mit burning of these coals without adverse environmental effects are approaching full development and should encourage wider use of coal in electricity generation for the next 25 years. Estimates indicate that more than 40 sulfur dioxide scrubbing units will be installed on power plants totaling about 20,000-Mw capacity by late 1976 (*15*). The cost of these units will approach $750 million. Although this is not a significant amount of our coal-fired generating capacity, these installations should give impetus to construction of more and larger ones by 1980 and the next decade; this would refute the tenet that wide use of coal and a clean environment are mutually exclusive. As the choice of proved scrubbing technology broadens, no single process will dominate the market. Individual utilities, in addition to considering the economics, will be faced with making choices on the basis of the type of coal burned; water, land, and air pollution regulations; and the marketability of the end products.

The cost of flue gas desulfurization will be high, ranging from 1.2 to 3.2 mill/kwh. The average increase in electricity cost to consumers is expected to be about 3 to 6 percent, and in some instances as much as 15 percent. However, the added burden may not be as high as that of dependence on foreign oil, both in terms of price and reliability of supply. Combustion of high-sulfur coal followed by stack gas cleanup appears to be the cheapest alternative for meeting our electricity needs in the next few decades.


### References and Notes

1. *U.S. Geol. Surv. Bull No. 1136* (1961); *ibid., No. 1275* (1969); *U.S. Bur. Mines Inform. Cir. No. 8531* (1971); Geological Survey, unpublished data; Bureau of Mines, unpublished data.
2. P. Averitt, *U.S. Geol. Surv. Prof. Pap. No. 820* (1973), p. 133.
3. W. G. Dupree, Jr., and J. A. West, *United States Energy Through the Year 2000* (Department of the Interior, Washington, D.C., 1972).
4. *Steam Electric Plant Factors/1967 Edition* (National Coal Association, Washington, D.C., ed. 17, 1967).
5. Data available from the Federal Power Commission and Bureau of Mines, *Bituminous Coal Data* (National Coal Association, Washington, D.C., 1973), pp. 108–109.
6. *Steam-Electric Plant Factors/1972 Edition*, (National Coal Association, Washington, D.C., ed. 22, 1972).
7. E. F. Osborn, *Science* **183**, 477 (1974).
8. *Fed. Reg.* **36**, 8185 (30 April 1971); *ibid.* **38**, 25678 (14 September 1973).
9. *Ibid.* **36**, 24875 (23 December 1971).
10. "East coast shifts to greater use of coal for electric generation, 'borrows' electricity from other utilities (press release and status report, Federal Energy Office, Washington, D.C., 6 February 1974).
11. "U.S. energy use up nearly 5 percent in 1973" (press release, Bureau of Mines, Department of the Interior, 13 March 1974).
12. T. L. Montgomery, J. M. Leavitt, T. L. Crawford, F. E. Gartrell, *J. Met.* **25** (No. 6), 35 (1973).
13. *Fed. Reg.* **38**, 25697 (14 September 1973).
14. National Academy of Engineering–National Research Council, *Abatement of Sulfur Oxide Emissions from Stationary Combustion Sources* (P.B. 192,887, National Technical Information Service, Springfield, Va., 1970).
15. Federal Interagency Committee Evaluation of State Air Implementation Plans, *Final Report of the Sulfur Oxide Control Technology Assessment Panel on Projected Utilization of Stack Gas Cleaning Systems by Steam-Electric Plants* (Report No. APTD-1569, Environmental Protection Agency, Research Triangle Park, N.C., 1973).
16. J. McLaren and D. F. Williams, *Combustion* **41** (No. 11), 21 (1970).
17. F. Princiotta, "EPA presentation on status of flue gas desulfurization technology," testimony at national power plant hearings sponsored by the Environmental Protection Agency, 18 October to 2 November 1973 (hearing records available for consultation at the Environmental Protection Agency, Washington, D.C.).
18. G. T. Rochelle, paper presented at the flue gas desulfurization symposium of the Environmental Protection Agency, New Orleans, 14 to 17 May 1973.
19. A. V. Slack, H. L. Falkenberry, R. E. Harrington, Preprint 39d, 70th national meeting, American Institute of Chemical Engineers, Atlantic City, N.J. 29 August to 1 September 1971.
20. J. K. Burchard, paper presented at the technical conference "Sulfur in utility fuels: the growing dilemma," sponsored by *Electrical World Magazine*, 25 to 26 October 1972.
21. I. S. Shah and C. P. Quigeley, Preprint 39e, 70th national meeting of the American Institute of Chemical Engineers, Atlantic City, N.J. 29 August to 1 September 1971.
22. W. R. Horlacher, R. E. Barnard, R. K. Teague, P. L. Haylen, paper presented at the 71st national meeting of the American Institute of Chemical Engineers, Dallas, Tex., 20 to 23 February 1972.
23. J. L. Martinez, C. B. Earl, T. L. Craig, in *AIME Environmental Quality Conference, Washington, D.C., June 7–9, 1971, Preprint Volume* (American Institute of Mining, Metallurgical, and Petroleum Engineers, Washington, D.C., 1971), pp. 409–420.
24. J. B. Rosenbaum, W. A. McKinney, H. R. Beard, L. Crocker, W. I. Nissen, *U.S. Bur. Mines Rep. Invest. No. 7774* (1973).
25. F. S. Chalmers, L. Korosy, A. Saleem, paper presented at the Industrial Fuel Conference, West Lafayette, Ind., 3 October 1973.


# Nuclear Eclectic Power


David J. Rose


Enough work has been done to permit a reasonable assessment of the major issues of nuclear power. Most of the recent fluctuations in energy patterns tend to reinforce what seemed evident even several years ago: a massive switch to nuclear power for electric energy generation, and perhaps later for other purposes. The total installed electric utility generating capacity in the United States is expected to be 480,000 megawatts by the end of 1974 (*1*); the average generation rate in March 1974 was 212,000 Mw (*2*). The present nuclear installed capacity is about 30,000 Mw. Serious predictions of 1,000,000 Mw of nuclear power installed by A.D. 2000 may come true; the total cost of those nuclear plants would be more than $600 billion. The grand total, including factories to produce the equipment and facilities to enrich uranium, process fuel, and handle wastes, may come to $1 trillion, plus the cost of transmitting and distributing the energy. Also, as alternate fuel costs rise, nuclear heat will become interesting for large-scale industrial and commercial applications. If events turn out this way, nuclear power will constitute the largest coherent technological plunge to date, with long-lasting consequences.

