrifuge and nozzle enrichment, offer the advantages, respectively, of much reduced energy requirements and greater simplicity of design. The important breakthrough in enrichment processes, however, lies in the comparatively new, still developing, laser enrichment process. Its promise of low cost, low energy requirements and compactness could make even weapons-grade material available to almost any government or technically competent organization.[9]

Once uranium has been sufficiently enriched by one of these four processes, it is sent to a fabrication plant. There it is shaped into small ceramic pellets that are sealed in metallic fuel rods. When uranium is enriched only 3 or 4 percent, diversion of this fissile material from enrichment facilities or fabrication plants presents little problem. However, High Temperature Gas-cooled Reactors (HTGR's) are fueled by more highly-enriched, dangerous, bomb-grade materials. Even in the much more common light water reactors, small numbers of fuel rods containing bomb-grade uranium are sometimes used in combination with a much larger number of rods with unenriched fuel to provide an overall fuel enrichment of about 3 percent.[10]

Nuclear reactors, the most complicated and expensive means of boiling water yet devised, are the center of the next stage in the nuclear fuel cycle. Steam from the reactor-heated water is used to turn generators and to produce electrical power. (Nuclear power plants differ from oil and coal-fired power plants only in that they heat water with energy obtained by splitting atoms of a fissile fuel rather than by burning fossil fuel.)[11]

A reactor designed to produce more plutonium-239 (or other fissile fuel) through neutron capture than it consumes through splitting is called a "breeder." One that consumes more fissile fuel than it produces is often called a "burner."[12]

Seventy percent of all planned burner reactors around the world are light water reactors (LWR's). Currently LWR's comprise 55 of the 56 operating commercial reactors in the U.S. and 59 of the 67 thousand megawatts of commercial nuclear capacity in the world. The water that circulates through the core of an LWR serves two functions: moderating and cooling. First, it moderates the free neutrons, slowing them down to energy levels that permit them to split other fissionable atoms easily, thus sustaining the chain reaction. Second, it transfers heat away from the core to where it is harnessed to generate electricity.[13]

Should this moderating water escape, a "LOCA" (loss of coolant accident)—the worst reactor accident most experts consider credible—might occur. With a loss of the moderating water, the nuclear reaction would automatically stop. However, the residual radioactive wastes in the core would continue to decay, and would quickly reach temperatures sufficient to melt the core. The melting core could destroy the reactor's containment vessel in any number of ways, and the spreading radioactivity would render the surrounding countryside a wasteland.[14]

Heavy water reactors (HWR's), like other burner reactors, consume more fuel than they produce. HWR's are moderated by heavy water and cooled by heavy water, ordinary water, or gas.[15]

Unlike LWR's, which require enriched uranium, HWR's can operate on natural uranium. In practice, however, many such reactors use at least slightly enriched uranium, which allows more design leeway. Perhaps the best-known heavy water reactors are the CANDU models manufactured in Canada, though West Germany and Sweden have also developed HWR's. The British government decided in 1975, after seven years of successful operation of a 100-megawatt prototype, to invest in a commercial heavy water reactor it calls the "steamer."

Gas cooled reactors (GCR's) are cooled by gas and moderated by graphite that, like heavy water, absorbs fewer neutrons than ordinary water. Hence these reactors too can be fueled with unenriched uranium. Gas-cooled reactors are also able to operate at much higher temperatures than water-cooled reactors, and, consequently, can convert heat into electricity more efficiently. England and France pioneered GCR's prior to building uranium enrichment facilities, and England is now constructing five advanced gas-cooled reactors with a total capacity of 6000 megawatts.

The leading breeder reactor candidate is the liquid metal fast breeder reactor (LMFBR), but work is also being done on gas-cooled breeders, light water breeders, and molten salt breeders. LMFBR's are cooled by liquid sodium. Since these reactors operate at a higher temperature than light water reactors, they can obtain higher thermal efficiencies. A French prototype operates at 43 percent efficiency, as opposed to the 33 percent efficiency of LWR's. No commercial LMFBR's are operating at present, but experimental and pilot units (with such interesting names as Rhapsodie Fortissimo, Phenix, and SNEAK) have been built by several countries, including England, France, the Soviet Union, and Germany.

The Phenix 250-megawatt prototype reactor near Marcoule in southern France, the most successful LMFBR to date, has produced full power 50 percent of the time. Its viability has encouraged the French to attempt a 1200-megawatt "Superphenix," which is scheduled to begin operation in the early 1980s. A somewhat more advanced reactor than the Phenix, the British 250-megawatt Prototype Fast Reactor at Dounreay, Scotland, will reach full power production in the spring of 1976. It succeeds the longest-running fast breeder in the world, a 14-megawatt fast reactor called the Dounreay Fast Reactor that has been in operation since 1959. In the early 1990s it will be superseded by a 1300-megawatt plant.[16]

Though reports of a major 1973 reactor explosion appear to have been exaggerations inspired by the flaring of a large amount of hydrogen gas, the Soviet Union's 350-megawatt breeder at the new city of Shevchenko on the Caspian Sea has been plagued with difficulties, mostly centering around pipe leaks. The Soviets are also constructing a 600-megawatt demonstration plant at Beloyarsk.

The United States trails Europe in prototype breeder development, despite an early U.S. lead in breeder technology. With comparatively large uranium reserves and three enrichment facilities, the U.S. has felt less pressure to rush the breeder than some other countries, and has concentrated its efforts on component testing. Nevertheless, work is now underway on a 350-megawatt prototype LMFBR on the Clinch River in Tennessee.

The "doubling time"—the amount of time needed for a reactor to accumulate twice as much fissile fuel as its initial inventory contained—is a critically important aspect of breeder development. Doubling times now vary from 50 years for the Phenix to around 30 years at Dounreay, while commercial breeder manufacturers have a 12-year doubling time as their goal. The more rapid the doubling time, the larger the amount of useless U-238 the breeder will convert into valuable plutonium-239 during a given operating period. Because the breeder converts a large amount of otherwise valueless material into fuel, it in effect increases the size of the uranium resource base: more energy is obtained per unit of fuel mined, and lower grades of fuel can be economically mined. If nuclear fission is viewed simply as a stopgap or supplementary power source, our meager known resource base of fissile fuels may be adequate and the breeder may be justifiably characterized as an expensive extravagance. If, on the other hand, nuclear fission were to become a long-term, significant energy option, breeder reactors—with all their attendant problems—would have to play a crucially important role.

All of these reactor types share the same purpose: to harness the heat from nuclear fission to generate electricity. However, each has peculiar advantages and disadvantages. Thus, a country intent upon pursuing a nuclear future can reasonably choose from among different reactor types, according to its perceived needs. It also chooses from among different risks.

Accidents capable of rupturing a reactor's containment structures are probably the primary dangers associated with nuclear power plants. Reactors are being designed to meet increasingly rigorous specifications and to include redundant safety systems, but the chance of a meltdown or other serious accident cannot be entirely eliminated. These less than foolproof machines will be constructed and operated by fallible beings too (15 percent of all abnormal nuclear occurrences in the U.S. are due to operator error). Moreover, nuclear power plants offer tempting targets to saboteurs.

After about three years, fission products build up in reactors to the point where they "poison" the fuel rods, absorbing neutrons and making the chain reaction difficult to sustain. The fuel from both burner and breeder reactors is then removed and stored under 50 feet of water at the reactor site until some of the most intense radioactivity dissipates. Then it is sent on to reprocessing plants where valuable materials like plutonium and unspent uranium are separated from radioactive wastes.

Reprocessing plants have in the past been major sources of radioactive emissions, and existing facilities are dwarfed by the reprocessing plants now being planned. All the krypton-85 and tritium contained in used fuel rods is routinely released into the environment, as are small amounts of strontium-90 and radioactive iodine. Unless 16 successfully controlled, the quantities of these materials released could eventually constitute a significant danger. Reprocessing plants also represent another attractive source of fissile materials for terrorist bombs, and they provide the primary sources of potential weapons materials for non-nuclear nations as well.

Since fuel reprocessing involves the separation of chemically different elements, the technology involved is much simpler than that for uranium enrichment. All the information needed to construct a reprocessing facility is a matter of public record. This is not to imply that building such a facility would be easy—only that any determined country, or even a large, technically competent, well-to-do organization would not find the task impossible. India built the reprocessing facility that isolated the materials for her bomb without outside help.

Reprocessing facilities reach commercial viability only when they are large enough to accommodate more than a dozen large reactors. Since few developing countries will have that level of electrical demand for quite some time, some nuclear strategists have suggested that all reprocessing be done in countries that already have nuclear weapons, or that reprocessing be handled in regional centers under international safeguards. Neither of these suggestions has thus far proven attractive to most non-nuclear weapons states, and France and Germany have recently sold reprocessing equipment to South Korea and Brazil, respectively (though Korea, under great pressure from the United States, subsequently withdrew from the contract).

While many countries—including Argentina, Iran, Pakistan, and South Africa—desire reprocessing facilities, some countries that already have them appear to be having second thoughts. The United States has three commercial reprocessing plants, none of them working. A facility in West Valley, New York, has been shut down for years due to excessive radioactive emissions. A $64 million General Electric plant at Morris, Illinois, has never operated; modifications to render it operable would at least double its cost, and indications are that G.E. will abandon its investment. A new facility at Barnwell, South Carolina, has suffered repeated challenges from activist groups seeking to bar its opening.

Another factor that has given pause to nuclear nations is the severe occupational threat to health in reprocessing facilities. At the facility in West Valley, New York, 39 workers inhaled plutonium and other fission products in 14 separate incidents—in which doses ranged up to 40 times the maximum permissible lung burden. At the Windscale facility in Britain, 33 workers suffered ruthenium poisoning.[17] 17

Finally, the economics of fuel reprocessing must be taken into account. For instance, the U.S. Nuclear Regulatory Commission has not yet decided whether it will allow plutonium to be recycled as a reactor fuel—a decision that will have enormous implications for the financial aspects of reprocessing operations.[18]

A major expansion of the Windscale reprocessing facility on the Cumbrian coast raises yet another question—that of nuclear waste. The British facility, which produces five cubic meters of liquid waste for every ton of fuel reprocessed, expects to reprocess more than 70,000 tons of nuclear fuel before the end of the century. One-third of this fuel will be earmarked for foreign customers. Prominent among present British customers are the Japanese, who will not have their own full-scale reprocessing facilities in operation before 1985. A front-page headline article in London's October 21, 1975, *Daily Mirror*, "Plan to Make Britain World Nuclear Dustbin," ignited a debate in England over acceptance of other nation's nuclear waste. British Energy Secretary Wedgwood Benn congratulated the *Mirror* "for sparking a public debate on Britain's nuclear dustbin problems." Benn noted that "this debate is long overdue in this country. I have been waiting for it, welcome it, and want it."

No country has yet devised an adequate solution to the problem of long-lived radioactive wastes.[19] A variety of repositories—including orbiting satellites, arctic ice caps, and deep salt mines—have been suggested. For the time being, wastes are kept in surface repositories from whence they occasionally leak, to the consternation of people living in adjacent areas. The storage of radioactive wastes from U.S. military operations has proven particularly troublesome. More than 400,000 gallons have leaked from the U.S. waste repository at Hanford, Washington, although this waste was stored in tanks expected to last hundreds of years. Smaller leaks have occurred at the Savannah River facility in Georgia.

The United States government was forced to abandon its plan to create a high-level nuclear waste dump near Lyons, Kansas, after
18 the local salt mine proved to have copious leaks. The proposed alternative dumping site, salt mines in the Carlsbad region of New Mexico, is also proving flawed. Salt storage would involve burying 10-foot steel canisters of waste in salt beds at least 1500 feet below the earth's surface. The salt would melt under heat generated by radioactive decay inside the canisters, and would then seal itself over the canisters as they sank. The U.S. Energy Research and Development Administration estimates that the American nuclear industry could produce up to 80,000 such canisters over the next 25 years. Salt bed storage is currently being investigated by West Germany and by Canada. Sweden and Canada are experimenting with disposal in granite, while Italy favors disposal in clay.

Even low-level nuclear waste is proving troublesome. By definition, low level wastes are dilute, but they can accumulate at various stages of the food chain until they eventually reach significant proportions. Like other radioactive substances, low-level wastes can threaten exposed individuals and their descendants by causing genetic damage in reproductive organs. The volume of low-level waste scheduled to be produced in the U.S. alone by the year 2000 will, according to the U.S. Environmental Protection Agency, be about one billion cubic feet—enough to cover a 4-lane coast-to-coast highway one foot deep.[20]

Burial grounds for low-level waste have been selected without first making hydrological and geological studies. Moreover, according to a disturbing study by the U.S. General Accounting Office, "there is little or no information available on the chemical or physical nature of the wastes." In early 1976, the U.S. Environmental Protection Agency found plutonium percolating through the soil at the low-level waste burial grounds at Maxey Flats, Kentucky.[21]

Much low-level radioactive waste is currently cast into the ocean. Prior to 1967, this dumping was unsupervised. Between the mid-1940s and the mid-1950s, the United States dumped radioactive rubbish into both the Atlantic and the Pacific oceans. Britain has

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used the Atlantic as its dumping ground. Controls have been gradually strengthened since the mid-1960s, but the problem persists.

