pletely acceptable from an ecological standpoint. In contrast, even without economic considerations, there is reason for us to have grave concern over the harmful ecological effects of the gypsy moth if this alien pest is left to spread to the limits of its range and become a permanent resident throughout the forest ecosystems of the country.

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    The following equation summarizes the calculations:

    $$M_n = \frac{[m + SM_{n-1}] \cdot [f + S(F_{n-1} - M_{n-1})]}{T + [f + S(F_{n-1} - M_{n-1})]}$$

    where M_n is the number of matings on day n, m is the number of males, and f is the number of females emerging each day; F_n is the number of unmated females on day n [or $F_n = f + S(F_{n-1} - M_{n-1})$], D is the number of days in the mating season, S is the survival rate per day, and T is the number of traps. Thus $\int_1^D M_n$ gives the total number of matings in the controlled population, and fD is the number of matings in the uncontrolled population.
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Social Institutions and Nuclear Energy

Alvin M. Weinberg

Fifty-two years have passed since Ernest Rutherford observed the nuclear disintegration of nitrogen when it was bombarded with alpha particles. This was the beginning of modern nuclear physics. In its wake came speculation as to the possibility of releasing nuclear energy on a large scale: By 1921 Rutherford was saying "The race may date its development from the day of the discovery of a method of utilizing atomic energy" (*1*).

Despite the advances in nuclear physics beginning with the discovery of the neutron by Chadwick in 1932 and Cockcroft and Walton's method for electrically accelerating charged particles, Rutherford later became a pessimist about nuclear energy. Addressing the British Association for the Advancement of Science in 1933, he said: "We cannot control atomic energy to an extent which would be of any value commercially, and I believe we are not likely ever to be able to do so" (*2*). Yet Rutherford did recognize the great significance of the neutron in this connection. In 1936, after Fermi's remarkable experiments with slow neutrons, Rutherford wrote ". . . the recent discovery of the neutron and the proof of its extraordinary effectiveness in producing transmutations at very low velocities opens up new possibilities, if only a method could be found of producing slow neutrons in quantity with little expenditure of energy" (*3*).

Today the United States is committed to over 100 × 10^6 kilowatts of nuclear power, and the rest of the world to an equal amount. Rather plausible estimates suggest that by 2000 the

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Table 1. Estimated total cost of power from 1000-Mwe power plants (mills per electric kilowatt hour). The costs include escalation to 1978. Nuclear fuel costs were taken from (*9*). The coal plant fuel costs are based on average delivered coal price of about $8 per ton in 1971, with escalation to 1978 at 5 percent per year. This leads to about $10.5 to $10.7 per ton in 1978. Estimates for costs of operating $\mathrm{SO_2}$-removal equipment range from zero to about 2×10^6 dollars per year.

	PWR plants		Coal plants			
	Run-of-river	With cooling towers	No $\mathrm{SO_2}$ system		With $\mathrm{SO_2}$ system	
			Run-of-river	Cooling towers	Run-of-river	Cooling towers
Capital cost ($/kwe)	365	382	297	311	344	358
Fixed charges	7.8	8.2	6.4	6.6	7.4	7.7
Fuel cost	1.9	1.9	3.9	3.9	3.9	3.9
Operation and maintenance cost	0.6	0.6	0.5	0.5	0.8	0.8
Total power cost (mills/kwhe)	10.3	10.7	10.8	11.0	12.1	12.4

United States may be generating electricity at a rate of 1000×10^6 kilowatts with nuclear reactors. Much more speculative estimates visualize an ultimate world of 15 billion people, living at something like the current U.S. standard: nuclear fission might then generate power at the rate of some 300×10^9 kilowatts of heat, which represents 1/400 of the flux of solar energy absorbed and reradiated by the earth (*4*).