Any assessment of nuclear power, to be useful, must be comparative; the question is, compared to what? Until about A.D. 2000, the major choices are nuclear power, fossil fuels (of various sorts), or nothing, in varying proportions. In the 21st century, they are advanced nuclear power, increasingly sophisticated chemical fuels, probably derived from coal or oil shales, perhaps hydrogen (but made with nuclear power), perhaps solar power (more likely for many small-scale applications, in my opinion), or nothing. Beyond that era, resource limitations increasingly exclude fossil fuels. The


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Table 1. U.S. uranium reserves (7). The amount of $U_3O_8$ available comprises reasonably assured plus estimated additional reserves; ppm, parts per million.

| Concentration: $U_3O_8$ in ore (ppm) | $U_3O_8$ | | Electricity producible ($10^3$ megawatt-years) | |
|---|---|---|---|---|
| | Cost (dollars per pound) | Amount available ($10^3$ tons) | Light water reactor | Breeder reactor |
| > 1600 | Up to 10† | 1,127 | 6,600 | 880,000 |
| > 1000 | Up to 15† | 1,630 | 9,500 | 1,270,000 |
| > 200 | Up to 30† | 2,400 | 14,000 | 1,860,000 |
| > 60 | Up to 50‡ | 8,400 | 49,000 | 6,500,000 |
| > 25 | Up to 100‡ | 17,400 | 102,000 | 13,500,000 |
| 3* | Several hundred | $10^6$–$10^7$ | | |

* Natural crustal abundance. † Includes copper leach residues and phosphates. ‡ Includes Chattanooga shale.

benefits of nuclear power are lower production costs, vastly larger resources, and (I will try to show) substantially less total adverse environmental impact compared with fossil fuels. Costs and hazards include not only the usual economic ones of the facilities themselves, but also those associated with (i) illegal diversion of nuclear fuels, (ii) accidents, (iii) radioactive waste storage, and (iv) other environmental and societal impacts.

In this article, I will not seriously entertain the notion of opting for less electric power, believing that economic, demographic, and other social forces already present will lead to substantial increases in demand over the next several decades. The precise amount of growth turns out not to affect this discussion. Thus, while recognizing the necessity, importance, and consequences of limiting growth and of conserving energy wherever possible, one can debate the issue of nuclear power during the next 50 years separately.

## Nuclear Plant Properties, Economic Costs, and Demand

This is not an article on reactor principles, but a few remarks will facilitate the debate that follows.

Virtually all present-day nuclear power reactors work on the basis of fissioning the relatively rare isotope uranium-235 (0.77 percent of natural uranium) to produce fission products (chiefly intermediate-weight elements), about 2.5 neutrons per event, and energy (200 million electron volts per event). Some neutrons go on to initiate further $^{235}U$ fissions; controlling the neutron fate by initial design and by adjustment of neutron-absorbing materials controls the reactor. Also, some neutrons are absorbed in the predominant uranium isotope $^{238}U$ to make a substantial amount of plutonium ($^{239}Pu$). The conversion ratio ($^{239}Pu$ formed/$^{235}U$ fissioned) is about 0.5 for reactors being installed today. Thus, current reactors bring with them plutonium handling and hazard problems, which are incorrectly thought by some to apply only to future breeder reactors. Some of the $^{239}Pu$ actually fissions in the reactor; most is removed at fuel reprocessing time, then stored for later use in the first breeder reactors, for which it is the fissionable fuel. Also, $^{239}Pu$ can be recycled as fuel in present-day reactors, but that has not been done yet.

Turning now to more specific types, the reactors most commonly used and ordered in the United States contain fuel and ordinary (light) water in large pressure vessels, the so-called light water reactors (LWR's). They operate at 1000 to 2200 pounds per square inch ($\sim 15 \times 10^6$ newtons per square meter) and 315°C; the safety of this arrangement and its associated piping has been the subject of recent lively debate. The relatively low operating temperature limits the net efficiency of these plants to 32 percent. There are two subspecies: the pressurized-water reactor, where the water does not boil, but passes into a heat exchanger that produces steam for the turbines in a separate loop; and the boiling-water reactor, where the steam from the pressure vessel passes directly through the turbines. The first of these was developed principally by the Westinghouse Electric Company, partly from experience in building smaller versions for the U.S. Navy. The second was developed solely by the General Electric Company. Importantly, both companies could afford to offer loss leaders, so to speak, in order to capture a substantial early share of the reactor market; thus, LWR's have proliferated, almost to the exclusion of other types. Advantages are: relatively well-developed technology and predictable performance, well-developed fuel cycle technology, best-known cost. Disadvantages are: low efficiency, public questions about reactor safety, only moderate conversion efficiency (0.5). A somewhat neutral feature is the requirement for fuel enriched to 3 percent $^{235}U$; present uranium enrichment facilities will require substantial augmentation, at a cost of several billion dollars, in the 1980's.

Other reactor species need mentioning here. In the United States the General Atomic Company has for years been developing slowly a high-temperature gas-cooled reactor (HTGR), but could not afford to offer a loss leader. Thus the HTGR, which many imagine to be a better idea, lagged until the Gulf Corporation, and later Shell also, took it over. Advantages are: higher operating temperature and efficiency (40 percent), possibly lower cost, higher conversion ratio (0.7, intermediate between the LWR converters and a true breeder), and the absence of some mechanical failure modes discussed in relation to LWR's. Disadvantages are: there is only one supplier, whose fuel must be fully enriched fissionable uranium, which is weapons-grade material and thus raises the specter of illegal diversion (but design changes could permit using lower enrichment); and the fuel cycle is incompletely developed. In this last respect, a typical problem is what to do with the large amount of slightly radioactive graphite in which the fuel will be embedded. Burning it freely seems not acceptable, but I see nothing to prevent turning it into an insoluble chemical (a carbonate?) and sequestering it safely. At present, one HTGR is about to commence operation, six more are on order, and some analyses have shown the HTGR taking over a substantial share of future markets. The present fuel for the HTGR is $^{235}U$, but eventually it would work mainly on the thorium-$^{233}U$ cycle.

Another candidate is the Canadian CANDU reactor, of which several are in operation there, with others on order for Mexico and outside North America. The CANDU is of pressure-tube construction (thought to be a safer design than the U.S. light water reactors) and permits on-line refueling. It can run on natural uranium (but does better with enriched fuel), because it is moderated and cooled with heavy water; it is an older design than most, and operates at even lower efficiency than the U.S.

light water reactors. It is probably more expensive than the U.S. reactors, but how much is hard to discover, because of differences between U.S. and Canadian costing policies. Another version is the heavy-water-moderated organic-liquid-cooled demonstration reactor at Whiteshell station, Manitoba. If the United States were starting its reactor program today, with no large commitment already made, the Canadian ideas would merit serious consideration; but under present circumstances, the need for development and prototype construction makes any such introduction to the U.S. market unlikely.

All modern nuclear power reactors are large, to capture economies of scale inherent in building larger components (up to a limit). The U.S. Atomic Energy Commission has limited all reactor approvals (until 1978 at least) to units that develop not more than 3800 Mw of nuclear heat. Thus, LWR's at 32 percent efficiency will be limited to 1200 megawatts electric [Mw(e)] and HTGR's at 40 percent to 1500 Mw(e).