In 1975, the Nuclear Energy Agency supervised the dumping of 4500 tons of low-level nuclear waste in the Atlantic dumping ground, 1300 kilometers due west of France. These drum-packaged wastes joined 34,740 tons of nuclear waste previously dumped at this location. Preliminary data gathered by radiochemist Vaughn Bowen, of the Woods Hole Oceanographic Institute, suggest that plutonium has become "widely distributed in the oceans as a result of man's activities, and may, in fact, be entering the food chain."[22]

Nuclear power plants themselves eventually become a form of low-level waste. Subject to intense neutron bombardment, the materials in a nuclear facility become radioactive during the structure's lifetime. When the facility has outlived its usefulness, the security of its radioactive components must be guaranteed. Among the options under serious consideration are sealing and patrolling the entire site, demolishing the superstructure while leaving the foundations and underground structures to be guarded, or totally demolishing and burying the facility in order to restore the area to a usable condition. At Port Hope in Ontario, Canada, a uranium mill was demolished by Eldorado Nuclear, Ltd., in 1958. Much of the contaminated rubble was "scrounged" by workers and other area residents, who used it to build at least 70 homes and one school.[23]

In addition to the perils inherent in the physically discrete stages of the nuclear fuel cycle, problems surround the transport of potentially dangerous materials from stage to stage. Today such transportation is frequently global in scope—witness the British agreement to reprocess 4000 metric tons of Japanese fuel. In 1974, in the U.S. alone, there were 1532 shipments involving about 50,000 pounds of enriched uranium, and 372 shipments totaling about 1600 pounds of plutonium. The record of transportation foul-ups is legendary, and the future danger from either accidental or willful mishaps is commensurate. Moreover, there has been an unpardonable sloppiness in the security accorded even plutonium and highly enriched uranium.[24]

In the general transport of non-nuclear goods, a loss rate of about 1 percent is common. A 1 percent loss of bomb-grade materials could jeopardize world stability; 1 percent of the cumulative expected plutonium flow through the year 2020 would be enough for 400,000 small bombs. The current total loss rate for plutonium, at a very modest scale of operation, is one-half percent.[25] Improvements are being made—including blast-off wheels to incapacitate trucks in case of hijackings, and heavy containers that are difficult either to steal intact or to break open. To prevent diversion by skyjacking, some nations have decreed that no airplane can carry enough fissile materials to create a bomb. Even today, however, international shipments of bomb-grade materials and nuclear wastes generally travel unguarded and are subject to accidents or sabotage.[26]

In time, the volume of transportation may be reduced through greater regionalization. The construction of huge self-contained nuclear parks, each housing 20 or more reactors, has even been suggested. In such parks, the entire nuclear fuel cycle could be contained within well-guarded boundaries. Although this set-up would reduce transportation problems, it would do so at a high price in terms of both the vulnerability of such centralized facilities and their environmental impact.

A review of the nuclear fuel cycle leads naturally to the specific arguments for and against nuclear power. Nuclear proponents claim that fission power is (1) cheap; (2) plentiful; (3) safe; (4) environmentally benign; and (5) less dependent upon the cooperation of foreign governments than other energy sources. Nuclear critics dispute these claims, and go on to contend that nuclear power (1) leads to weapons proliferation; (2) provides a significant new area of vulnerability for terrorists to exploit; and (3) necessarily leads to undesirable forms of social organization. Closely examined, the critics' case is more persuasive than that of the nuclear advocates.

Nuclear Economics

Nuclear power is not cheap. Donald Cook, Chairman of American Electric Power—the largest utility system in the U.S.—believes that "an erroneous conception of the economics of nuclear power" sent U.S. utilities "down the wrong road. The economics that were projected but never materialized—and never will materialize—looked so good that the companies couldn't resist it."[27]

The true cost of nuclear power has been confused by the quasi-public nature of much nuclear development. Billions of dollars spent on government research and development costs are not included in most nuclear cost totals. Neither are the costs of constructing the fuel enrichment facilities needed for the current generation of light water reactors—an especially grave error since the price of enriched fuel will be multiplied if enrichment becomes a private venture. Also generally ignored are the costs of regulation, the costs of waste disposal, the health costs associated with increased environmental radiation, and the premiums that should be paid for full insurance against catastrophic risk. The costs of natural uranium are often slighted, too, even though they are likely to mount rapidly in the next few years.

The principal costs admitted by nuclear proponents are the costs of the reactor and associated facilities, the reactor's environmental controls, and the interest on borrowed capital for construction. Typically, the cost of nuclear power is calculated in terms of the capital cost per kilowatt of power produced when the reactor is running at full capacity. However, for safety reasons, many reactors often run at considerably less than full capacity. Moreover, reactors are often shut down entirely for repairs and for refueling. The cost of the average amount of power produced, rather than the cost per kilowatt of capacity on those occasions when the reactor is functioning perfectly, is the true cost.

The capacity factor, the most important index of a reactor's usefulness, is found by dividing the number of kilowatt-hours of electricity actually produced during a period of time by the number of kilowatt-hours that would have been produced if the reactor had operated full-time at total capacity. While variation among reactor types and between individual reactors is considerable, the average 1973 capacity factor for commercial reactors in the United States was 58.4 percent. In 1974, it was 52.4 percent and in 1975 it rose slightly to 54.9 percent. The cumulative capacity factor for all U.S. commercial reactor operations through December, 1975, was 54.3 percent.[26] Yet nuclear vendors continue to base their economic analyses upon an 80 percent capacity factor.

A parabolic pattern seems to govern the lifespan of a typical reactor. For the first three years, as one might expect, the reactor has a low, capacity factor as construction mistakes are discovered and remedied and as employees grow more familiar with the plant's operating procedures. For the next three years, a comparatively high capacity factor—in the 70 percent range—is achieved. Then corrosion, fuel leaks, component fatigue, and similar problems of aging occur. Since much of the reactor contains high levels of radioactivity by this time, repairs are slow. Thousands of workers have had to participate in the repair of a single plant so that no single worker exceeds his maximum permissible radiation exposure.

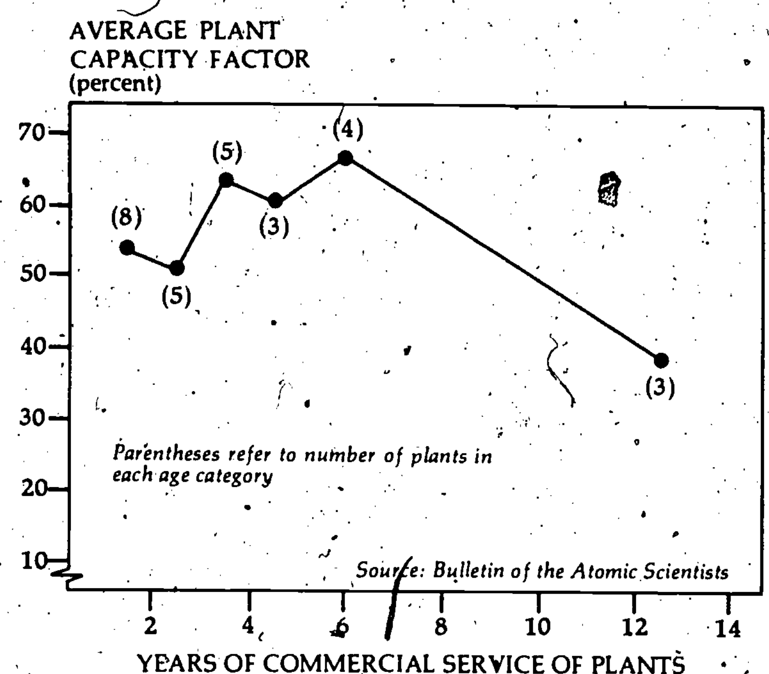

Figure 1. Average Capacity Factor of Nuclear Reactors by Age of Units, 1973-74

This pattern can be clearly seen in Figure 1, which shows the capacity factors for all U.S. reactors of all ages for 1973-74. The youngest reactors have capacity factors in the mid-fifties, the 4-to-6 year-old reactors have capacity factors in the high sixties, and the older reactors have capacity factors down around forty percent.[29]

Figure 2, which plots the average capacity factors of nuclear units by size, describes a phenomenon that could prove to be of even greater importance. It shows that the cumulative U.S. operating record of very large plants has been dismal. For units 800 megawatts and larger, the size of most new reactors planned around the world, cumulative capacity factors are in the mid-forty percent range. Because there is so little operating experience with nuclear power plants, the data base is limited. Figures 1 and 2 do not imply an immutable pattern. The trend might improve over time, or it might worsen. However, Figures 1 and 2 do summarize the unhappy experience to date in the country with the greatest commitment to nuclear power.

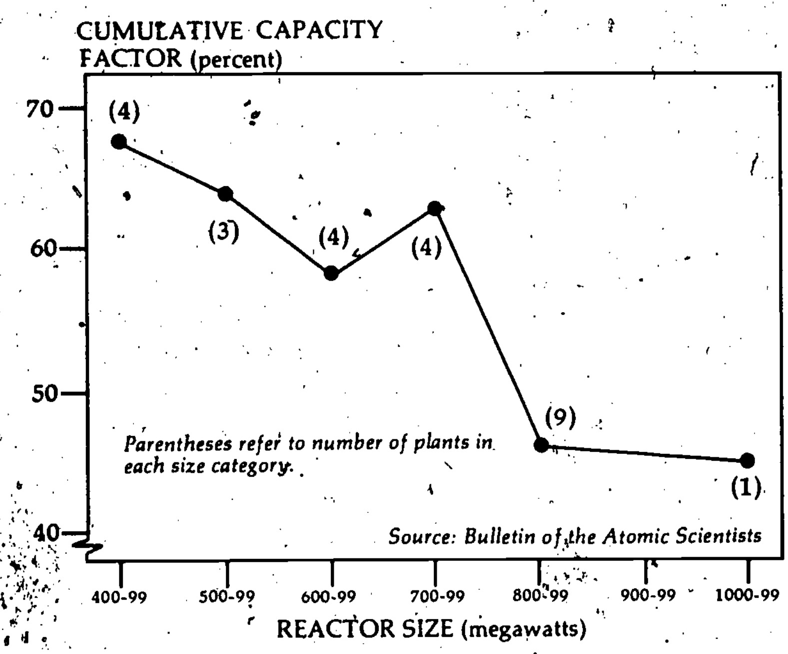

Figure 2. Average Capacity Factor of Nuclear Reactors by Size of Units Cumulative to Jan. 1, 1975

Nuclear power plants in the United States are not the only ones plagued with leaking pressure tubes, cracks in bypass piping, and swelling fuel rods. In one recent three-month period, Japan's overall nuclear capacity factor sank to 37.2 percent. Yukihiko Ikenaga, writing in the *Japan Times*, noted that "On the average, one half of the reactors have been shut down every day for some reason or other during the last six months." Capacity factors in various countries in 1974 ranged from 76 percent in Switzerland to 20 percent in Sweden.

The capital costs of nuclear power are generally expressed in dollars per unit of installed generating capacity. Such direct construction costs have soared from about $100 per kilowatt of capacity in the early sixties to more than $500 today. Land, design, administration, interest, and extraordinary inflation often catapult this figure to over $1000 per kilowatt of installed capacity.[30]

Electricity at the perimeter of the nuclear facility is useless; it must be sent to a user. Transmission lines needed to carry the full output of the operating plant cost an average of more than $100 per kilowatt of installed capacity.