This large commitment to nuclear energy has forced many of us in the nuclear community to ask with the utmost seriousness questions which, when first raised, had a tone of unreality. When nuclear energy was small and experimental and unimportant, the intricate moral and institutional demands of a full commitment to it could be ignored or not taken seriously. Now that nuclear energy is on the verge of becoming our dominant form of energy, such questions as the adequacy of human institutions to deal with this marvelous new kind of fire must be asked, and answered, soberly and responsibly. In these remarks I review in broadest outline where the nuclear energy enterprise stands and what I think are its most troublesome problems; and I shall then speculate on some of the new and peculiar demands mankind's commitment to nuclear energy may impose on our human institutions.

Nuclear Burners—Catalytic and Noncatalytic

Even before Fermi's experiment at Stagg Field on 2 December 1942, reactor designing had captured the imagination of many physicists, chemists, and engineers at the Chicago Metallurgical Laboratory. Almost without exception, each of the two dozen main reactor types developed during the following 30 years had been discussed and argued over during those frenzied war years. Of these various reactor types, about five, moderated by light water, heavy water, or graphite, have survived. In addition, breeders, most notably the sodium-cooled plutonium breeder, are now under active development.

Today the dominant reactor type uses enriched uranium oxide fuel, and is moderated and cooled by water at pressures of 100 to 200 atmospheres. The water may generate steam directly in the reactor [so-called boiling water reactor (BWR)] or may transfer its heat to an external steam generator [pressurized water reactor (PWR)]. These light water reactors (LWR) require enriched uranium and therefore at first could be built only in countries such as the United States and the U.S.S.R., which had large plants for separating uranium isotopes.

In countries where enriched uranium was unavailable, or was much more expensive than in the United States, reactor development went along directions that utilized natural uranium: for example, reactors developed in the United Kingdom and France were based mostly on the use of graphite as moderator; those developed in Canada used $\mathrm{D_2O}$ as moderator. Both $\mathrm{D_2O}$ and graphite absorb fewer neutrons than does $\mathrm{H_2O}$, and therefore such reactors can be fueled with natural uranium. However, as enriched uranium has become more generally available (of the uranium above ground, probably more by now has had its normal isotopic ratio altered than not), the importance of the natural ^{235}U isotopic abundance of 0.71 percent has faded. All reactor systems now tend to use at least slightly enriched uranium since its use gives the designer more leeway with respect to materials of construction and configuration of the reactor.

The PWR was developed originally for submarine propulsion where compactness and simplicity were the overriding considerations. As one who was closely involved in the very early thinking about the use of pressurized water for submarine propulsion (I still remember the spirited discussions we used to have in 1946 with Captain Rickover at Oak Ridge over the advantages of the pressurized water system), I am still a bit surprised at the enormous vogue of this reactor type for civilian power. Compact, and in a sense simple, these reactors were; but in the early days we hardly imagined that separated ^{235}U would ever be cheap enough to make such reactors really economical as sources of central station power.

Four developments proved us to be wrong. First, separated ^{235}U which at the time of *Nautilus* cost around $100 per gram fell to $12 per gram. Second, the price of coal rose from around $5 per ton to $8 per ton. Third, oxide fuel elements, which use slightly enriched fuel rather than the highly enriched fuel of the original LWR, were developed. This meant that the cost of fuel in an LWR could be, say, 1.9 mills per kilowatt hour (compared with around 3 mills per electric kilowatt hour for a coal-burning plant with coal at $8 per ton). Fourth, pressure vessels of a size that would have boggled our minds in 1946 were common by 1970: the pressure vessel for a large PWR may be as much as 8½ inches thick and 44 feet tall. Development of these large pressure vessels made possible reactors of 1000 megawatts electric (Mwe) or more, compared with 60 Mwe at the original Shippingport reactor. Since per unit of output a large power plant is cheaper than a small one, this increase in reactor size was largely responsible for the economic breakthrough of nuclear power.

Although the unit cost of water reactors has not fallen as much as optimists such as I had estimated, present costs are still low enough to make nuclear power competitive. I compare the relative position of a 1000-Mwe LWR and of a coal-fired plant of the same size (Table 1).