These comparisons have international impact. New electric plants in France will be LWR's of the U.S. type. The United Kingdom is finishing a complex internal debate over whether to build more of its ancient but familiar (to the British) gas-cooled Magnox reactors, to adopt LWR's of U.S. type, or to adopt a version of the Canadian reactors.

Turning now to costs, an excellent study has been made of nuclear and fossil fuel possibilities for the Northeast Utilities system by Arthur D. Little, Inc. (*3*). A.D.L. estimates total capital cost per kilowatt of $389 for an oil-fired plant, $588 for a coal plant with sulfur and particulate removal, and $702 for an LWR, all for operation in 1981. These figures are much higher than those guessed in the 1960's for several reasons: substantially higher construction costs of all kinds, need for environmental controls on fossil fuel plants, need for more experience by the nuclear industry, increasing complexity of nuclear plants, and construction delays (which add interest and inflation charges). These capital costs appear in the electric bill at about 1¢ per kilowatt-hour for each $500 (for 7000 operating hours per year and a 14 percent rate of return on capital before taxes). Thus, at this stage nuclear power has a disadvantage of about 0.2¢/kwh with respect to coal and 0.64/kwh with respect to oil.

Operation and maintenance costs (0.09¢, 0.18¢, 0.135¢ per kilowatt-hour for oil, coal, and nuclear fuel, according to A.D.L.) give a slight further advantage to oil. But the greatest single fact influencing present demand for nuclear power is that petroleum at $10 per barrel (0.16 $m^3$) represents 1.5¢/kwh of the cost of electricity, using the most efficient plant available (40 percent). Total nuclear fuel cycle costs will be less than 0.3¢/kwh, giving an advantage over oil of 1.2¢/kwh, and an overall system advantage of 0.5¢/kwh. Much the same situation is predicted for coal, and the gap between nuclear and fossil fuels will widen with time. Petroleum prices, now about three times higher than those prevailing in early 1973, are not likely to decline very much, being supported both by a shortage of cheap oil in oil-consuming countries and increasing economic sophistication in the oil-producing ones. The likely advent of more domestic crude oil at prices of $7 to $10 a barrel, or of synthetic crude at perhaps the same price (after the middle 1980's?) still leaves nuclear power with strong economic advantage.

Studies like this show that nuclear power has become by far the most attractive large option for electric power generation, both in the United States and abroad, with few exceptions. The energy crisis of 1973–1974 is one of fossil fuels, not nuclear ones, and nuclear power tends to benefit on that account. Development of a strong conservation ethic will not have the effect of strongly decreasing the growth rate of nuclear power; the first results would be a limitation of nonnuclear plant construction or operation.

Here are some projections. The year A.D. 2000 is a good date to focus on: Plants planned today will be halfway through their operating life. The AEC estimates 1,200,000 Mw of nuclear capacity installed by that date (*4*), and Dupree and West's predictions (*5*) amount to about 960,000 Mw. Considering the capacity of plants now operating (30,000 Mw), under construction, or planned for operation before 1985 (about 200,000 Mw), the various factors mentioned above, and the traditional growth of electric power (7 percent per year), an installed capacity of 1,000,000 Mw nuclear seems likely to be exceeded. Beyond A.D. 2000, the rate of growth is more difficult to predict: acceptable sites will be particularly hard to find, even with use of wet cooling towers, and dry cooling towers are even larger and more expensive ($100/kw?); and the likelihood and timing of new major applications (such as making hydrogen from cheap nuclear heat or electricity, or powering personal electric vehicles) are unknown factors at present. The 1,000,000 Mw of nuclear electric power is imagined to be perhaps two-thirds of the total electric capacity predicted for A.D. 2000, about four times the capacity of present installations. Western Europe and Japan, with less fossil fuel resources than the United States, find nuclear electric power even more attractive.

**Resources**

Various scenarios (*6*) predict a total cumulative requirement of about 2.5 million tons of uranium oxide ($U_3O_8$) by A.D. 2000 and 4 to 4.5 million tons by A.D. 2010. The precise amount depends on the mix of reactor types, on when breeder reactors are introduced, and on the actual future electric demand.

The U.S. uranium resources according to the AEC (*7*) are shown in Table 1. The resources available up to $10 a pound (~ 0.45 kg) would, if used in LWR's, generate 6,000,000 megawatt-years of electricity, a total electric supply for almost 30 years at present rates, but not enough for the growing nuclear demand to A.D. 2000. With LWR's, the increase in the cost of electricity would be 0.1¢/kwh for each increase of $17 a pound in $U_3O_8$. To wipe out the present nuclear cost advantage of at least 0.5¢, $U_3O_8$ would have to reach nearly $100 a pound, at which cost Table 1 shows a great deal of uranium available.

The numbers in Table 1 provide a substantial fraction of the input for the debate pro and con nuclear power and especially for the nuclear breeder debate. The AEC saw trouble ahead, from these and similar estimates made a few years ago: If used in LWR's, the low-cost reserves are modest, and rising $U_3O_8$ prices after (say) A.D. 2000 would place a new penalty on nuclear power, perhaps 0.1¢/kwh. Thus, it was necessary to develop the breeder reactor; by converting the common $^{238}U$ to fissionable plutonium, it utilizes almost all the nuclear energy of the uranium, instead of only the $^{235}U$ plus a small additional plutonium conversion. In effect, not only are the nuclear energy resources multiplied by a factor of

Table 2. Summary of health effects of civilian nuclear power, per 1000 Mw(e) plant-year (8).

| Activity | Fatalities | | | Injuries (days off) |
|---|---|---|---|---|
| | Accidents (not radiation-related | Radiation-related (cancers and genetic) | Total | |
| Uranium mining and milling | 0.173 | 0.001 | 0.174 | 330.5 |
| Fuel processing and reprocessing | 0.048 | 0.040 | 0.088 | 5.6 |
| Design and manufacture of reactors, instruments, and so on | 0.040 | | 0.040 | 24.4 |
| Reactor operation and maintenance | 0.037 | 0.107 | 0.144 | 158 |
| Waste disposal | | 0.0003 | 0.0003 | |
| Transport of nuclear fuel | 0.036 | 0.010 | 0.046 | |
| Totals | 0.334 | 0.158 | 0.492 | 518 |

100, but (since almost all of it is used) the resource cost per energy unit drops similarly. Thus, to a good approximation, the cost of electricity from nuclear breeders becomes independent of uranium prices. Also, at least by implication, if the breeder were not developed and massively deployed in time, nuclear power might become expensive enough to drive electric utilities back to fossil fuels. Thus, a "slot" in time was imagined when breeder reactors must be introduced—late enough that plutonium would be available from existing LWR's to make initial fuel charges, but not so late that power from LWR's would have become expensive because of the rising cost of uranium. The period 1985 to 1995 was envisaged for commercial introduction.