Installed capacity is not, for many reasons, the most relevant figure to use to gauge costs. As we have seen, the average nuclear power plant produces less than 60 percent of its idealized full capacity. The average cost of power *actually produced* is accordingly much higher than the installed capacity figure suggests.[31] Ten percent of the electricity produced is, on average, lost during transmission and distribution, lowering the amount actually delivered still further. Net energy analysts contend that 4 to 7 percent of a reactor's output is needed to power other parts of the fuel cycle, lowering the *net* energy produced per dollar of investment still further.[32]

Insurance costs for nuclear reactors are artificially held down by a legislated ceiling on liability. In the U.S. this ceiling is about 4 percent of the government's most recent damage estimates of the worst accident scenario, and critics say that the government's damage estimates are unreasonably low. If nuclear power were, like other technologies, forced to bear insurance expenses commensurate with its risks, the cost per kilowatt would be even higher.[33]

If we add the costs of the initial fuel core, and if we assign to each reactor a share of the costs of constructing other parts of the fuel-cycle, of federal research and development, of national and international regulation, and of disposing and safeguarding nuclear wastes, the total expenditure per kilowatt of net, usable, delivered electricity might exceed $3000. Thus the generating capacity required for a 100-watt electric light bulb requires a $300 investment. Many of these costs are unique to nuclear power; others will be borne by all technologies employing large, centralized generating facilities. Many large coal-fired plants, for example, have had disappointing capacity factors. But the principal argument always cited *for* nuclear power is that it is *cheap*, and this claim is demonstrably untrue. Energy for many purposes can be obtained much less expensively from non-nuclear sources, including decentralized, on-site sun and wind energy systems, than from nuclear power.

The costs of nuclear power are mostly at the front-end—in research and development and capital construction. Consequently, reactors will necessarily be at a severe disadvantage in a time of general capital scarcity. And while all capital costs have been increasing dramatically in recent years, the costs of nuclear construction have outpaced the rising construction costs of other power facilities. The per kilowatt price of nuclear facilities rose two and one-half times as much between 1969 and 1975 as did that for coal-fired power plants.[34]

The costs of breeder reactors, without which nuclear power has a limited life expectancy, are extremely uncertain. Cost estimates for the small Clinch River Breeder Reactor in the U.S. have grown from an original estimate of $700 million to a current guess of $2 billion.

A nuclear-dominated energy system would impose severe financial strains on most poor countries. In some developing countries, the cost of a single reactor may exceed the nation's total annual capital investment. Nonetheless, the International Atomic Energy Agency predicts that nuclear plants will produce 8 percent of all electricity in the less developed countries by 1980, and that nuclear growth will speed up greatly in the subsequent decade.

Nuclear investments represent a grievously injudicious use of scarce capital, a use completely at odds with the auspicious trend toward adoption of intermediate technologies in many poor countries. A generally accepted guideline is that no single power plant should represent more than 15 percent of the capacity of a power grid. Otherwise the shut-down of a single power plant can impair the entire system. Using this rule of thumb, only those countries having at least 4000 megawatts of installed capacity should consider even a single small (600-megawatt) reactor. Argentina, Brazil, Egypt, India, Korea, Mexico, and Venezuela are the only developing countries that could currently support even one such nuclear plant. However, nuclear vendors are hungry for new markets and are therefore willing to offer much more liberal credit arrangements than would generally be available for alternative technologies. The U.S. Export-Import Bank, for example, has made loans of about $3 billion in support of American nuclear sales in 11 countries. Consequently, many small countries are mortgaging their futures to purchase reactors that are demonstrably inappropriate to their requirements.[35]

Uranium Supplies

Uranium is not a plentiful substitute for scarce oil and gas. Total non-communist uranium resources available at *double* the current price have been estimated (in a comprehensive 1975 study by the OECD Nuclear Energy Agency and the International Atomic Energy Agency) at about 3.5 million tons—about half of which was reasonably assured. Three countries control 80 percent of the current production: the U.S., with 9000 tons per year; Canada, with 4700 tons; and South Africa, with 2600 tons. These three countries (or four, if Namibia is considered separate from South Africa) plus Australia hold 85 percent of all non-communist reserves. Eighteen other countries have discovered small uranium deposits, but the total from these countries represents only 15 percent of the non-communist resource base. Public information is not available on the uranium resources of the Soviet bloc or of the People's Republic of China.[36]

The 236 reactors currently operated or planned in the United States will consume at least one million tons of uranium oxide over their lifetime. The 800 U.S. reactors commonly projected to be in operation by the year 2000 will cumulatively demand over 2 million tons through that year, and will demand 4 million tons altogether during their operating span. These fuel demands—projected by the U.S. Energy Research and Development Administration—are higher than the reserves of all known non-communist uranium suppliers.

"No new significant uranium deposits have been discovered in the U.S. since 1965, despite considerable recent drilling."

Considerable uncertainty as to how much electricity can be generated per unit of fuel further complicates the uranium reserve controversy. For example, in July of 1973, a member of the U.S. Atomic Energy Commission testified that a ton of uranium could produce 33 million kilowatt-hours. A bit later, at the same hearing, a staff member of the A.E.C.'s Division of Planning and Analysis stated that a ton of uranium would generate about 60 million kilowatt-hours. Hans Bethe, a leading U.S. nuclear proponent, claims that a ton of uranium will yield 70 million kilowatt-hours. However, F.B. Baranowski, Director of the Division of Production and Materials Management of the U.S. Atomic Energy Commission, claims that during 1971, 1972, and 1973, U.S. reactors generated only 14 million kilowatt-hours per ton. If this figure holds for the future, nuclear power sources will either require more uranium or produce less energy than is currently projected.[37]

Let us assume, however, that the E.R.D.A. figures are correct. Can a 4 million ton demand square against the U.S. resource base? The United States government estimates the nation's potential uranium at 2.6 million tons, including *all* hypothetical resources up to a price of $30 per pound. (Private estimates range both higher and lower than the official government figures.) Of this, a total of 600,000 tons—only about half of what's needed to fuel U.S. reactors now operating or on the drawing boards—is in the form of proven reserves.

Low-cost ores over and beyond those now postulated may well be unearthed; on the other hand, almost 85 percent of the government's 2.6 million estimated tons are hypothetical, and actual deposits could easily fall short of estimates. The United States has the largest uranium resource base in the non-communist world, but no new significant uranium deposits have been discovered in the U.S. since 1965, despite considerable recent drilling.

What holds true for the U.S. is, in this instance, even more emphatically true for the world. While cumulative demand for uranium oxide in the U.S. could total two million tons by the year 2000, cumulative non-U.S. demand is expected to exceed that amount. Proposed non-U.S. reactors will have a lifetime demand far in excess of the world's known and suspected deposits of economical uranium.

Could reactors possibly be sold in the knowledge that there was no fuel to power them? In a modified form, this has already occurred.

Westinghouse Corporation, in soliciting orders for nuclear power plants, long made a practice of contracting to supply fuel for its reactors for several years. In the fall of 1975, with a fuel inventory of 15 million pounds and contractual commitments to deliver 80 million pounds at an average price of $9.50 per pound, Westinghouse 28 defaulted on its supply contracts. The company claimed that it could not find enough uranium at the quoted prices to fulfill its commitments. General Electric, with about 10 million more pounds contracted for delivery than it has lined up, still claims it will be able to meet its contractual obligations.[38]

Canadian uranium producers are also facing a gap. They have signed contracts to export 120,000 tons of uranium, two-thirds of which has been approved by the government for export. But Canada's measured recoverable reserves, even at prices of $30 a pound, amount to only 81,000 tons. Although inferred reserves may amount to 321,000 tons, the higher figure rests on great uncertainties.[39]

Without breeder reactors, known uranium reserves will not long support nuclear development. Of course, as prices rise, the amount of uranium recoverable will also rise. At $100 a pound a good deal of low-grade ore—over 5 million tons in the U.S. alone—can probably be found. But at such a high price, uranium is not competitive with coal, and is about equal to oil at $12.50 per barrel. Moreover, exploiting such low-grade ore incurs heavy non-economic costs. In the U.S., uranium is now mined from western sandstone, in which it comprises one thousand parts per million. In the lower-grade Chattanooga shale, uranium constitutes only 60 to 80 parts per million—less uranium than the tailings currently being discarded from uranium milling operations. Of that miniscule amount of uranium, less than one percent is fissionable U-235.

The energy cost of extracting so little fissile fuel from so much ore may topple the nuclear industry's house of cards. Although one preliminary study suggests there can still be a net energy gain, that gain may not be worth the effort, and may not represent a judicious investment of manpower and capital. Ton for ton, Chatanooga shale contains less energy than does bituminous coal, and the environmental costs of uranium extraction from this ore will be high. Some scientists have proposed with straight faces that fissile fuel be "mined" from granite and from sea water. But only with breeder reactors can we derive sufficient energy from otherwise unusable U-238 and thorium to make such low-grade sources attractive. Current-model breeders, however, are designed to maximize the production of plutonium. If shipment of either breeder reactors or plutonium to countries without nuclear weapons is banned, the scarcity of low-cost, high-grade uranium ore would constrain international nuclear development severely.

Safety

Nuclear fission entails risks qualitatively different from those involved with other energy sources. A 1000-megawatt reactor, after sustained operations, has about 15 billion curies of radioactive material in its core.[40] The heat of decay from this material constitutes about 7 percent of the reactor's thermal output (the other 93 percent coming from the fission reaction). While the fission process can be regulated, radioactive decay cannot be so controlled. The decaying core can only be cooled. Uncooled, the core would grow so hot that it could melt through its containment vessel, and would then continue to melt its way down into the earth. This "loss of coolant accident" (LOCA) is the most serious of the potential light water reactor accidents, and it has been the focus of the reactor safety controversy. There is no question but that such accidents will occur; they are a statistical certainty. The questions, rather, are: (1) How dangerous will a meltdown be? (2) How frequently is a meltdown likely to occur?

Most of the analysis of reactor safety has been done in the United States and has concentrated upon light water reactors. This is somewhat ironic, as the United States has safety standards far more rigorous than those of any other country.

In France, nuclear regulation is spread through five ministries and various subordinate bodies, all closely coordinated with the nuclear industry. The Service Centrale de Sûreté des Installations Nucleaires de Base (SCSIN), which is responsible for the security of reactors and of waste disposal sites, polices the entire country with fewer than 20 officials—all of whom work part-time and not one of whom is a radiation specialist. Nuclear managers are always forewarned of a coming SCSIN inspection, and are always told in advance what the object of the inspection will be. Radiation monitoring is taken care of by another group, plant security is the responsibility of still another, and the transport of nuclear materials is in different hands. Nuclear industrial hygiene falls under the jurisdiction of a separate agency and other regulatory functions fall within other bureaucratic domains. The French explained the division of responsibility, and the complacency with which they view nuclear regulation, by pointing out that the French nuclear power industry is not profit-oriented. Whereas private enterprise might be expected to skimp on safety and security, they say, most French nuclear development rests in ostensibly safer public hands.

What might be the precise cost of a foul-up—technical or bureaucratic? An authoritative 1957 report, prepared by the Brookhaven National Laboratory for the U. S. Atomic Energy Commission, concluded that the worst possible reactor meltdown could kill 3400 people, injure 43,000, and cause 7 billion dollars in damage. By 1964, larger reactors were on the market, and an updated Brookhaven report upped the toll of the worst possible accident to 27,000 deaths, 17 billion dollars worth of damage, and contamination of an area the size of Pennsylvania. A study conducted by the Engineering Research Institute of the University of Michigan for the owners of the Enrico Fermi reactor outside Detroit found that the worst credible accident for this relatively small breeder reactor would cost 133,000 lives.

None of these studies dealt with the probability of such an accident occurring. The lack of actuarial data regarding reactor safety made such computations so speculative that it was long believed that only a "fringe member of the statistical community" would attempt them. However, in the mid-1960s, the Planning Research Corporation, a respected U.S. think tank, contracted with the A.E.C. to perform such a statistical analysis. The 1965 report stated that researchers were "95 percent confident . . . that the probability of occurrence of a catastrophic accident during a reactor year is less than 1 in 500."

In 1972, amid a raging scientific debate over the efficacy of "emergency core cooling systems," the United States A. E. C. sponsored yet another reactor safety study. Known by the name of its principal author, the Rasmussen study traced the sequences of events that could—as the analysts saw it—lead to a LOCA, and assigned a probability to each event and then to the sequences.[41]

By the time the Rasmussen report was issued in 1975, the entire world had logged only 927 reactor-years of commercial nuclear experience—only a small fraction of which was obtained with the new generation of giant-sized reactors.[42] Consequently, the performance records of the various components (such as valves) were derived from experience with identical or similar parts in non-nuclear equipment, on the assumption that they would behave identically in reactors. This critically important assumption may not be valid. Conditions unique to reactors may elicit unpredictable responses. As Sir Alan Cottrell, the distinguished English scientist, has observed, "Whenever you step into a different regime of temperature and pressure, nature will always have some subtleties up her sleeve."[43]

The Rasmussen report claims that a core meltdown will occur about once every 17,000 reactor years for pressurized water reactors, and about once every 33,000 years for boiling water reactors. This calculation presumes that the reactor is built with flawless workmanship and flawless materials, that it is operated only by highly-skilled experts, that neither God nor terrorists intervene with unscheduled events, and that Dr. Rasmussen's assumptions are all correct.