Water-moderated reactors burn ^{235}U, which is the only naturally occurring fissile isotope. But the full promise of nuclear fission will be achieved only with successful breeders. These are reactors that, essentially, burn the very abundant isotopes ^{238}U or ^{232}Th; in the process, fissile ^{239}Pu or ^{233}U acts as regenerating catalyst—that is, these isotopes are burned and regenerated. I therefore like to call reactors of this type *catalytic nuclear burners*. Since ^{238}U and ^{232}Th are immensely abundant (though in dilute form) in the granitic rocks, the basic fuel for such catalytic nuclear burners is, for all practicaltical purposes, inexhaustible. Mankind will have a permanent source of energy once such catalytic nuclear burners are developed.

Most of the world's development of a breeder is centered around the sodium-cooled, ^{238}U burner in which ^{239}Pu is the catalyst and in which the energy of the neutrons is above 100 × 10^{3} electron volts. No fewer than 12 reactors of this liquid metal fast breeder reactor (LMFBR) type are being worked on actively, and the United Kingdom plans to start a commercial 1000-Mwe fast breeder by 1975. Some work continues on alternatives. In the ^{233}U–^{232}Th cycle, on the light water breeder and the molten salt reactor; in the ^{239}Pu–^{238}U cycle, on the gas-cooled fast breeder. But these systems are, at least at the present, viewed as backups for the main line which is the LMFBR.

Nuclear Power and Environment

The great surge to nuclear power is easy to understand. In the short run, nuclear power is cheaper than coal power in most parts of the United States; in the long run, nuclear breeders assure us of an all but inexhaustible source of energy. Moreover, a *properly* operating nuclear power plant and its subsystems (including transport, waste disposal, chemical plants, and even mining) are, except for the heat load, far less damaging to the environment than a coal-fired plant would be.

The most important emissions from a routinely operating reactor are heat and a trace of radioactivity. Heat emissions can be summarized quickly. The thermal efficiency of a PWR is 32 percent; that of a modern coal-fired power plant is around 40 percent. For the same electrical output the nuclear plant emits about 40 percent more waste heat than the coal plant does; in this one respect, present-day nuclear plants are more polluting than coal-fired plants. However, the higher temperature nuclear plants, such as the gas-cooled, the molten salt breeder, and the liquid metal fast breeder, operate at about the same efficiency as does a modern coal-fired plant. Thus, nuclear reactors of the future ought to emit no more heat than do other sources of thermal energy.

As for routine emission of radioactivity, even when the allowable maximum exposure to an individual at the plant boundary was set at 500 millirems (mrem) per year, the hazard, if any, was extremely small. But for practical purposes, technological advances have all but eliminated routine radioactive emission. These improvements are taken into account in the newly proposed regulations of the Atomic Energy Commission (AEC) requiring, in effect, that the dose imposed on any individual living near the plant boundary either by liquid or by gaseous effluents from LWR's should not exceed 5 mrem per year. This is to be compared with the natural background which is around 100 to 200 mrem per year, depending on location, or the medical dose which now averages around 60 mrem per year.

As for emissions from chemical reprocessing plants, data are relatively scant since but one commercial plant, the Nuclear Services Plant at West Valley, New York, has been operating, and this only since 1966. During this time, liquid discharges have imposed an average dose of 75 mrem per year at the boundary. Essentially no ^{131}I has been emitted. As for the other main gaseous effluents, all the ^{85}Kr and ^{3}H contained in the fuel has been released. This has amounted to an average dose from gaseous discharge of about 50 mrem per year.

Technology is now available for reducing liquid discharges, and processes for retaining ^{85}Kr and ^{3}H are being developed at AEC laboratories. There is every reason to expect these processes to be successful. Properly operating radiochemical plants in the future should emit no more radioactivity than do properly operating reactors—that is, less than 10 percent of the natural background at the plant boundary.

There are some who maintain that even 5 mrem per year represents an unreasonable hazard. Obviously there is no way to decide whether there is any hazard at this level. For example, if one assumes a linear dose-response for genetic effects, then to find, with 95 percent confidence, the predicted 0.5 percent increase in genetic effect in mice at a dose of, say, 150 mrem would require 8 billion animals. At this stage the argument passes from science into the realm of what I call trans-science, and one can only leave it at that.