With present oil and coal prices and environmental protection costs the slot is virtually open-ended, and the nuclear advantage is unlikely to be overcome by any large-scale fossil option, except in special locations. Also, the entire debate is likely to have been mistaken, as follows. With a real market for $U_3O_8$ at (say) $10 a pound, prospectors seriously searched for high-grade ore, and the 1,127,000 tons of reserves shown in Table 1 is the result. But what of the approximately equal increment represented by the third row of Table 1, supposed to include all ores with a $U_3O_8$ concentration greater than 200 parts per million? Those lower grades were not actively sought per se, but were found somewhat incidentally. Thus we can explain the anomalous dip in reserves at intermediate prices and concentrations—no one seriously looked for them. The outcome of the reasoning is that if a definite offer to purchase were made at more than $10 a pound, a great deal more would easily be found, and the AEC would have no scarcity argument in favor of the breeder until well into the 21st century. Three additional circumstances support this interpretation: (i) In the middle and late 1950's and 1960's, when the federal government offered incentives to discover new uranium resources, much showed up at $8 to $10 a pound. (ii) The reserves at $10 a pound are enough for nearly 30 years for domestic purposes. This is an anomalously large amount in terms of the economic optimum (at private investment rates); for decades our reserves of many minerals have represented a supply for 8 to 10 years, and this has been determined by economic pressures to buy them and economic penalties for exploring for things that will not be used for a long time. (iii) Canada and Australia, for instance, report increasingly large resources.

A generally similar debate could be constructed for thorium, which can be used in a breeder to make $^{233}U$; it is thought to be at least as plentiful as uranium.

## Diseconomies and Nonmarket Costs

More important issues appear here than there is space properly to discuss, so I choose to develop three in subsequent sections—illegal acts, accidents, and radioactive waste disposal—and give brief mention to others that have already been well illuminated in public debate.

Present nuclear plants are less efficient than fossil fuel ones, and in addition do not exhaust any waste heat directly to the atmosphere through a chimney. Thus a light water nuclear plant will reject into cooling water almost twice as much waste heat as do the most efficient fossil fuel plants, for the same electric power. Siting problems then ensue, exacerbated by the large size of the power plants. But these problems seem surmountable, perhaps at a cost of visual pollution from cooling towers or design complications arising from siting off-shore; and introducing more efficient reactors will eventually ameliorate the difficulty.

Licensing is a complex issue. Two separate federal licenses are required: before construction and again before operation. At each stage, detailed studies are required, including environmental impacts, and interveners must be heard. Long delays then become possible; they are expensive—$50,000,000 a year in interest and other charges on a completed nonoperating plant. One might imagine, therefore, some reversion to fossil-fueled plants for which, alas, no such licensing is required; but cost penalties make that alternative unattractive.

## Illegal Acts

The problem is vexatious, and even discussion can be dangerous. Two nonproblems are: (i) Present security arrangements at reactors make it highly unlikely that one or a few persons, even well-prepared, can cause a large disruptive accident. (ii) Stealing new fuel for LWR's is useless, because the fuel is nonradioactive and cannot be enriched to weapons-grade $^{235}U$ (90 percent +) without a technology capable of doing the whole job, starting with natural uranium.

However, a number of possibilities exist for illegal acts, against which the reactor operators and public authorities (particularly the federal government) take increasingly strict precautions, whose adequacy has from time to time been questioned.

1) A large, organized raid on an operating reactor. The outer containment shell will resist the impact of moderate-size airplanes, and shells of reactors near airports are designed to resist the impact of the largest loaded airplanes. Thus, ingress would have to be made by direct attack on the entrances, and various security steps have been taken against this possibility. It would be logical to arrange reactor protective devices so that the reactor would shut down when any such hostile event occurred and could not be restarted except through time-consuming operations by experts; in that case attackers could cause financial mischief, but no public calamity. In addition,

reactors are so complex that the active assistance of knowledgeable persons inside seems necessary; thus, to summarize this item, an economic calamity causable by an irrational employee seems the dominant danger.

2) Theft of used fuel elements. Until recently, used fuel was shipped in technically safe casks, but with almost no guard. That has now been corrected, and the used fuel is monitored during shipment in various ways. Making a bomb from it requires technological facilities and sophistication comparable to those of the AEC itself. The most likely threat would come from the fuel being ground up and used for blackmail, a strategy which would be very hazardous to the conspirators.

3) Theft of makeup fuel for high-temperature gas-cooled reactors, which is 93 percent $^{235}U$. This is weapons-grade material, and must be handled as such.

4) In the future, theft of breeder fuel, which is weapons-grade plutonium. The possibilities for mischief and handling requirements are the same as for item 3 above; but the risk to conspirators is immense, because plutonium is so lethal (see below).

It seems to me that the greatest diversionary hazard is related not to civilian nuclear power, but to weapons and their components. At increasing cost, more protection can be bought, and no one—public or private—would imagine settling for less than enough. But in dealing with irrationality, how much is enough? No one knows. It would be bitter irony if civilization had to renounce its claim to that name through inability to control these aspects of nuclear power; meanwhile, illegal use is to me the most worrisome and least resolved hazard, and a prime motivation for exploring the possibilities of controlled nuclear fusion.

### Accidents and Related Hazards

An immense amount has been done; the situation is in no way as some critics of nuclear power portray it, but trouble spots persist. Before some hotly debated topics are assessed, consider Table 2, which summarizes a study made by Walsh (*8*) of the casualties associated with nuclear power. Events are normalized per unit of electric energy produced—per 1000 Mw(e) plant-year ($8.76 \times 10^9$ kwh).

Several features of Table 2 are notable: (i) "conventional" accidents are dominant, especially in the hazardous occupation of mining; (ii) the total fatality rate is about 0.5 per reactor-year, *tout compris*; (iii) most of the hazards are occupational, not public. These numbers will be compared later with others for fossil fuel power.

The data of Table 2, gleaned from a large number of sources, are in reasonable agreement with those of other studies. Hub *et al.* (*9*) report 0.932 fatality and 373 total days off due to injuries, and Sagan (*10*) reports 0.390 and 1022, respectively. The AEC (*11*) settles on the range 0.161 to 0.364 for fatalities, and does not give an estimate of injuries. A variation of a factor of 2 should be expected because of the periods studied, assignment of casualties, and so forth. For example, of 11,870 short tons of $U_3O_8$ produced domestically in 1969, 4700 were sold for electricity production and only about 350 were actually used up that year in operating reactors (1 short ton $\sim$ 0.9 metric ton). Also, the various investigators agree fairly well that occupational accidents unrelated to radiation dominate. For example, Lave and Freeburg (*12*), in an exceptionally well-documented comparison of the effects on health of electricity generation from coal, oil, and nuclear fuel, cite about 0.12 fatality per 1000 Mw(e) plant-year from mining and milling accidents, compared with Walsh's 0.173.