In general, Rasmussen argues that the likelihood of an accident decreases as its severity increases, a belief that the American Physical Society, an association of U.S. physicists, found credible but open to question. The report maintains that the emergency core cooling system (ECCS) will work successfully more than 98 percent of the time, unless some pump, valve, or other component fails. However, many experts doubt the ECCS can prevent a meltdown *even when working perfectly*, and the system has never been tested. The worst possible meltdown, the study holds, would do less damage than the Brookhaven report suggested, and such an accident would occur only once every billion reactor years. The report dealt only with light water reactors; it did not examine the accident potential of fast breeder reactors (which are widely believed to be far more dangerous than light water reactors but which will be necessary if nuclear fission is to play a significant role much beyond the year 2000).

Even if we assume the Rasmussen study to be correct—and virtually no nuclear critics do—questions about nuclear safety remain. Statisticians claim that we should compare the risks of alternative technolo-

gies by multiplying the magnitude of the accident by the probability that it will occur. Objectively, the statistical approach makes some sense, but it makes no psychological sense whatsoever. One large event is infinitely more disturbing than many small ones. People accept with some equanimity a hundred people dying in one hundred
32 automobile accidents, but they are shocked at the prospect of a hundred people dying in one massive automobile pile-up or in a plane crash. Nuclear accidents—with the potential to kill thousands of people and to discharge radioactive material that will be lethal for thousands of years—present a different ethical situation than other accidents. Statistical techniques can offer little guidance to a society grappling with the small risks assigned to utterly unacceptable events. Nor can they offer solace or recompense.

During the brief period since the arrival of commercial nuclear power, there have been many reactor accidents—some of them potentially catastrophic. Human error played a serious role in most. Edward Teller, father of the hydrogen bomb, believes that "so far we have been extremely lucky . . . But with the great number of simians monkeying around with things that they do not completely understand, sooner or later a fool will prove greater than the proof even in a foolproof system." Three U.S. astronauts were immolated in a device that was much more closely scrutinized than any run-of-the-mill reactor is likely to be.

On December 12, 1952, a tragedy of errors occurred at the NRX reactor in the Canadian village of Chalk River, 200 kilometers northwest of Ottawa. A technician accidentally opened the wrong set of valves, causing the reactor control rods to begin rising out of position. In the ensuing bewilderment, wrong buttons were pushed and the scram equipment—which should have immediately shut down the reactor—failed to operate correctly. The expensive heavy water moderator was dumped, bringing the fission reaction to a halt. The reactor core was largely destroyed; a hydrogen explosion dislodged a 4-ton gasholder; and a million gallons of highly radioactive water flooded the structure.

In November of 1955, the United States' EBR-I reactor in Idaho Falls had a partial core meltdown. Fast action by the chief scientist at the site minimized damage, although the reactor was destroyed and much low-level contamination ensued.

"Statistical techniques can offer little guidance to a society grappling with the small risks assigned to utterly unacceptable events. Nor can they offer solace or recompense."

In October of 1957, a uranium fire occurred at Windscale Number One on the Cumbrian coast in England. At one point, eleven tons of uranium were ablaze. The fire was brought under control after several days, but because of the huge volume of radioactive iodine released, a radiation ban was imposed on the sale of milk produced in the surrounding countryside.

In January of 1961, the SL-1 reactor at the Idaho Falls complex experienced a power excursion that lasted 1/500 of a second. A three-man crew was killed on the spot. The victims were so severely irradiated that their exposed hands and heads had to be severed from their bodies and buried in a dump for radioactive waste. Years were required to disassemble the radioactive wreckage of SL-1, and its eventual burial ground will have to be guarded *forever*. The official A.E.C. investigation report stated: "We cannot say with any certainty what initiated the SL-1 explosion, and it is possible that we may never know."

In October of 1966, instruments on the Enrico Fermi breeder reactor, in Lagoona Beach, Michigan, began to behave erratically. Suddenly, the reactor's radiation warning devices registered an emergency. It was impossible to tell what was occurring in the reactor core, but the instrument readings supported the hypothesis that at least one fuel subassembly had melted. Safety was of special concern at Fermi because 4 million people resided within a 30-mile radius of its site.

The Fermi reactor was successfully shut down. During the next several days, reactor experts were flown in from all over the world to speculate upon what might be happening in the reactor's core. The greatest fear was that a damaged subassembly might collapse into other parts of the core, causing a secondary nuclear accident of catastrophic dimensions. Unfortunately, this risk would be at its greatest whenever any action was taken to remove fuel from the reactor. Another concern was that the radioactive sodium coolant might explode upon air contact. Slowly, the delicate operations were begun. As it turned out, four fuel subassemblies had melted, and two of them had stuck together. More than a year and a half of careful work was required before the cause of the accident could be discovered. A triangular piece of zirconium, installed as an add-on safety measure, had worked loose and clogged the flow of coolant.

In January of 1969, the Lucens reactor (a gas-cooled reactor, built in a rock-encrusted cavern in Switzerland) was destroyed by a LOCA. The cavern was eventually converted to a storage area for radioactive waste. In April of 1972, 200 tons of steam poured out of a stuck valve of the Wuergässen reactor, a LWR in the Federal Republic of Germany. Reinforcement structures were torn off the floor of the chamber and water ran through the screw holes, damaging wires that provided power for the control rods. Fortunately, by this time the reactor had been successfully scrammed.

In March of 1975, an electrician was checking for possible leaks from the secondary containment area of the Browns Ferry Number One reactor in Alabama. He held a lit candle near the point where electric cables penetrated the wall and where any leaks in the seals would cause the flame to flicker. The sealant caught fire, and the fire spread first to the cable insulation and then to the containment area. The electrical cables powering several different "redundant" safety systems passed through a confined area, and these systems were all simultaneously knocked out by the fire. Before the fire was successfully brought under control, two 1100-megawatt reactors (representing 15 percent of all power on the Tennessee Valley Authority grid—the world's largest) were incapacitated. The shutdown cost T.V.A. in excess of $100 million.[44]

Most of the danger to human life as a result of a serious reactor accident arises from exposure to the cloud of radioactive material that would be released if the reactor containment vessel were breached. The number of people affected would depend upon the population density in the surrounding area, upon climatological conditions, and upon the effectiveness of evacuation procedures. Much of the equanimity with which the Rasmussen report viewed meltdowns can be traced to its belief that millions of people can be successfully evacuated within a few hours. Sixteen million people live within a 40-mile radius of the three reactors at Indian Point, New York. In February, 1976, Robert Pollard, the safety official directing regulatory activities at Indian Point, resigned and announced on national television that Indian Point Number Two was "almost an accident waiting to happen." The likelihood of a successful rapid evacuation of a congested area containing several million people is equal to that of an apple falling upward, and this is frankly admitted by state officials. "What's my plan to evacuate Chicago?" asks the nuclear

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"In none of the near-misses discussed in this paper was the public even informed that there was a potential danger until after the critical period had passed."

chief of the Illinois Office of Civil Defense. "I don't have one. There's no way you can evacuate Chicago." In none of the near-misses discussed in this paper was the public even informed that there was a potential danger until after the critical period had passed. The head of civil defense in the Browns Ferry area didn't hear about the fire until two days later.

The United States Navy's fleet currently includes about one hundred nuclear-powered ships. The aircraft carrier Enterprise has eight reactors. Though various ships put into numerous ports, no realistic evacuation plans have been developed for those cities to use in the event of a serious accident.

In November of 1973, a Swedish radio program describing a fictional reactor accident in southern Sweden was broadcast. The resulting public panic recalled the shock created by Orson Welles' *The War of the Worlds* some four decades earlier. The phone system broke down under the stress of calls; within ten minutes an enormous traffic jam had tied up the countryside; and frantic citizens were reluctant to believe official assurances that no accident had taken place.

Despite the problems and fears engendered by the use of breeder reactors, all known data on uranium scarcity indicate that breeders will be necessary to the development of a significant long-term world nuclear industry. Because of the exceedingly limited experience with breeders, and the proprietary nature of much developmental work, safeguarding these devices is an even foggier business than that of safeguarding light water reactors. However, LMFBR's are likely to hold perils without parallel among light water reactors.[45]

Fast neutrons cause a vast atomic stir inside a LMFBR. Even if the breeder is operated conservatively, with the fuel removed when 5 percent of it has undergone fission, every atom in the metal fuel assemblies is displaced about 70 times before removal. This neutron bombardment creates voids in the crystalline structure of metallic fuel rods, swelling both the metal cladding and the fuel itself as a consequence. If fuel pins bow and touch as a result of this swelling, temperatures increase greatly at the contact points. Under some circumstances, this heat could spread to other parts of the core and cause melting. The current breeder safety debate centers around whether or not the fuel could become arranged in an explosive configuration during a coremelt (a condition known as "recriticality") and blow the reactor apart (or in technical jargon, cause a "rapid disassembly"). Unknown is just how much energy such an explosion will release.

The easiest "solution" to the swelling problem is to design more
36 space between the fuel pins so that, even if they bend, they won't touch. However, the sodium between the pins slows down the neutrons and reduces the breeding rate. The contribution of the breeder to fuel supplies will be marginal unless the breeding time is brought down substantially from the present 40-60 year range. Here safety and speed are at loggerheads, for a cut in the breeding time will require a closer fitting of fuel pins unless new fuels—probably carbide compounds—that could double more rapidly than the oxide fuels currently in use are developed.

Another fuel problem is that of the "sodium void coefficient." If sodium boils in certain parts of the reactor, the result may be a major increase in temperature that cannot correct itself. It is hypothesized that a high-temperature bubble might move like a can-opener along a fuel rod.

How safe is nuclear power? The answer is a mystery. The scale of potential damage from a bad reactor accident is monstrous, but the likelihood of such an accident is a matter of controversy.

The U.S. Atomic Energy Commission, charged by critics with lax enforcement, nonetheless finds hundreds of safety violations in domestic facilities every year. The Quad Cities Unit Two, in the American Mid-West, was started up with a complete welding rig inadvertently left inside its pressure vessel. The control rods of the Vermont Yankee reactor were installed upside down, and the reactor was once started up with no lid on its vessel. At Palisades, Michigan, a loose core support barrel wreaked havoc with the reactor's innards; Consumer's Power, the utility owning the reactor, sued Combustion Engineering, the builder, for $300 million. More significant problems may lie in such countries as France and Russia, where safety standards are much lower. The most frightening prospect may be in the developing countries. Many countries now ordering nuclear facilities have no nuclear regulatory framework, and only scant expertise. Clifford Beck, director of the Government Liaison-Regulation Office of the United States Atomic Energy Commission, has termed the Tarapur reactor in western India "a prime candidate for a nuclear disaster." Fahir Yenicay, director of the Nuclear Energy Center near Istanbul, Turkey, announced in early 1976 that two nearby lakes had become "dangerously radioactive" and urged that they not be used for fishing, irrigation or drinking.[46]

The nuclear safety debate has been a source of great confusion to the layman. One team of experts is lined up against an equally expert opposing team, each armed with computer print-outs and technical jargon. Each tries to "prove" its case. But most nuclear issues are not amenable to proof; they are matters of judgment. It is impossible to eliminate all risk. The level of acceptable risk is an ethical rather than a technical matter. Consequently, the final decisions are not scientific, but are, rather, social and political.

Environmental Impact

Although fission was at one time viewed as a "clean" source of energy, it is now opposed by almost every major environmental organization in the world. Nonetheless, nuclear proponents continue to argue that nuclear power is ecologically benign.

The environmental argument is almost always framed in terms of the relative environmental costs of nuclear power and coal. Moreover, the environmental effects of a perfectly functioning nuclear fuel cycle are usually measured against the American experience with coal *before* the passage of the landmark Coal Mine Safety Act and *before* the implementation of the Clean Air Act of 1970. Coal mine accidents in the United States have decreased steadily over the last few years, and improvements in mining conditions will result in a dramatic decrease in the incidence of black lung disease. When electric utilities are finally compelled to meet the terms of the Clean Air Act, airborne emissions (which in the past have been a major health menace, causing widespread premature death among the elderly and people suffering from respiratory ailments) will be significantly reduced.

Moreover, comparisons between coal and nuclear power plants are irrelevant to the great majority of nations without significant coal reserves. Thus, if environmental comparisons are to be made, they ought to focus upon the relative impacts of nuclear power and renewable energy sources (solar power, wind power, wood and other organic sources, etc.) that are available to all countries.

At present, thermal pollution and radiation are the principal environmental dangers spawned by the nuclear fuel cycle. Other threats may be unleashed. Should nuclear power grow to the point where massive amounts of low-grade ore were being processed for fuel, environmental repercussions would surely be felt. If nuclear power were to survive until mankind stumbled into a nuclear war, the environmental consequences would be of an altogether different magnitude.