My main point is that nuclear plants are indeed relatively innocuous, large-scale power generators if they and their subsystems work properly. The entire controversy that now surrounds the whole nuclear power enterprise therefore hangs on the answer to the question of whether nuclear systems can be made to work properly; or, if faults develop, whether the various safety systems can be relied upon to guarantee that no harm will befall the public.

The question has only one answer: there is no way to guarantee that a nuclear fire and all of its subsystems will never cause harm. But I shall try to show why I believe the measures that have been taken, and are being taken, have reduced to an acceptably low level the probability of damage.

I have already discussed low-level radiation and the thermal emissions from nuclear systems. Of the remaining possible causes of concern, I shall dwell on the three that I regard as most important: reactor safety, transport of radioactive materials, and permanent disposal of radioactive wastes.

Avoiding Large Reactor Accidents

One cannot say categorically that a catastrophic failure of a large PWR or a BWR and its containment is impossible. The most elaborate measures are taken to make the probability of such occurrence extremely small. One of the prime jobs of the nuclear community is to consider all events that could lead to accident, and by proper design to keep reducing their probability however small it may be. On the other hand, there is some danger that in mentioning the matter one's remarks may be misinterpreted as implying that the event is likely to occur.

Assessment of the safety of reactors depends upon two rather separate considerations: prevention of the initiating incident that would require emergency safety measures; and assurance that the emergency measures, such as the emergency core cooling, if ever called upon, would work as planned. In much of the discussion and controversy that has been generated over the safety of nuclear reactors, emphasis has been placed on what would happen if the emergency

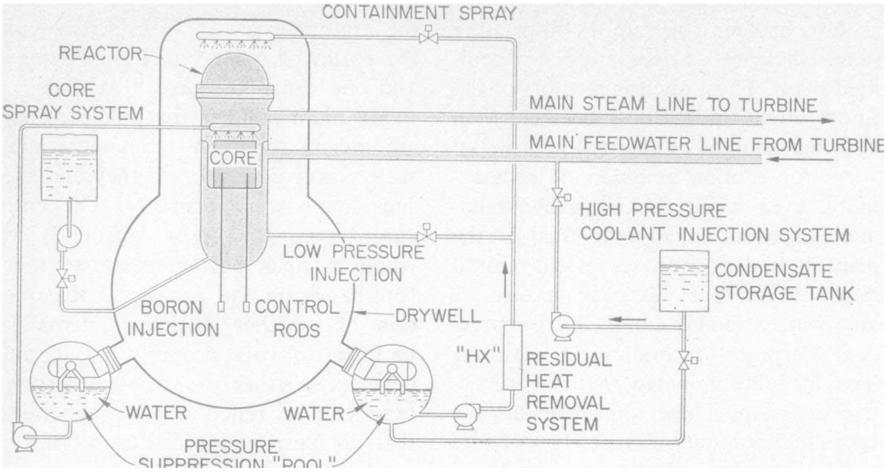

Fig. 1. Boiling water reactor emergency cooling systems.

measures were called upon and failed to work. But to most of us in the reactor community, this is secondary to the question: How certain can we be that a drastic accident that calls into play the emergency systems will never happen? What one primarily is counting upon for the safety of a reactor is the integrity of the primary cooling system: that is, on the integrity of the pressure vessel and the pressure piping. Excruciating pains are taken to assure the integrity of these vessels and pipes. The watchword throughout the nuclear reactor industry is *quality assurance*: every piece of hardware in the primary system is examined, and reexamined, to guarantee insofar as possible that there are no flaws.

Nevertheless, we must deal with the remote contingency that might call the emergency systems into action. How certain can one be that these will work as planned? To better understand the analysis of the emergency system, Figs. 1 and 2 show, schematically, a large BWR and a PWR.