Table 2 does not seem to contain the item most hotly debated: the probability of large nuclear accidents, for example from a pipe rupture, followed by failure of the emergency core cooling system, followed by transfer of a substantial fraction the radioactive mess to the external environment. It was just this possibility that stimulated a marathon debate between the Union of Concerned Scientists and the AEC from 1972 to 1974 (*13*). An intensive study of hypothetical large accidents has been made by N. C. Rasmussen and co-workers for the AEC. No such reactor failures have occurred, but the data base is nevertheless substantial—all the large high-technology, high-pressure, high-temperature chemical processors and vessels. According to Chairman Ray of the AEC (*14*) the Rasmussen study can be roughly summarized by assigning a chance of about $10^{-6}$ per reactor-year of a major accident with loss of several hundred lives, including later cancers and genetic deaths. For the sake of argument, make this 1000 lives. The actuarial hazard would be $10^{-3}$ per 1000 Mw(e) plant-year, and it duly appears as a 1 percent contribution to one of the entries in Table 2.

Also present in Table 2 are the public hazards from releasing radioactive gases—principally $^{85}Kr$ and tritium—from boiling-water reactors during operation, from pressurized-water reactors during refueling, and from fuel reprocessing plants. Radioactive xenon presents less total hazard, because it decays quickly. New reactors built with longer gas holdup permit even lower releases.

No substantial quantitative study is in disagreement with these results. The AEC itself prepared a now-notorious report (*15*) predicting several thousand deaths and billions of dollars damage if a large amount of material from a modest-size reactor got into the atmosphere under adverse meteorological conditions. The authors of that work never considered the probability of any sequence of events leading to the hypothetical radioactive release; this makes it somewhat like analyzing (say) the consequences of the New York World Trade Center falling over.

If Rasmussen's estimates are believed, the fatality rate per person would be about $10^{-12}$ per hour in A.D. 2000, about the same as the probability of being struck by a meteorite, and a thousand times less than the probability of being electrocuted.

Having seemed to bury the reactor accident bogey, let me now resurrect it. Accidents seem so remote only because of intense, persistent, and highly competent professional effort. Will that continue indefinitely, or not, and is reactor technology that good worldwide? One can easily imagine inadequate vigilance, both here and abroad, or what is just as bad, lack of social responsibility toward these matters; then disaster would surely follow.

The accident issue cannot be closed without mention of plutonium, a principal and proximate cause for the worry. An excellent and convenient review has been given by Bair and Thompson (*16*); the AEC has long been concerned (*17*). Plutonium is an alpha-particle emitter; when introduced into the body in a soluble form, it (i) circulates as complexes in the blood in large molecules; (ii) gets into the bones; (iii) goes to the liver, where it tends to stay unless there is a stress on the body's iron stores; and (iv) as with iron, gets caught up in the body's transport and storage system, which prevents loss and promotes reuse. When introduced as particulates (usually the oxide) through wounds or by inhalation, some of it forms local tiny hot spots, and some travels throughout the body. It is thought to be about five times as toxic as radium, and present maximum occupational body burden is now set at 40 nanocuries (0.6 microgram of $^{239}Pu$, but only 2.3 nanograms of $^{238}Pu$). These limits, based in part on comparisons with the effects of radium, have been questioned because of the concentration in the liver, which is not the case with radium, and the problem of hot spots. On this latter point, Tamplin and Cochran (*18*) pick a probability of 1/2000 that a single hot plutonium particle will cause cancer, and propose a body burden limit of two such particles. That would be $1.4 \times 10^{-13}$ curie, a factor of 300,000 below the present limits. So far, the evidence indicates that plutonium is not that dangerous, and that something near the present limits will eventually be well justified. In the meantime, experimental work on animals continues, and persons inadvertently exposed in the past to plutonium are carefully monitored.

It is very unsettling that present reactors contain substantial amounts of plutonium, and breeder reactors will contain a huge quantity—close to $10^6$ curies. The extreme ratio between the resource available and the allowable body burden emphasizes the necessity of vigilance, which must be presumed to exist everywhere, forever. If the Tamplin and Cochran risk estimates turn out to be correct, nuclear fission power will need to be rethought, because the consequences of even a single large accident become disastrous.

## Nuclear Waste Disposal

The costs of proper waste disposal are higher than were originally imagined, but still small compared to the total costs of nuclear power. The main problems seem to have been failing to appreciate the importance of public concern and failing to explore the available options with enough money and imagination. Fortunately, those shortcomings in the civilian waste disposal program are being corrected.

A more comprehensive assessment of the situation has appeared (*19*), and a brief summary will suffice here. The wastes fall into two categories. First, there are fission products of intermediate atomic weight, $^{90}Sr$, $^{137}Cs$, and $^{85}Kr$, for example, and all the main ones have half-lives of 30 years or less; thus, in 700 years less than $10^{-7}$ of the waste remains, which further calculation shows is innocuous. Second, there are the so-called actinides, mainly plutonium, neptunium, curium, americium, and so on, all heavy elements made by neutron absorption in the original uranium (or thorium, if the reactor works on a $^{232}Th$-$^{233}U$ breeding cycle). These typically have very long half-lives—24,600 years for $^{239}Pu$, for example. All these elements are very toxic, because of their radioactivity, proclivity to settle in bone and other body sites, and so on. If merely stored they last a million years or more, beyond the time horizon of present rational planning.

At present, only plutonium and uranium values are extracted from the wastes, and that only to about 99.5 percent (the limit of profitable recovery); this narrow economic optimum is clearly not the social one; an extraction of 99.9 percent of uranium, neptunium, and plutonium and 99 percent of americium and curium reduces the long-term activity by a factor of 100 compared to present practices, leaving essentially just the fission products. The extracted actinides can be recycled in the reactor at small penalty; they all turn eventually into fission products, and the million-year problem is effectively eliminated. Kubo and Rose (*19*) estimated an additional cost of perhaps 0.02¢/kwh for implementing this option.

Now the nuclear waste problem becomes a 700-year one—a long time, but short compared to geologic eons. Sequestering the remainder, perhaps in the form of a borosilicate glass, in selected salt deposits, hard rock sites, or even near-surface repositories (with complete retrievability) makes sense; such sequestrations can be accomplished with great assurance (for example, in granite monoliths near the sea where any drainage paths would lead under the continental shelf).

Some options that are not appealing at present are disposal in the ocean deeps (either buried or not), in ice sheets or continental rocks, or in space; but the possibilities should be reviewed from time to time.

Certainly, the responsibility for radioactive waste disposal must eventually lie with the government, because the time horizon of conventional economic groups cannot guarantee concern for so long; private industry can at best act as the agent of the public interest. Narrowly regional solutions are also difficult to find, because the patterns of desirable sites for nuclear reactors, fuel reprocessing plants, and waste disposal do not come anywhere near coinciding. Thus, for example, it would be highly desirable for Europe to develop an integrated nuclear waste management strategy; but a set of national decisions to accept wastes and the responsibility for them must presage workable broader agreements (*20*).