All mechanical processes that generate electricity also generate thermal pollution. But nuclear power plants cast off more waste heat per unit of electricity produced than does any other commercial technology. This heat must be dissipated, either through the use of cooling towers or through direct discharge into a body of water. Since cooling towers are exceedingly expensive, most reactors planned around the world will inject heat directly into lakes or streams. If a power plant operates constantly, the local habitat would undergo a massive transformation and a new ecosystem that could thrive at the higher temperature would develop. However, reactors must be shut down regularly for fuel changes, and irregularly for various other reasons. Thus, the consequent erratic temperature changes make it difficult for any stable ecological community to survive.[47]

Many of the problems associated with a nuclear reactor would be multiplied manyfold with the coming of a proposed pattern of intensive nuclear development misleadingly called a "nuclear park." The park would contain uranium enrichment facilities, a fuel fabrication plant, a large number (10 to 40) of individual reactors, and a fuel reprocessing plant. The thermal burden associated with such a development could be sufficient to alter the local climate and, possibly, to generate a continuous cloud cover. Yet Dr. Chauncey Starr, President of the Electric Power Research Institute, considers such parks the "inevitable result of the growth of the nuclear power industry."[48]

The environmental threats posed by the nuclear power cycle cannot be fully measured without an understanding of the effects of radiation on life at the molecular level—an understanding that is at present far from complete. The radiation associated with nuclear power is emitted through the spontaneous decay of reactor-produced radioactive materials. (In addition to its 100 tons of uranium oxide fuel, one large modern reactor contains about two tons of various radioactive isotopes—one thousand times as much radioactive material as the Hiroshima bomb produced.)[49] Each radioactive isotope has a precisely measurable half-life (time during which half the atoms in any piece of that radioactive material will decay) that ranges from less than a second to more than a million years. The half-life of plutonium-239, the most controversial isotope associated with nuclear power, is 24,400 years.

As sub-atomic particles of radiation shoot out from decaying atoms, they collide with other matter, generally with electrons. In such collisions, the electron is almost always jarred free from the atom of which it is a part. This electron loss transforms the atom into a positively charged ion. The radiation that causes this change—the x-rays, gamma-rays, alpha particles, beta particles, and neutrons—is slowed down by such collisions. The distance the radiation travels before being "stopped" is determined by its size, charge, and energy level and by the nature of the substance encountered. Alpha particles travel only about an inch in air, and can be stopped by a piece of paper or skin; neutrons travel hundreds of feet in the air and can be stopped by several feet of water or concrete.

The effects of "ionizing radiation" have been studied in many experiments performed on hamsters, guinea pigs, and beagles. Some clear statistical correlations have emerged—especially in experiments involving high dosages of radiation. But we have almost no knowledge of the cancer-causing and mutation-causing mechanisms at the molecular level. We know that radiation causes cancer, but we don't know *how* it causes cancer.

Information on the effects of radiation on human beings is sketchier than that on radiation-exposed laboratory animals. The debate over the effects of atmospheric nuclear bomb tests, sparked by two-time Nobel Prize winner Linus Pauling, has never been resolved (although a large and growing body of evidence seems to support Pauling's claims). A U.S. medical data bank, established in 1968 to monitor nuclear workers, has been handicapped by the refusal of some private nuclear companies to cooperate. Moreover, this "Transuranium Registry" has been unable to track down many exposed workers from the early years of the nuclear era—a severe research handicap since many radiation-induced effects have very long lag times before symptoms appear.[50]

Because we lack a scientific understanding of how ionizing radia-
40 tion actually affects discrete biological processes, the link between cause and effect is necessarily speculative (much as is the case with cigarette smoking). This inductive leap leaves the experts divided. The Natural Resources Defense Council, an environmental group, is petitioning U.S. authorities to lower the permissible concentration of plutonium aerosols by 115,000 times.

Many radiation disputes revolve around linear concepts, around the probability of an ill-effect increasing in direct proportion to the amount of radiation received. Will even very low dosages cause some cancers, or is there a threshold below which exposure to radiation is harmless? If a miniscule amount of lung tissue is subjected to a very high dosage of radiation, should the likelihood of cancer be derived from the high intensity in the physically affected area or from the low intensity in relation to the whole lung?

We don't understand the molecular biology of radiation-induced cancer, so our policies are necessarily based upon statistical inferences. But radiation statistics are particularly ambiguous because (1) routine radiation from nuclear power is in addition to inescapable radiation from other sources and considerable variation exists in the amount of natural background radiation and medical radiation that people are subjected to; (2) interrelationships between different types of cancers and different types of radiation are extremely confusing; (3) the public is exposed to many carcinogens other than radiation that cannot be controlled in large-scale epidemiological surveys; and (4) because of the lag time, many potential radiation victims die from other causes before radiation-induced effects appear.

The low levels of radioactive isotopes routinely emitted through a perfectly functioning nuclear fuel cycle, or from a leaking low-level waste repository, have not been "proven" either safe or unsafe. In several developed countries, reactor emission standards have been dramatically tightened in recent years, although not enough to satisfy many critics. Other countries have no standards whatsoever—even though radionuclides can become concentrated up to several thousand times as they move up a food chain, so dilute emissions may be in a more dangerous form when ingested by people at the top of the food chain.[51]

Plutonium is now the focus of a major public health debate. One school of thought contends that plutonium is carcinogenic in doses too small to allow practicable detection. Each large light water reactor contains half a ton of plutonium and each breeder will produce much more. Common nuclear-power projections will require the cumulative production of 440 million pounds of plutonium by 2020.[52]

While plutonium-239 will be the radioactive isotope produced in largest volume by the current nuclear strategy, it is by no means the only highly carcinogenic, mutagenic, or toxic substance in a reactor's innards. Knowledge of many other radioactive isotopes is even more limited than knowledge of plutonium. We know almost nothing about the rates, routes, and reservoirs characteristic of these dangerous man-made isotopes when they are released in bulk into the environment. The wall of uncertainties that separates natural scientists from a precise understanding of the effects of radiation on the body and on the environment ought to restrain even the boldest, for what we don't know can kill us.

Energy Independence

Nuclear power cannot lead most countries to national energy independence. In the wake of the Arab oil embargo, and the associated dramatic rise in the price of petroleum products, many countries thought that nuclear power could usher in energy autonomy. This belief was capitalized upon by reactor vendors; 1974 saw a significant increase in the role of nuclear power in the energy plans of most developing countries. But such a belief is insupportable. The global distribution of uranium ore is no more equitable than that of oil. Access to enrichment facilities and to reprocessing plants will, if anything, be more severely regulated than access to petroleum refineries. And nuclear reactor technology is far more complex and trouble-ridden than are most other energy technologies.

Fissile fuels are unevenly distributed in the earth's crust, and nothing prevents uranium-rich nations from engaging in an OPEC-style restraint of trade. Such restraint might be motivated by the simple desire of producing countries to retain their uranium for their own nuclear needs, or it could be tethered to political considerations.[53] South Africa (if one includes the controversial Rossing deposits in Namibia) has the second largest known uranium resource base in the non-communist world. A.J.A. Roux, president of South Africa's Atomic Energy Board, claims that his country wishes to use its uranium, not for political purposes, but to assist an energy-short world. But he adds, "Naturally, in assisting the world, we look at countries friendly to South Africa in the first place."

Canada, with the non-communist world's third-largest uranium resource base, will sell uranium only with a prohibition on use for explosives. Canadian utilities are also concerned about what the recent multiplying of the world price of uranium has done to their domestic cost projections, and they are calling for protection of low-priced domestic supplies. Australia, with the non-communist world's fourth largest supply of uranium, may refrain from exporting the resource altogether, except for medical purposes. And the United States, with the non-communist world's largest uranium resource-base, will begin importing uranium again in 1977. Since the U.S. does not have enough fissile material to meet the lifetime needs of its own reactors projected for the year 2000, it intends to build up a large stockpile of enriched fuel to guard against future fuel market uncertainties.[54]

Countries that export nuclear technologies have met frequently under the aegis of "the London Group," which was established secretly to consider the problems associated with nuclear proliferation and nuclear terrorism. The clandestine nature of the London Group's activities has led some observers to speculate that a national dependence upon nuclear exporting countries might be even less tenable than a similar reliance upon the oil exporting countries.

Also arguing against sole reliance upon nuclear energy is the fact that international uranium resources are privately owned. An investigation by the staff of the respected U.S. business journal, *Forbes,* revealed that the Rothchild empire has a financial interest "in nearly every major uranium mine in the world." The corporations involved in uranium production meet regularly "to stabilize the market" under the auspices of the Uranium Producer's Forum. But, according to

"The regionalization of nuclear fuels processing would leave each of the participating nations dependent upon the goodwill of the country in which the operation is located—a prospect that no non-processing nation can relish."

Forbes, "the function of the Uranium Producer's Forum could be performed at a board meeting of Imetal," the huge Rothchild company.[55]

In early 1975, the U.S. Nuclear Regulatory Commission stopped issuing export licenses for nuclear materials until it completed a review of transport safeguards. The decision was prompted by the discovery of 300 pounds (147 kilograms) of plutonium from Italy at Kennedy airport in New York. The plutonium—enough for a score of small bombs—had been shipped through regular commercial channels. The American export halt, which occurred without prior consultation with affected governments, reminded the European continent just how mercurial its suppliers can be. Western Europe has begun to turn increasingly to the Soviet Union for nuclear fuel. In 1975, the Common Market countries obtained less than 20 percent of their enriched uranium from the Soviet Union, but during the next two years dependence upon Soviet uranium is expected to leap (temporarily) to over 60 percent. A European diplomat recently remarked, "Relying on the Arabs and Russians at the same time for our fuel supplies is not my idea of a secure energy posture."[56]

HWR's, which can use unenriched natural uranium, allow those countries with indigenous uranium supplies to avoid a dependence upon foreign uranium enrichment facilities, and also provide a hedge against enriched-fuel inflation. On the other hand, heavy water reactors are also more capital-intensive than light water reactors. And heavy water reactors do not increase the energy autonomy of nations lacking a domestic supply of uranium or a heavy water production capacity.

In an effort to diminish the weapons potential inherent in the proliferation of nuclear power, the United States has been advocating regional nuclear processing centers. These centers would enrich uranium, fabricate fuel rods, and reprocess spent fuel. A center in the Philippines, for example, might perform these tasks for all of East Asia. In an ideal world, such a plan makes some economic sense; such countries as Korea, Taiwan, Thailand, or Indonesia will not—under any plausible near-term scenarios—each have enough nuclear power plants to support an economical reprocessing operation. However, the regionalization of nuclear fuels processing would leave each of the participating nations dependent upon the goodwill of the country in which the operation is located—a prospect that no non-processing nation can relish.

Weapons Proliferation

44 Today the five members of the U.N. Security Council have exploded nuclear bombs. So has India. Approximately 15 more countries are in what could be termed 'near nuclear' status; they could, no doubt, produce nuclear weapons within a very short time if they chose to do so.[57]

Virtually all nations agree that the widespread dissemination of nuclear armaments would gravely jeopardize not only global stability, but perhaps even the survival of the human species. In the event of an accidental or intentional nuclear war, the incredible impact of the initial conflagration (the world's nuclear arsenals today contain the equivalent of 20 billion tons of TNT), would be followed by long-term radiation damage, ozone depletion, and possible major climatological shifts. Our ignorance of the effects of such a massive assault on the global environment is nearly total.[58]

Fear of nuclear weapons proliferation can be traced back almost to the first formal admission of the existence of such devices. Three months after Hiroshima, the United States, the United Kingdom, and Canada issued a joint statement suggesting that a nuclear monopoly was impossible, and that the only choices were nuclear disarmament or nuclear proliferation. They called for disarmament. In 1946, the United States presented the Baruch Plan to the United Nations, calling for the creation of a worldwide nuclear inspection system followed by nuclear disarmament. The plan ran aground on the rocks of the Cold War.

By 1953, both the United States and the Soviet Union had acquired the hydrogen bomb and nuclear disarmament seemed an increasingly remote possibility. President Eisenhower delivered his "Atoms for Peace" address that year to the United Nations. In it, he called for the development of commercial nuclear power, and took special note of the bright promise this energy source held for the less developed parts of the world. In 1957, the International Atomic Energy Agency (I.A.E.C.) was established to promote the peaceful uses of nuclear power around the world.

"Many believe that the fewer the fingers on nuclear buttons, the safer the world. Even so, nations cannot be counted upon to act in the human interest unless to do so is in their national interest as well."