Three barriers prevent radioactivity from being released: fuel element cladding, primary pressure system, and containment shell. In addition to the regular safety system consisting primarily of the control and safety rods, there are elaborate provisions for preventing the residual radioactive heat from melting the fuel in the event of a loss of coolant. In the BWR there are sprays that spring into action within 30 seconds of an accident. In both the PWR and BWR, water is injected under pressure from gas-pressurized accumulators. In both reactors there are additional systems for circulating water after the system has come to low pressure, as well as means for reducing the pressure of steam in the containment vessel. This latter system also washes down or otherwise helps remove any fission products that may become airborne.

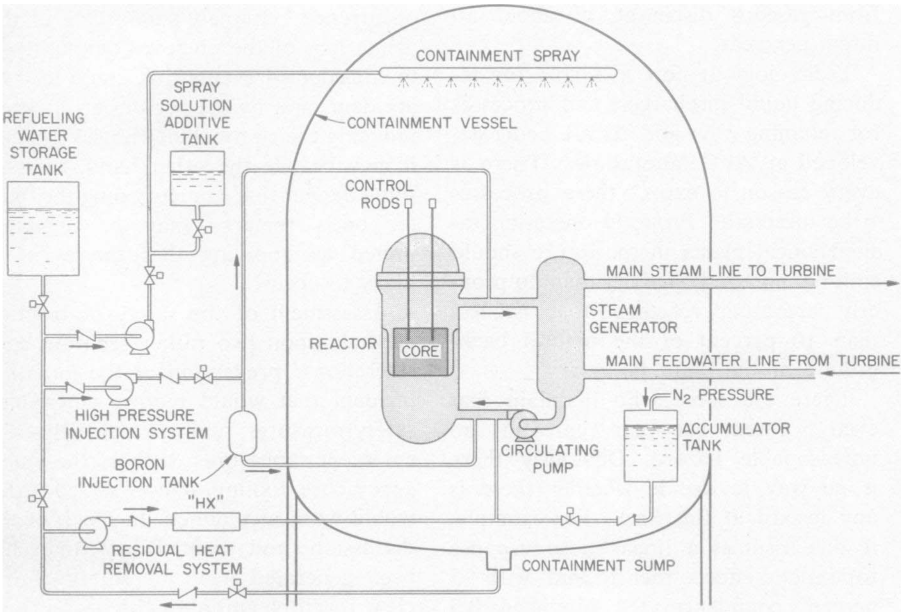

Fig. 2. Pressurized water reactor emergency cooling systems.

In analyzing the ultimate safety of a LWR, one tries to construct scenarios—improbable as they may be—of how a catastrophe might occur; and then one tries to provide reliable countermeasures for each step in the chain of failures that could lead to catastrophe. The chain conceivably could go like this. First, a pipe might break, or the safety system might fail to respond when called upon in an emergency. Second, the emergency core cooling system might fail. Third, the fuel might melt, might react also with the water, and conceivably might melt through the containment. Fourth, the containment might fail catastrophically, if not from the melt itself, then from missiles or overpressurization, and activity might then spread to the public. There may be other modes of catastrophic failure—for example, earthquakes or acts of violence—but the above is the more commonly identified sequence.

To give the flavor of how the analysis of an accident is made, let me say a few words about the first and second steps of this chain. As a first step, one might imagine failure of the safety system to respond in an emergency, say, when the bubbles in a BWR collapse after a fairly routine turbine trip. Here the question is not that some safety rods will work and some will not, but rather that a common mode failure might render the entire safety system inoperable. Thus if all the electrical cables actuating the safety rods were damaged by fire, this would be a common mode failure. Such a common mode failure is generally regarded as impossible, since the actuating cables are carefully segregated, as are groups of safety rods, so as to avoid such an accident. But one cannot *prove* that a common mode failure is impossible. It is noteworthy that on 30 September 1970, the entire safety system of the Hanford-N reactor (a one-of-a-kind water-cooled, graphite-moderated reactor) did fail when called upon; however, the backup samarium balls dropped precisely as planned and shut off the reactor. One goes a long way toward making such a failure incredible if each big reactor, as in the case of the Hanford-N reactor, has two entirely independent safety systems that work on totally different principles. In the case of BWR, shutoff of the recirculation pumps in the all but incredible event the rods fail to drop constitutes an independent shutoff mechanism, and automatic pump shutoff is being incorporated in the design of modern BWR's.