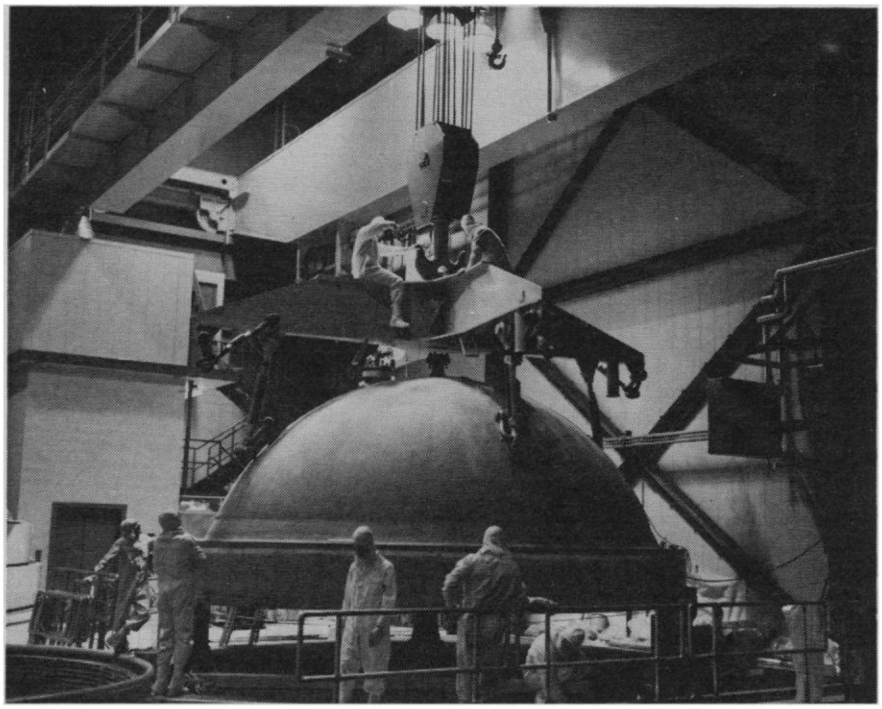
## Breeder Reactors

A few more remarks are required on breeders, to augment material in previous sections. The liquid metal fast breeder reactor (LMFBR) has been the prime energy goal of the AEC, which budgeted $357 million for it in fiscal year 1975 and plans a total of $2556 million from 1975 to 1979. The 1974 allotment is 36 percent of the entire federal budget for energy research and development; similar or higher percentages in previous years, plus the attitudes expressed by the AEC, the Executive Office of the President, and the Joint Committee on Atomic Energy, have led to criticism of "all the eggs in one basket."

The LMFBR has substantial technical points in its favor, besides the eventual but presently slippery advantage of resource conservation. It is nonpressurized, and in that respect more completely sealed, simpler, and safer. It will operate at higher temperatures than LWR's, giving an efficiency of 41 percent, comparable to the HTGR's or modern fossil fuel plants. The high thermal conductivity and heat capacity of its coolant—liquid sodium—make it virtually immune to damage in case of mechanical failure of the cooling system external to the reactor. It may eventually be cheaper, but that depends on the outcome of the expensive development program presently under way. There are disadvantages too. The liquid sodium is at about 620°C, and becomes intensely radioactive, forcing refueling and other operations on the reactor to be carried out blind, and constituting a chemical hazard in respect to failures in circulation pumps, pipes, or heat exchangers. The plutonium hazard has already been discussed. The Soviet Union and France have prototype or demonstration LMFBR's already operating, and the United Kingdom will soon follow. The U.S. program has suffered from a plethora of rigid directions from the AEC to its field offices and contractors, which has led to excessive delay and expense. The Fast Flux Test Reactor, a prototype for the U.S. demonstration reactor, has escalated in cost from an initial $80 million to an uncertain $600 million to $800 million; the first demonstration plant, planned to be built in Tennessee, is slated to cost $700 million including development costs, and will produce 300 Mw(e).

The LMFBR is not the only breeder. The General Atomic Company, with some AEC help, is making slow progress on a helium gas–cooled fast breeder reactor; having no massive coolant, it promises to breed plutonium with much higher conversion ratio than the LMFBR; but by the same token it has very little internal thermal inertia, and overheats in seconds if the cooling gas fails to circulate. It has little internal resemblance to General Atomic's HTGR other than utilizing the same sort of prestressed concrete pressure vessel and helium circulation system, but leans substantially on the AEC's LMFBR program, for example for fuel and fuel rod development. Another possible candidate is the molten-salt breeder, where a mixture of lithium, beryllium, and uranium fluorides circulates through the reactor space, then through the heat exchangers and pumps. There is no solid fuel. The principal advantages are that it can operate completely on the thorium-$^{233}$U breeder cycle, there is no need for outside fuel reprocessing (the molten salt is continuously purified on-line), and it utilizes quite different technology from the other reactors. Thus, it is a possible alternate route to fission breeders, in case the other programs fail. Its main disadvantage is chemical engineering complexity, plus the fact that hot radioactive salt must flow outside the reactor. Even the LWR and the HTGR can be technologically upgraded, to increase their conversion ratio and extend fissionable uranium resources.

The AEC has supported these alternate breeder approaches only reluctantly, and sometimes not at all, through fiscal year 1974, and now plans to allocate $11 million for them in 1975. That is better, but will do little more than keep those high-technology programs alive.



Nuclear operators at Boston Edison's Pilgrim Station nuclear power plant at Plymouth, Massachusetts, prepare the 80-ton reactor vessel head for replacement on the plant's reactor at the completion of recent refueling operations. [Courtesy of Boston Edison Co., Boston, Massachusetts]

When should the breeder reactor be introduced? That cannot yet be answered exactly, but the preceding discussion permits some guesses. The breeder promises to be cheaper because of its very low uranium cost per unit of energy. But fuel costs are not the dominant ones in any reactor, and the saving over LWR's will be about 0.1¢/kwh for each $17-a-pound rise in the cost of $U_3O_8$. To avoid offsetting penalties of expensively reprocessing the plutonium fuel too often, the burnup in the breeder must be high. Long fuel life means more fission products to absorb neutrons, plus mechanical limitations imposed because of dimensional changes—all of which conflicts with good plutonium breeding. If goals of (say) 100,000 Mw-days per ton of burnup and a breeding ratio of 1.24 can be achieved, a saving corresponding to about $50-a-pound $U_3O_8$ would accrue to the breeder, translatable into a capital advantage of $150/kw. If the burnup is less for that breeding ratio, or if the breeder costs more, or when plutonium is recycled in present-day reactors (thus introducing competition for the fuel), then the advantage shrinks. I estimate that the breeder will almost surely be attractive when $U_3O_8$ reaches $50 a pound in 1974 dollars. That will not happen in the first few decades of the 21st century (see the "resources" debate). In the meantime, nuclear power is in no danger of losing out to other fuels, and there does not need to be a crash breeder program. Economic introduction at A.D. 2000 would be a sign of technological good fortune, not of resolving an energy crisis with a time limit.