After the Cuban missile crisis of 1962, the U.S. and the USSR became more acutely aware of the fragility of the nuclear age. The following year the Limited Nuclear Test Ban Treaty was signed. In 1967, the Treaty of Tlatelolco prohibited nuclear weapons in Latin America. And on March 5, 1970, the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) entered into force.[59]

The NPT was authored by the United States and the Soviet Union, and, from a superpower perspective, the treaty makes a good deal of sense. Both countries retain their vast arsenals (the U.S. has 30,000 nuclear weapons), and each continues to manufacture three hydrogen bombs a day.[60] Non-weapons states, however, are prohibited from developing weapons or otherwise acquiring them. Non-weapons states are subjected to I.A.E.A. inspections; the nuclear powers are not. The superpowers' sole obligation is to make good faith efforts toward nuclear disarmament; virtually no non-nuclear power believes such efforts have actually been made.

"If I had known in 1968 how little the nuclear powers would do over the next six years (to control the arms race)," remarked one highly-placed senior diplomat of a non-nuclear country, "I would have advised my government not to sign the treaty."[61] Countries that have not signed the treaty include India and Pakistan, Argentina and Brazil, Egypt and Israel, China and Japan, South Africa and France.

The principal effect of the NPT has been to maintain the nuclear status quo. Many believe that the fewer the fingers on nuclear buttons, the safer the world. Even so, nations cannot be counted upon to act in the human interest unless to do so is in their national interest as well. The regrettable fact is that the NPT offers nothing, or less than nothing, to its non-weapons participants. None of the nuclear exporting nations is willing to limit its nuclear exports to states agreeing to place all their nuclear activities under I.A.E.A. safeguards; none wishes to lose a potential sale. Thus, parties to the NPT voluntarily relinquish a degree of sovereignty, while non-parties have nuclear vendors beating down their doors with offers of nuclear hardware.

A measure of the general disillusionment with NPT may be gleaned from the record of the long-awaited NPT 5-Year Review Conference held in Geneva in May, 1975. The prelude to the conference deserves note. India had detonated her first nuclear device on May 18, 1974. In June of that year, the American President offered 600-megawatt reactors to Egypt and Israel—two fiercely antagonistic non-NPT states. And the 1974 Vladivostok agreement between the U.S. and the USSR—far from upholding the superpowers' NPT obligations to bring the arms race to a timely conclusion—was widely perceived as a slightly modified set of ground rules for the continuation of that race.[62]

The NPT Review Conference was attended by only 57 of the 96 countries that have ratified the treaty. France, China, and India were, of course, not represented. Taiwan—a party to the treaty and a country with advanced nuclear capabilities—had been expelled from the United Nations and the I.A.E.A. and was not invited to attend. The Canadian foreign minister was the only official of his rank to appear, and he attended only long enough to deliver a speech.

The most creative thinking, and the strongest leadership, at the 1975 conference came from Mexican Ambassador Alfonso Garcia Robles (the father of the Treaty of Tlatelolco). Robles proposed two draft protocols. Under the first, the nuclear parties would cease underground nuclear weapons tests for ten years when the number of NPT parties reached 100; each additional five parties would extend the moratorium for three years; and the moratorium would become permanent if and when all the nuclear powers became parties to the NPT. The protocol was rejected by both the U.S. and the Soviet Union, both of whom were conducting underground tests at the time of the conference. The second protocol linked reductions in the superpowers' nuclear delivery systems to increases in the number of NPT parties; it was also rejected out of hand. Both these protocols were addressed to Article 6 of the NPT, which calls for cessation of the nuclear arms race at an early date.

A third, and exceedingly modest, protocol was offered under which the nuclear powers would agree not to use nuclear weapons against countries not having nuclear weapons, to assist non-nuclear countries that were threatened or attacked with nuclear weapons, and to encourage negotiations to establish nuclear weapon-free zones. The nuclear powers refused this protocol as well—a traditional posture for the United States, but a new one for the Soviet Union. Thus, non-weapons countries that agreed to become parties to the Non-

"Thus, non-weapons countries that agreed to become parties to the Non-Proliferation Treaty were unable to obtain assurances that the nuclear powers would not launch nuclear strikes against them!"

Proliferation Treaty were unable to obtain assurances that the nuclear powers would not launch nuclear strikes against them! At about this time, James Schlesinger, the U.S. Secretary of Defense, publicly reaffirmed his nation's willingness to initiate the use of nuclear weapons in response to a conventional attack.

The nuclear weapons states at the conference dismissed all proposals made by developing nations as "political" in nature, and urged instead that the conference limit itself to the technical problems of NPT implementation. By this they meant the strengthening of safeguards on nuclear material. But they provided no concrete proposals as to how this might be accomplished. The nuclear powers further supported the concept of international nuclear centers, but offered only vague ideas about how these might be handled. Regional centers able to serve both Argentina and Brazil, India and Pakistan, Israel and the Arab states struck many observers as problematical.

The conference, viewed from any perspective, was a failure. It broke down into the same confrontation between developed countries and less developed countries that has characterized all recent international meetings. Shortly after the conference, West Germany announced its four billion dollar sale of a complete nuclear fuel cycle to Brazil, a non-party to the NPT. While Brazil has agreed to put the German facilities under I.A.E.A. safeguards, nothing stops Brazil from duplicating the technology and using its own uranium to manufacture explosives.

Weak and weakening, the NPT remains the principal dam against a global flood of nuclear weapons. Adherence to the treaty holds no advantage to any country other than a superpower, and development of nuclear explosives arguably does. China, virtually ignored until it exploded its bomb in October of 1964, has since obtained a seat on the U.N. Security Council and become a respected force in the community of nations. The Indian bomb, far from eliciting international opprobrium, evoked only a spate of political cartoons and short-lived censure from two or three countries. In India, the explosion greatly strengthened the internal stature of the ruling Congress Party and of its leader, Indira Gandhi. U.S. Secretary of State Kissinger, visiting India five months after the blast, asked only that India act responsibly on the export of nuclear technology. Small wonder that on April 1, 1975, while introducing a bill calling upon his country to construct an atom bomb, one Argentinian legislator stated that "Recent events have demonstrated that nations gain increasing recognition in the international arena in accordance with their power."

The existence of nuclear weapons in some lands leads almost inexorably to their development in others. The Chinese bomb arguably spawned the Indian device, and the Indian explosion seems certain to beget a Pakistani bomb. Pakistani Prime Minister Zulfikar Ali Bhutto growls that he will "never surrender to any nuclear blackmail by India. The people of Pakistan are ready to offer any sacrifice, and even eat grass, to ensure nuclear parity with India." Even in Japan—the only country ever to have suffered nuclear attack—a broad consensus holds that the advent of a Korean bomb would turn Japanese opinion around overnight. Israel is widely believed to have between 10 and 20 small nuclear weapons, using plutonium from the un-safeguarded reactor at Diamona. The U.S. President, in a 1974 "goodwill" gesture, promised a new commercial reactor to Egypt.

Beyond the threat of neighboring bombs, there is almost certainly a threshold number of nuclear nations, the existence of which would serve to convince hold-out countries that continued abstinence is purposeless. At that point, wherever it is, the NPT dam will break and the world will go nuclear. "I'm glad I'm not a young man, and I'm sorry for my grandchildren," says David Lilienthal, the first chairman of the U.S. Atomic Energy Commission. Such concerns are intensified by the fact that planned international sales by U.S. reactor manufacturers alone over the next decade will produce enough plutonium *each year* to make 3000 small bombs.

The military governments in control of South Korea, Taiwan, Libya, and Argentina are acutely aware of the strategic importance of nuclear weapons. Pakistan has a strong incentive to explode a bomb. Israel and South Africa are widely believed to already possess modest nuclear arsenals. West Germany is delivering a complete nuclear fuel cycle to Brazil—though Brazil has vowed to develop nuclear explosives "for peaceful purposes" only. Fred Ikle, head of the U.S. Arms Control and Disarmament Agency, has noted that a very sophisticated warhead could be tested in a 'peaceful' explosion designed to build a dam.[63]

Such fears are spurred not just by those countries that haven't ratified the NPT. Any country can withdraw from the treaty on three months' notice. Yugoslavia, deeply disturbed by the lack of progress at the NPT Review Conference, has announced that it is re-examining its position on the treaty. Yet the major nuclear powers steadfastly refuse to take those modest "political" steps that might make the NPT meaningful in the eyes of countries that will otherwise opt for independent nuclear arsenals.

With so many near-nuclear states not parties to the NPT, with the future of that treaty clouded by uncertainties, and with the nuclear exporting countries engaged in a fierce competition for international markets, the future worth of the I.A.E.A. safeguards program is highly questionable. However, if only because nuclear proponents generally express great confidence in I.A.E.A. policing activities, the safeguards program requires a brief examination.

Conceded by even its strongest admirers to be a shoestring operation, the I.A.E.A. safeguards program is responsible for inspections in 92 NPT countries and in non-treaty states that have agreed to such inspections. (All nuclear vendors except France now demand such inspections as a condition of sale.) To accomplish this task the I.A.E.A. employs 70 technicians and has a budget of about $5 million. The organization's primary regulatory activity is the auditing of records. Occasional on-site examinations are ordinarily announced well in advance.

Besides its exceedingly modest scale and budget, four other major problems hamstring the I.A.E.A. First, a nation violating its commitments would have to be remarkably inept to be caught in an auditing error. When volumes of fissile materials are large, even a small margin of uncertainty can lead to significant losses; and bomb-sized gaps are simply not covered by existing safeguards. One-half of 1 percent of a pound of plutonium won't make a bomb; one-half of 1 percent of a ton might. When a material is converted to and from gaseous, liquid, and solid states—as is necessary in the fuel cycle—losses and inaccuracies are inevitable. The United States clearly has the finest nuclear safeguards program in the world, yet cumulative U.S. losses of fissile material could fill an enormous arsenal. The most significant losses occurred in the early years of the nuclear program, but, as recently as December of 1975, a fuel fabrication plant in Erwin, Tennessee, reported a discrepancy of 20-40 kilograms (44-110 pounds) of fully enriched uranium.[64]

The second problem with the international safeguards program is that coups, revolutions, and other dramatic changes in government will often invalidate all agreements made by previous leaders. The United States flew a secret team of experts into South Vietnam to de-fuel and then demolish that country's only reactor shortly before the fall of the Thieu regime.[65]

A third weakness of the NPT safeguards program is that, like Cock Robin, the I.A.E.A. has no authority to take any action against violations other than to announce them. Indeed, most countries consider occasional inspections to impinge upon their sovereignty; few, if any, would grant an international team police authority to confiscate diverted bomb-grade materials.

Finally, selling hardware necessarily means selling knowledge. French sales of nuclear technology are not subject to I.A.E.A. inspections. Sales of nuclear hardware by other countries are subjected to inspection; but duplicate facilities built by the receiving country will not be inspected. Brazil, for example, is less apt to build a bomb by sneaking material out of the German-built facilities than it is to openly build similar facilities of its own for the avowed purpose of developing peaceful nuclear explosives.

India put an end to the U.N. Security Council's nuclear hegemony. At least 15 other countries have the fissile materials and the technical competence to manufacture bombs. And widespread weapons proliferation is sure to follow the rapid growth of commercial nuclear power facilities.

Nuclear Terrorism

Discussions of nuclear terrorism have generally focused on the use of fissile materials to manufacture nuclear weapons, a vitally important topic. But neglected are a motley range of other opportunities for nuclear sabotage and disruption.[66]

The three bomb-grade materials of concern are plutonium-239 and two isotopes of highly-enriched uranium: U-235 and U-233. Plutonium, named for the Greek god of hell, is made inside all existing commercial reactors; it is highly toxic, carcinogenic, and explosive.

"No wizardry is required to build an atom bomb that would fit comfortably in the trunk of an automobile."

U-235 is the fuel of most existing commercial reactors, and U-233 is produced in reactors containing thorium. Spheres of Pu-239, U-235, and U-233, encased in a beryllium neutron reflector have critical masses of four kilograms (under nine pounds), eleven kilograms, and four and one-half kilograms, respectively. Sophisticated implosion techniques can lower the critical mass requirements considerably; for plutonium used in implosion bombs, the official "trigger quantity" is about two kilograms. A skilled bombmaker with access to the proper neutron reflector would require slightly less than these official figures suggest. (The theoretical minimums are classified.) An amateur bombmaker could make a less sophisticated weapon employing correspondingly larger amounts of fissile material.[67]

Until 1970, the United States government purchased all the plutonium produced in U.S. reactors. In 1970, the purchases ceased, and private companies began stockpiling the material. If reliance on nuclear power grows at the rate commonly projected, far more plutonium will be produced in commercial reactors in the next couple of decades than is now contained in all the nuclear bombs in the world. Theodore Taylor, a nuclear safeguards expert, estimates that by the year 2000 enough fissile material will be in transit to manufacture 250,000 bombs. If U.S. Atomic Energy Commission growth projections for nuclear power through 2020 were to be met, Arthur Tamplin and Thomas Cochran have calculated, the cumulative flow of plutonium in the United States alone would amount to 200 million kilograms (440 million pounds).[68]

Once assembled, nuclear weapons could be rather convenient to use. The dimensions of the Davy Crockett, a small fission bomb in the U.S. arsenal, are two feet by one foot (0.6 meters by 0.3). The smallest U.S. atom bomb is under six inches (0.15 meters) in diameter. Such bomb miniaturization is well beyond the technical skill of any likely terrorist group, but no wizardry is required to build an atom bomb that would fit comfortably in the trunk of an automobile. Left in a car just outside the exclusion zone around the U.S. Capitol during the State of the Union address, such a device could eliminate the Congress, the Supreme Court, and the entire line of succession to the Presidency.

With careful planning and tight discipline, armed groups could interrupt the fuel cycle at any vulnerable point and escape with fissile material. Perhaps more frightening, however, is the inside thief—the terrorist sympathizer or the person with gambling debts or the victim of blackmail. In 1973, for example, the Director of Security for the U.S. Atomic Energy Commission was found to have borrowed almost a quarter of a million dollars, to have spent much of it on racing wagers, and to have outstanding debts of $170,000.[69] Quiet diversion of bomb-grade material may have taken place already. There are many documented instances of plutonium being found where it should not have been, and, worse, not being found where it should have been. A smuggling ring was discovered selling stolen Indian uranium in Nepal in 1974.

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Determining whether or not weapons-grade material has already fallen into the wrong hands is impossible. Charles Thornton, former director of Nuclear Materials Safeguards for the United States' A.E.C., claims that "The aggregate MUF (materials unaccounted for) from the three U.S. diffusion plants alone is expressible in tons. No one knows where it is. None of it may have been stolen, but the balances don't close. You could divert from any plant in the world, in substantial amounts, and never be detected . . . The statistical thief learns the sensitivity of the system and operates within it and is never detected."[70]

It was long and incorrectly believed in the United States, as it is still believed elsewhere, that building a bomb from stolen materials would require "a small Manhattan project." Theodore Taylor, formerly the leading American atom bomb designer, has described at length where the details of construction can be found in unclassified literature and how the necessary equipment can be mail-ordered. A television station commissioned an undergraduate at MIT who, working alone and using only public information, produced a workable bomb design in five weeks. In 1970, a 14-year-old school boy prepared a crude (but credible) diagram for a hydrogen bomb and nearly succeeded in extorting one million dollars from Florida authorities.

Even without the successful diversion of fissile materials, the operation of a nuclear fuel cycle affords terrorists exceptional opportunities. In November of 1972, three men with guns and grenades hijacked a Southern Airlines DC-9 and threatened to crash it into a reactor at the Oak Ridge National Lab if their ransom demands were not met. In March of 1973, Argentine guerillas seized control of a reactor

"One visitor to the San Onofre reactor in California recently pulled a knife marked 'lethal weapon' and a bottle of vitamin pills marked 'nitroglycerine' from his pocket when his tour was next to the control room."

under construction, painted its walls with political slogans, and departed carrying the guards' weapons.

A former official in the U.S. Navy underwater demolition program testified to Congress that he ". . . could pick three to five ex-underwater demolition Marine reconnaissance or Green Beret men at random and sabotage virtually any nuclear reactor in the country. . . . The amount of radioactivity released could be of catastrophic proportions."[71]

One visitor to the San Onofre reactor in California recently pulled a knife marked "lethal weapon" and a bottle of vitamin pills marked "nitroglycerine" from his pocket when his tour was next to the control room, to demonstrate how easily the reactor could be penetrated. Various magazine articles have described how a saboteur might initiate a core meltdown in a reactor.

Werner Twardzik, a parliamentary representative in West Germany, joined a tour of the 1200-megawatt Bilbis-A reactor carrying a 2-foot (60 centimeter) "panzer-faust" bazooka under his jacket. He passed undetected through the sophisticated security instruments of the world's largest operating reactor, and presented the bazooka to the power plant's director at the end of the tour.

Threats to destroy a reactor in such a way as to release much of the radiation in its core are truly terrifying. Yet two French reactors were bombed by terrorists in 1975; a nearly completed nuclear plant in New York was damaged by arson; a total of 64 bombing incidents involved utilities in the United States in 1974; and all investigations of a series of mishaps in an Illinois nuclear power plant pointed to in-house sabotage.

If the radioactive iodine in a single LWR were uniformly distributed, it could contaminate the atmosphere over the lower 48 United States at eight times the maximum permissible concentration to an altitude of about six miles (ten kilometers). The same reactor contains enough strontium-90 to contaminate all the streams and rivers in the United States to the maximum permissible concentration 12 times over. Such an even distribution of these materials would be impossible, but the figures serve to indicate that every reactor is a veritable Pandora's box.[72]

An even greater source of dangerous material is the fuel storage pond. According to a report by the U.S. General Accounting Office, storage areas are much more vulnerable than reactors. In such ponds, several spent reactor fuel-cores await reprocessing. And the reprocessing plant itself, in addition to being a handy source of plutonium, will contain about 150 times as much radioactive strontium as a reactor. If these concentrated and vulnerable sources of radioactive material became the target of a nuclear explosive—delivered either by a terrorist group or a hostile power—the destructive potential of the resulting hybrid would be mind-boggling.[73]

J. Bowyer-Bell comments in *Transnational Terror* on the recent terrorist "recognition of the potential for exploitation of the mass media." When terrorists kidnapped several OPEC oil ministers from Vienna in December, 1975, one of their demands was that their communique be read in full over television. A city held hostage to a nuclear threat would be a far more compelling lure for media coverage than the kidnapping of an ambassador or hijacking of an airliner.

The prospect of nuclear terror may at first seem attractive to partisans sympathetic to any particular terrorist cause, but an enemy is as likely to engage in nuclear terrorism as is an ally. Moreover, increasing numbers of terrorist episodes seem attributable to psychological rather than political motives: the Charles Manson massacre and Richard Speck killings had about as much ideological content as a street mugging.[74]

Guarding against terrorism requires foresight. But it also requires "2020" vision. Who in 1975 would have expected a group of South Moluccan extremists to hijack a train in the Netherlands in order to bargain for Moluccan independence from Indonesia? Protecting ourselves against future terrorism means nothing less than building a nuclear system able to withstand the tactics of future terrorists fighting for a cause that has not yet been born.

Nuclear Power and Society

Every major energy transition brings with it profound social change. The substitution of coal for wood and wind ushered in the industrial revolution. The petroleum era revolutionized mankind's approach to movement—restructuring our cities and shrinking our world. Now, at the twilight of the petroleum age, we face another energy transition in the certain knowledge that it will radically alter tomorrow's society. Each of the many energy options available to us today carries with it far-reaching social implications.

Nuclear power is highly centralized, technically complex, capital intensive, and fraught with long-term dangers. It produces electricity, a form of energy that is difficult to store and that can be transported only along expensive, vulnerable corridors. Some of the consequences of the widespread use of nuclear power can be easily anticipated. 55

Increased deployment of nuclear power must lead to a more authoritarian society. Reliance upon nuclear power as the principal source of energy is probably possible only in a totalitarian state. Nobel Prize winning physicist Hannes Alfven has described the requirements of a stable nuclear state in striking terms:

> Fission energy is safe only if a number of critical devices work as they should, if a number of people in key positions follow all of their instructions, if there is no sabotage, no hijacking of transports, if no reactor fuel processing plant or waste repository anywhere in the world is situated in a region of riots or guerrilla activity, and no revolution or war—even a "conventional one"—takes place in these regions. The enormous quantities of extremely dangerous material must not get into the hands of ignorant people or desperados. No acts of God can be permitted.[75]

The existence of highly centralized facilities and their frail transmission tendrils will foster a garrison mentality in those responsible for their security. Such systems are vulnerable to sabotage, and a coordinated attack could immobilize even a large country, since storing a substantial volume of "reserve" electricity is so difficult. Moreover, 100,000 shipments of plutonium each year would saddle societies with risks that have no peacetime parallel.

Nuclear power is viable only under conditions of absolute stability. The nuclear option requires guaranteed quiescence—internationally and in perpetuity. Widespread surveillance and police infiltration of all dissident organizations will become social imperatives, as will deployment of a paramilitary nuclear police force to safeguard every facet of the massive and labyrinthine fissile fuel cycle.

Broad nuclear development could, of course, be attempted with precautions no more elaborate or oppressive than those that have characterized nuclear efforts to date. Such a course would assure a nuclear tragedy, after which public opinion would demand authoritarian measures of great severity. Orwellian abrogations of civil liberties would be tolerated if they were deemed necessary to prevent nuclear terrorism.

Guarding long-lived toxic radioactive waste will require not just the sworn vigilance of centuries; it will require an eternal commitment. Thoughtful nuclear supporters are suggesting the creation of a nuclear "priesthood" to assume the burden of perpetual surveillance. Since the nuclear wastes now being created will remain toxic for 100 times longer than all recorded human history, an approach with quasi-religious overtones is only fitting.[76]

The capital-intensive nature of nuclear development will foreclose other options. As governments channel massive streams of capital into directions in which they would not naturally flow, investment opportunities in industry, agriculture, transportation, and housing—not to mention those investments in more energy-efficient technologies and alternative energy sources—will be bypassed. The U.S. Project Independence effort would require one trillion dollars by 1985, four-fifths of which would be earmarked for new rather than replacement facilities. Under such a scenario, new energy plants would require two-thirds of all net capital investment during that period. If Project Independence were more exclusively nuclear, the figure would be even higher.

With such a large portion of its capital tied up in nuclear investments, a nation will have no option but to continue to use this power source, come what may. Already it has become extremely difficult for many countries to turn away from their nuclear commitments. If current nuclear projections hold true for the next few years, it will be too late. Already there have been frightening examples of falsified reports filed by nuclear owners seeking to avoid expensive shutdowns. When vast sums are tied up in initial capital investments, every idle moment is extremely costly. After some level of investment, the abandonment of a technology becomes unthinkable.

In a world where money is power, these same large investments will cause inordinate power to accrue to the managers of nuclear energy.

"The nuclear Siren is presently attracting much interest, but hopefully her appeal will prove short-lived. Alternatives are abundant."

These managers will be a highly trained, remote, technocratic elite, making decisions for an alienated society on technical grounds beyond the public ken. C.S. Lewis has written that, "what we call Man's power over Nature turns out to be a power exercised by some men over others with nature as its instrument." As nations grow increasingly reliant upon exotic technologies, the authority of the technological bureaucracies will necessarily become more complete. Energy planners now project that by the year 2000 most countries will be building the equivalent of their total 1975 energy facilities *every three years*. Although central planners may have no difficulty locating such a mass of energy facilities on their maps, they will face tremendous difficulties siting them in the actual countryside of a democratic state.

A nuclear world would have international as well as national consequences. It would lead to increased technological dependence among nations, especially as the nuclear superpowers conspire to keep secret the details of the complete fuel cycle. Worldwide dependence upon nuclear power could lead to a new form of technological colonialism, with most key nuclear personnel being drawn from the technically advanced countries. The enormous costs of reactors will result in a major flow of money from poor countries to rich countries, as the former squander their scarce resources on these technological white elephants.

The nations of the world must together make an end-of-an-epoch decision. As the finite remaining supply of petroleum fuels continues to shrink, the need for a fundamental transition becomes increasingly urgent. The nuclear Siren is presently attracting much interest, but hopefully her appeal will prove short-lived. Alternatives are abundant.

Coal can play an important role in the immediate future. The energy content of the world's remaining coal far exceeds that of the remaining oil, and recent advances in mining and combustion will allow much of this resource to be tapped without imposing unacceptable environmental costs.

A wide range of solar devices is becoming available. Systems to capture low-grade heat to warm buildings and water—uses which constitute more than 25 percent of current energy needs in all countries—

are now on the market at competitive prices. Photovoltaics, thermal-electric systems, bioconversion processes, windpower, and other benign, renewable options promise large amounts of relatively low-cost, reliable, high quality energy with less effort than would be required by the new generation of breeder reactors. Solar options can be decentralized, simple, adapted to indigenous materials, and dependent only upon a country's energy "income" from the sun. They produce no toxic wastes and no potential bomb materials.[77]

Finally, it is of critical importance that greater attention be paid to opportunities for energy conservation. The United States could, according to several analyses, eliminate about half of its fuel budget without significant alterations in its economic system or its way of life. Even greater reductions might be accompanied by improvements in public health and the general quality of life. Sweden and West Germany manage to achieve an excellent standard of living on about half the U.S. per capita level of fuel consumption. Enormous savings can be made throughout much of the industrialized world, where for the last several decades cheap energy has been systematically substituted for labor, capital, and materials. Even in poor countries, the replacement of open fires with cheap, efficient stoves, the use of inexpensive pressure cookers instead of pots, etc., would allow significant energy savings. Moreover, such countries should employ anticipatory conservation measures in their development plans, taking care to avoid the sloppiness and wastefulness that characterize those nations that industrialized in the era of cheap oil.