### Controlled Fusion

Controlled nuclear fusion may appear as a 21st-century option to (say) advanced fission reactors, but that is not yet assured. The U.S. fusion program has grown from its inception in the early 1950's, through a long level period of physics-oriented experimentation supported at $20 million to $30 million a year, to its present stage of rapid growth ($102 million for fusion via magnetic confinement, plus $66 million for laser fusion, in fiscal year 1975).

The trick is to heat up a mixture of deuterium and tritium to a temperature between $10^8$ and $10^9$°K ($10^4$ to $10^5$ ev) at a density high enough and for a time long enough that the product of the two quantities exceeds (about) $3 \times 10^{14}$ $cm^{-3}$ $sec^{-1}$. This is the so-called Lawson criterion. One major class of schemes depends on confining the highly ionized plasma with strong magnetic fields, say 50,000 to 100,000 gauss, at a density of $10^{14}$ $cm^{-3}$ for a few seconds. The most successful example of this technique so far is the Tokamak, wherein the plasma is confined and heated in a toroidal magnetic field.

It seems fairly clear that the scientific feasibility of controlled fusion can and will be demonstrated: A large enough well-designed magnetic structure can be made to achieve the Lawson criterion. Whether laser fusion will get there is less certain: the process depends critically on the laser pulse ablating a deuterium-tritium target pellet so fast and so evenly that the reaction forces on its surface compress it by a volumetric factor exceeding 1000. Then it undergoes nuclear fusion in about $10^{-12}$ second.

Controlled fusion has, during this scientific stage, been the most challenging and difficult of all such assignments ever given to physical scientists, and they deserve credit for doing so well. But there is much more to controlled fusion than applied plasma physics, and now controlled fusion shows signs of becoming, in addition, the most difficult and challenging assignment given to technologists and engineers. Thin-section vacuum walls, operating at high temperatures, cooled by liquid lithium or gas, possibly under cyclic mechanical stress as well, and bathed in an immense flux of 14-Mev neutrons—what will they be made of? No one knows, or even whether materials with adequate life under those conditions are developable. Many of the fusion concepts require pulsed or cyclic operations, which introduces new complexities and constraints, further eroding the option space desired by any fusion reactor designer. While having a favorable neutron balance in the fusion reactor still does not seem to be a problem, power balance may be one: in every concept, a great deal of energy must be spent to heat the fusion plasma, overcome energy losses while building up or taking down large magnetic fields, operate lasers, or do other tasks. Thus, the deuterium-tritium fusion reaction, which has some inherent disadvantages but the great advantage of 50 times the reaction rate of any other, seems mandatory. Because of all these, and a host of other problems connected with recovering tritium fuel, removing spent plasma, injecting new fuel, and assuring reasonable possibilities of repairing such a complicated device, the AEC's implied goal of beneficial installation after 1995 seems optimistic. If economic attractiveness then could be assured, the fission breeder would be superfluous. But such success with fusion is still problematic; so the breeder programs, which are the only assured routes to long-term nuclear energy, should not be appreciably modified now on account of fusion.

The advantages of success are substantial: (i) deuterium fuel is sufficient for $10^{10}$ years, and lithium (used with fusion neutrons to breed the tritium fuel component) is in somewhat uncertain supply but probably adequate for any technological age to come; (ii) the only appreciable radiation hazard is from tritium, which is less hazardous than plutonium by many orders of magnitude, per unit of weight or nuclear energy content; (iii) the reactor structure, while surely made radioactive by 14-Mev neutrons, is not liable to pose any appreciable hazard; (iv) there is no reason to steal the nuclear material: hydrogen bombs are best made by other processes, and require atomic bombs to trigger them.

Thus, a strong sense of social purpose keeps driving the controlled fusion program, with $1450 million planned for fiscal years 1975 to 1979; it is the next largest federal plan after the LMFBR and the newly upgraded coal programs.

## Nuclear versus Fossil Power

With some reservations, the social costs of nuclear power are being measured, as has been shown earlier. The social costs of burning fossil fuels to generate electricity are very hard to determine: one must extract the electric power contribution from the general costs associated with extracting, processing, and burning fossil fuels, which are quite different for different modes (local pollution by home heating equipment differs from the effects of effluents from tall power plant stacks, for instance). In addition, the studies themselves have been on a relatively small scale.

Lave and Freeburg (*12*) in their general comparison of power from coal, oil, and nuclear fuel, conclude that nuclear power is substantially less hazardous than coal. First, the hazard for coal mining was judged to be 18 times as high (per unit of energy) as that for uranium mining; on that count alone, coal would rank much worse than all the nuclear power hazards of Table 2. In addition, Lave and Freeburg estimate mortality and morbidity arising from power plant effluents, finding that a pressurized-water reactor appears to offer at least 18,000 times less health risk than a coal-burning power plant, and a boiling-water reactor 24 times less health risk. Comparing low-sulfur oil and nuclear fuels, they are less sure: uranium mining is more hazardous than oil drilling, but power plant effluent data would again favor nuclear power.

Preliminary results of studies under way at Massachusetts Institute of Technology tend to support the view that even low-sulfur fuels are unlikely to be as benign as nuclear ones. Lave and Seskin's earlier data (*21*) indicate that lowered urban air quality reduces the average life span by about 3 years. They also show that the most hazardous pollutant is $SO_2$, and that most of it comes from home heating systems (*22*). Even so, an appreciable fraction comes from electric power production, and analysis of their data and other data indicates a fatality rate on this account alone at least ten times the total nuclear one (per unit of energy), even after cleanup to the Environmental Protection Agency's $SO_2$ standard of 80 $\mu g/m^3$. These analyses assume a linear relation between concentration and damage, which of course will lead to overestimates of damage if a threshold exists; the same linear approximation is applied over many more orders of magnitude to effects of penetrating radiation, in the nuclear case.