It is already too late to halt entirely the widespread dissemination of the scientific principles underlying nuclear power. What *can* still be sought, however, is the international renunciation of this technology and all the grave threats it entails. Although the nuclear debate has been dominated by technical issues, the real points of controversy fall in the realm of values and ethics. No person, regardless of technical skill, has a right to impose a personal moral judgment on society. No country, regardless of strength, will be able to make the nuclear decision for the world. But if increasing numbers of people and countries begin independently and actively to oppose nuclear power, the world may follow.

Notes

1. Stockholm International Peace Research Institute, "A Tragic Paradox," *The Unesco Courier*, November, 1975.

2. Atomic Industrial Forum, "Nuclear Power Facts and Figures," December, 1975; United States, *Statistical Yearbook*, 1974; *World Environment Report*, June 9, 1975 (Special Nuclear Issue); International Atomic Energy Agency, *Market Survey for Nuclear Power in Developing Countries: 1974 edition*, IAEA-165 (Vienna: IAEA, 1974).

3. An overview of the Swedish position can be found in Lennart Daleu's "A Moratorium in Name Only," *Bulletin of the Atomic Scientists*, Oct., 1975; U.S. figures were obtained from Atomic Industrial Forum, *op. cit.*, and *Weekly Energy Report*, Jan. 5, 1975; *The Japan Times* has given much coverage to nuclear issues, and information on the Mutsu was obtained from the Jan. 16, 17, 19, 22, and Feb. 11, 17, 1976 issues; Information on France appeared in the *New York Times* for August 8, 1975, and *Weekly Energy Report* for May 26, 1975. Most other national data are from various issues of *Not Man Apart*, a publication of the U.S. branch of Friends of the Earth.

4. In 1975, nuclear exports amounted to $3.6 billion, two-thirds of which were U.S. sales (*The Economist*, December 6, 1975). William Casey, president of the Export-Import Bank, predicts that "within the next three years nuclear technology will become the U.S. economy's biggest export item." By far the most comprehensive analysis of nuclear exports is in Richard J. Barber, Associates, *L.D.C. Nuclear Power Prospects 1975-1990*, ERDA-52 (Springfield, Virginia: N.T.I.S., 1975). For insight into the attitude of the American business community on this issue, see Tom Alexander, "Our Costly Losing Battle Against Nuclear Proliferation," *Fortune*, December, 1975.

5. For a more detailed treatment, see John P. Holdren, "Hazards of the Nuclear Fuel Cycle," *Bulletin of the Atomic Scientists*, October, 1974.

6. Arell S. Schurgin and Thomas C. Hollocher, "Radiation-Induced Lung Cancers Among Uranium Miners," in Union of Concerned Scientists, *The Nuclear Fuel Cycle* (Cambridge, Mass.: The MIT Press, 1975).

7. Thomas C. Hollocher and James C. MacKensie, "Radiation Hazards Associated with Uranium Mill Operations," in Union of Concerned Scientists, *The Nuclear Fuel Cycle, op. cit.* David Dinsmore Comey ("The Legacy of Uranium Tailings," *Bulletin of the Atomic Scientists*, September, 1975) argues that the likely consequences of U.S. uranium processing through the year 2000 will be 5,741,500 lung cancer deaths over the next 80,000 years, assuming the population level soon stabilizes. Assuming that an inevitable death tomorrow is as tragic as a death today, this is an enormous health cost for a comparatively trifling amount of energy.

8. A controversy is developing as to whether the uranium enrichment should be trusted to private corporations. In the U.S. this issue has received particular attention, as the growing domestic market alone might require six to nine additional huge enrichment facilities during the next twenty-five years. A private consortium headed by the Bechtel Corporation is seeking federal financing guarantees for a large, private gaseous diffusion facility.

60 9. In centrifuge enrichment, uranium hexaflouride gas is fed into a spinning centrifuge. Here U-238 is spun towards the walls while the lighter U-235 passes into an upper chamber. The principal advantage of centrifuge enrichment is an energy requirement equal to about 10 percent that required by the gasious diffusion process.

Centrifuge enrichment has been successfully developed to the pilot-plant stage, and Urenco, Ltd., a British-Dutch-West German collaboration, is building one small facility at Capenhurst, England, and another at Almelo, Holland. In the United States, the federal government is constructing a slightly larger centrifuge facility at Oak Ridge, using a different technology, and three U.S. corporations are also seeking to enter the field.

In nozzle enrichment, a jet of uranium hexaflouride gas is squirted into a low pressure tank. The heavier U-238 tends to flow straight to a "paring" tube on the other side of the tank while the lighter U-235 tends to drift to the side.

Nozzle enrichment was developed in West Germany in the mid-1950s. Nozzle enrichment facilities should be comparatively easy to engineer, although their total energy requirements will be rather high. South Africa has done much of the commercial development of nozzle enrichment, and West Germany has contracted to build such a plant in Brazil.

Laser enrichment, the least developed of all enrichment technologies, is based on the fact that laser beams can sometimes selectively excite individual isotopes. Excited isotopes enter into chemical reactions that allow them to be separated from other isotopes of the same element. If laser enrichment technology becomes well-developed and widespread, the impact could be enormous. The energy requirements are comparatively slight; little space is required; and the cost will be trivial. Laser enrichment could make weapons-grade material available to any government and to any determined organization.

Nobel Laureate Hans Bethe, a forceful advocate of commercial nuclear power, has expressed the hope that, when developed, laser enrichment technology will be kept secret for as long as possible—perhaps even twenty or thirty years. However, this seems to be wishful thinking. Ground-breaking work has already been done in several countries, and important advances in the field of laser enrichment are even now being reported in unclassified publications.

10. David R. Inglis, *Nuclear Energy: Its Physics and Its Social Challenge* (Reading, Mass.: Addison-Wesley, 1972).

11. When the U-235 nucleus is split, its components (92 protons and 143 neutrons) become rearranged in two smaller atoms and several subatomic particles. Less "binding energy" is needed to hold together the nuclei of the several small atoms than was needed to bind the sub-atomic particles in the one large atom. When the large atom is split, the excess binding energy is released, captured as heat in the reactor, and used to boil water. **61**

When a U-235 atom is split into smaller atoms, neutrons not incorporated into the new elements fly off. Some of the free neutrons strike and split other U-235 atoms, causing a self-sustaining chain reaction. Many of the neutrons, however, do not encounter U-235 atoms. Some are absorbed by the moderator in the reactor core; some bombard the walls and other parts of the reactor vessel, causing them to weaken and become radioactive; and some neutrons encounter atoms of non-fissionable U-238.

Under certain circumstances a U-238 atom will "capture" a stray neutron. This addition changes the stable U-238 atom into an unstable uranium isotope that quickly decays into plutonium-239. Plutonium-239 is itself a fissile fuel, which can be split to power a reactor, giving off free neutrons that serve to continue the chain reaction. All uranium-fueled reactors transform some U-238 into plutonium. As soon as plutonium is formed, it begins contributing to the reactor's fissions. By the time fuel is removed from an LWR, about half the fissions are of plutonium. A 1000-megawatt LWR, operating at full power, will produce about 375 pounds of fissionable plutonium each year.

12. An excellent introduction to nuclear reactors by a thoughtful and knowledgeable nuclear critic is Walter Patterson's *Nuclear Power* (Harmondsworth, England: Penguin Books, Ltd., 1976).

13. LWR's are of two principal types: boiling water reactors, which are favored by General Electric; and pressurized water reactors, which grew out of the atomic submarine program and are now being promoted by Westinghouse Corporation, Babcock and Wilcox, and Combustion Engineering. G.E. and Westinghouse have licensed their reactor designs widely to firms in other countries.

14. Daniel F. Ford and Henry W. Kendall, "Catastrophic Nuclear Reactor Accidents," in Union of Concerned Scientists, *The Nuclear Fuel Cycle*, *op. cit.*

15. Hugh C. McIntyre, "Natural-Uranium Heavy-Water Reactors," *Scientific American*, October, 1975.

16. William D. Metz, "European Breeders: France Leads the Way," *Science*, December 26, 1975.; Walter C. Patterson, "The British Atom," *Environment*, December, 1972; Simon Rippon, "Fast Reactor Progress in the Soviet Union," *New Scientist*, December 4, 1975.

17. "NFS's Abnormal Occurrences Reports," U.S.A.E.C. Docket No. 50-201, 266-1972; Amory Lovins, private communication.

18. Marvin Resnikoff, "Expensive Enrichment," *Environment*, July-August, 1975.

19. Thomas C. Hollacher, "Storage and Disposal of High Level Radioactive Wastes," in the Union of Concerned Scientists, *The Nuclear Fuel Cycle*, *op. cit.*; Robert Gillette, "One Danger of Nuclear Progress: Nuclear Waste," *New York Times*, May 11, 1975.

20. Testimony by Henry Eschwage, Director of The Resources and Economic Development Division of the U.S. General Accounting Office, before the Subcommittee on Conservation, Energy, and Natural Resources of the House Committee on Government operations, Feb. 23, 1976.

21. The U.S. General Accounting Office, "Improvements in the Land Disposal of Radioactive Waste—A Problem of Centuries," 1976.

22. Norma Turner, "Nuclear Waste: Drop in the Ocean," *New Scientist*, October 30, 1975; *Weekly Environment Report*, June 23, 1975; Vaughn Bowen, private communication, April 23, 1976; Proceedings of the Conference on Transuranium Nuclides in the Environment, Nov. 17-21, 1975 (to be published by IAEA in late 1976).

23. *Business Week*, February 2, 1976.

24. *Wall Street Journal*, October 23, 1975; *Journal of Commerce*, January 5, 1975.

25. Testimony of Carl Builder, Director of the Division of Safeguards of the U.S. Nuclear Regulatory Commission before the House Interior Subcommittee on Energy and the Environment, February 27, 1976.

26. See, for example, Marc Ross, "The Transportation of Radioactive Wastes: The Possibility of Release of Cesium," in Union of Concerned Scientists, *The Nuclear Fuel Cycle*, *op. cit.*

27. *Energy Finance Week*, September 10, 1975.

28. David Dinsmore Comey, private communication, April 13, 1976.

29. See David Dinsmore Comey, "Will Idle Capacity Kill Nuclear Power?" *Bulletin of the Atomic Scientists*, November, 1974. Figures 1 and 2 are derived from subsequent articles by Comey (October, 1975), responding to criticisms of his 1974 article. 63

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32. A considerable body of literature on the net energy of nuclear power has been produced over the last two years. See P. Chapman and N. Mortimer, "Energy Inputs and Outputs for Nuclear Power Stations," Research Report ERG 005, Open University, Milton Keynes, U.K., 1974; John Price, "Dynamic Energy Analysis and Nuclear Power," in Amory B. Lovins and John H. Price, *Non-Nuclear Futures* (Cambridge, Mass.: Ballinger Publishing, 1975); Gerald Leach, *Nuclear Energy Balances in a World With Ceilings* (London: International Institute for Environment and Development, 1974); Ralph M. Rotly, A.M. Perry, and David B. Reister, "Net Energy from Nuclear Power," (Oak Ridge, Tennessee: Institute for Energy Analysis, 1975).

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34. Irwin C. Bupp, et. al., "The Economics of Nuclear Power," *Technology Review*, February, 1975.

35. There is talk of tailoring a standardized 300-megawatt unit for export to poorer countries. However, such units might require ten years of development and still prove more costly than many available alternatives.

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39. *Weekly Energy Report*, September 8, 1975.

40. U.S. Atomic Energy Commission, "The Safety of Nuclear Power Reactors (Light Water Cooled) and Related Facilities," WASH-1250 (1973).

41. U.S. Atomic Energy Commission, "Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants," WASH-1400, (1975). For a critique of the techniques employed by the Rasmussen study, see Milton Kamins, *A Reliability Review of the Reactor Safety Study*, (Santa Monica, California: The Rand Corporation, 1975).

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43. Cottrell was commenting on unexpected metallurgical developments in a 1975 disaster involving a chemical factory in Flixborough.

44. The cost of repairing actual fire damage was about $7 million. The cost of idle investment in the two shut down reactors, according to the TVA public information office (April 9, 1976), was about $10 million per month.

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DENIS HAYES is a Senior Researcher with Worldwatch Institute. His research encompasses alternative global energy strategies, energy conservation, and nuclear proliferation. Prior to joining Worldwatch, he was director of the Illinois State Energy Office, a guest scholar at the Woodrow Wilson Center of the Smithsonian, and head of Environmental Action.

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