Other workers tend to the same general conclusion: for example, Starr *et al.* (*23*). What seems increasingly clear is that the hazards of burning fossil fuels are substantially higher than those of burning nuclear ones, yet many debates have enticed the uncritical spectator to just the opposite conclusion. Several reasons can be put forward to explain this peculiar response. First, the hazards of reactors and radiation were perceived as "unknown," and hence very possibly large. Second, the public had come to accept the social cost of polluted air, not realizing (i) that much could be done (until recently) and (ii) that its perception of the fossil fuel hazard was faulty. But I think a third reason dominates: over the past 20 or 30 years, the federal government has invested well over $1 billion attempting to measure the public health costs associated with nuclear power, and until recently almost nothing was done to measure similar hazards of fossil fuel power—in retrospect, a scandalous omission. Thus, even with sometimes clumsy words and bad grace, a vast amount of literature appeared about nuclear hazards, providing material for a great public debate. The absence of any appreciable parallel assessment of fossil fuels ensured that the debate would be unbalanced, and only now are semiquantitative social cost figures starting to appear. This profound issue can hardly fail to be resolved in the next few years as more data accumulate, especially on effects of fossil fuels. I conclude from the evidence to date that all the costs—economic and social—will favor nuclear power, unless the problem of illegal use of nuclear materials gets out of hand, or plutonium turns out to be as bad as its worst critics believe.

## Conclusion

The uranium and thorium resources, the technology, and the social impacts all seem to presage an even sharper increase in nuclear power for electric generation than had hitherto been predicted. There are more future consequences.

*The "hydrogen economy."* Nuclear power plants operate best at constant power and full load. Thus, a largely nuclear electric economy has the problem of utilizing substantial off-peak capacity; the additional energy generation can typically be half the normal daily demand. Thus, the option of generating hydrogen as a nonpolluting fuel receives two boosts: excess nuclear capacity to produce it, plus much higher future costs for oil and natural gas. However, the so-called "hydrogen economy" must await the excess capacity, which will not occur until the end of the century.

*Nonelectric uses.* By analyses similar to those performed here, raw nuclear heat can be shown to be cheaper than heat from many other fuel sources, especially nonpolluting ones. This will be particularly true as domestic natural gas supplies become more scarce. Nuclear heat becomes attractive for industrial purposes, and even for urban district heating, provided (i) the temperature is high enough (this is no problem for district heating, but could be for industry; the HTGR's and breeders, with 600°C or more available, have the advantage); (ii) there is a market for large quantities (a heat rate of 3800 Mw thermal, the reactor size permitted today, will heat Boston, with some to spare); and (iii) the social costs become more definitely resolved in favor of nuclear power.

*Capital requirements.* Nuclear-electric installations are very capital-intensive. One trillion dollars for the plants, backup industry, and so forth is only 2 percent of the total gross national product (GNP) between 1974 and 2000, at a growth rate of 4 percent per year. But capital accumulation tends to run at about 10 percent of the GNP, so the nuclear requirements make a sizable perturbation. Also increasing the electric share of energy provision means increasing electric power utilization, which has a high technological content and demands yet more capital. Thus, provision of capital is a major problem ahead, especially for electric utilities.

*The need for people.* The supply of available trained technologists, environmental engineers, and so on, especially in the architect-engineer profession, is insufficient for the task ahead, especially since the same categories of people will be in demand to build up a synthetic fuels industry and do other new things.

Beyond these specific items and beyond the technological discussion, one can feel deeper currents running in this debate. Issues that started out seeming technological ended up being mainly societal: prevention of clandestine use, either by vigilance or by public spirit; a determination to maintain quality and to safeguard wastes that transcends narrow interests; a perception of social benefits and damage much more holistic than before; the need to manage programs more openly and better than before. Questions and doubts become more acute, answers and methods less sure.

Here is a final question. We have never before been given a virtually infinite resource of something we craved. So far, increasingly large amounts of energy have been used to turn resources into junk, from which activity we derive ephemeral benefit and pleasure; the track record is not too good. What will we do now?

### References


1. From a survey by the National Electrical Manufacturers Association, as quoted in *IEEE (Inst. Electr. Electron. Eng.) Spectrum* **11**, 115 (1974).
2. Edison Electric Institute, *Elec. Output No. 49* (6 March 1974).
3. "A study of base-load alternatives for the Northeast Utilities System," report to the Board of Trustees of Northeast Utilities by Arthur D. Little, Inc., Acorn Park, Cambridge, Mass., 5 July 1973. The report has had substantial circulation.
4. "Nuclear power 1973 to 2000," *USAEC Rep. WASH 1139* (1972).
5. W. G. Dupree, Jr., and J. A. West, *United States Energy through the Year 2000* (Government Printing Office, Washington, D.C., 1972).
6. For example, see *Report of the Cornell Workshops on the Major Issues of a National Energy Research and Development Program* (College of Engineering, Cornell University, Ithaca, N.Y., 1973), chapter 4 by H. A. Bethe and appendix G thereto by H. A. Bethe and C. Braun.
7. "Nuclear fuel supply," *USAEC Rep. WASH 1242* (1973); "Nuclear fuel resources and requirements," *USAEC Rep. WASH 1243* (1973).
8. P. Walsh, Environmental Engineer's thesis, Massachusetts Institute of Technology (1974).
9. K. Hub, J. G. Asbury, W. A. Buehring, P. F. Gast, R. A. Schlenker, J. T. Weills, *A Study of Social Costs for Alternate Means of Electric Power Generation for 1980 and 1990* (Argonne National Laboratory, Argonne, Ill., 1973).
10. L. Sagan, *Science* **177**, 487 (1972).
11. "The safety of nuclear power reactors and related facilities," *USAEC Rep. WASH 1250* (1973).
12. L. B. Lave and L. C. Freeburg, *Nucl. Saf.* **14**, 409 (1973).
13. D. F. Ford, T. C. Hollocher, H. W. Kendall, J. J. MacKenzie, L. Scheinman, A. S. Schurgin, *The Nuclear Fuel Cycle, a Survey of the Public Health, Environmental and National Security Effects of Nuclear Power* (Union of Concerned Scientists, Cambridge, Mass., 1973); see especially chapter 3; "Emergency core cooling systems (ECCS) hearings," AEC Docket RM50-1, AEC Public Document Room, Atomic Energy Commission, Washington, D.C.
14. Reported by AEC Chairman Dixy Lee Ray, at the National Press Club, Washington, D.C., 21 January 1974.
15. "Theoretical possibilities and consequences of major accidents in large nuclear power plants," *USAEC Rep. WASH 740* (1957).
16. W. J. Bair and R. C. Thompson, *Science* **183**, 715 (1974).
17. For example, see the report "Meeting of the advisory committee on reactor safeguards, plutonium information meeting" (Los Alamos, New Mexico, 4 and 5 January 1974), AEC Document Room, Atomic Energy Commission, Washington, D.C.
18. A. R. Tamplin and T. B. Cochran, *Radiation Standards for Hot Particles* (Natural Resources Defense Council, Washington, D.C., 1974).
19. A. S. Kubo and D. J. Rose, *Science* **182**, 1205 (1973).
20. D. J. Rose and G. Tenaglia, *Ambio* **2**, 233 (1973).
21. L. Lave and E. P. Seskin, *Science* **169**, 723 (1970).
22. ———, *Am. J. Publ. Health* **62**, 909 (1972).
23. C. Starr, M. A. Greenfield, D. F. Hausknecht, *Nucl. News* **15**, 37 (1972).