The other step in the chain that I shall discuss is the failure of the emergency core cooling system. At the moment, there is some controversy whether the initial surge of emergency core cooling water would bypass the reactor or would in fact cool it. The issue was raised recently by experiments on a very small scale (9-inch-diameter pot) which indeed suggested that the water in that case would bypass the core during the blowdown phase of the accident. However, there is a fair body of experts within the reactor community who hold that these experiments were not sufficiently accurate simulations of an actual PWR to bear on the reliability or lack of reliability of the emergency core cooling in a large reactor.

Obviously the events following a catastrophic loss of coolant and injections of emergency coolant are complex. For example, one must ask whether the fuel rods will balloon and block coolant channels, whether significant chemical reactions will take place, or whether the fuel cladding will crumble and allow radioactive fuel pellets to fall out.

Such complex sequences are hardly susceptible to a complete analysis. We shall never be able to estimate everything that will happen in a loss-of-coolant accident with the same kind of certainty with which we can compute the Balmer series or even the course of the ammonia synthesis reaction in a fertilizer plant. The best that we can do as knowledgeable and concerned technologists is to present the evidence we have, and to expect policy to be based upon informed—not uninformed—opinion.

Faced with questions of this weight, which in a most basic sense are not fully susceptible to a yes or no scientific answer, the AEC has invoked the adjudicatory process. The issue of the reliability of the emergency core cooling system is being taken up in hearings before a special board drawn from the Atomic Safety and Licensing Board Panel. The record of the hearings is expected to contain all that is known about emergency core cooling systems and to provide the basis for setting the criteria for design of such systems.

Transport of Radioactive Materials

If, by the year 2000, we have 10^6 megawatts of nuclear power, of which two-thirds are liquid metal fast breeders, then there will be 7,000 to 12,000 annual shipments of spent fuel from reactors to chemical plants, with an average of 60 to 100 loaded casks in transit at all times. Projected shipments might contain 1.5 tons of core fuel which has decayed for as little as 30 days, in which case each shipment would generate 300 kilowatts of thermal power and 75 megacuries of radioactivity. By comparison, present casks from LWR's might produce 30 kilowatts and contain 7 megacuries.

Design of a completely reliable shipping cask for such a radioactive load is a formidable job. At Oak Ridge our engineers have designed a cask that looks very promising. As now conceived, the heat would be transferred to air by liquid metal or molten salt; and the cask would be provided with rugged shields which would resist deformation that might be caused by a train wreck. To be acceptable the shipping casks must be shown to withstand a 30-minute fire and a drop from 30 feet onto an unyielding surface (Fig. 3).

Can we estimate the hazard associated with transport of these materials? The derailment rate in rail transport (in the United States) is 10^{-6} per car mile. Thus, if there were 12,000 shipments per year, each of a distance of 1000 miles, we would expect 12 derailments annually. However, the number of serious accidents would be perhaps 10^{-4}- to 10^{-6}-fold less frequent; and shipping casks are designed to withstand all but the most serious accident (the train wreck near an oil refinery that goes into flames as a result of the crash). Thus the statistics—between 1.2×10^{-3} and 1.2×10^{-5} serious accidents per year—at least until the year 2000, look quite good. Nevertheless the shipping problem is a difficult one and may force a change in basic strategy. For example, we may decide to cool fuel from LMFBR's in place for 360 days before shipping: this reduces the heat load sixfold, and increases the cost of power by only around 0.2 mill per electric kilowatt hour. Or a solution that I personally prefer is to cluster fast breeders in nuclear power parks which have their own on-site reprocessing facilities (*5*). Clustering reactors in this way would make both cooling and transmission of power difficult; also such parks would be more vulnerable to common mode failure, such as acts of war or earthquakes. These difficulties must be balanced against the advantage of not shipping spent fuel off-site, and of simplifying control of fissile material against diversion. To my mind, the advantages of clustering outweigh its disadvantages; but this again is a trans-scientific question which can only be adjudicated by a legal or political process, rather than by scientific exchange among peers.

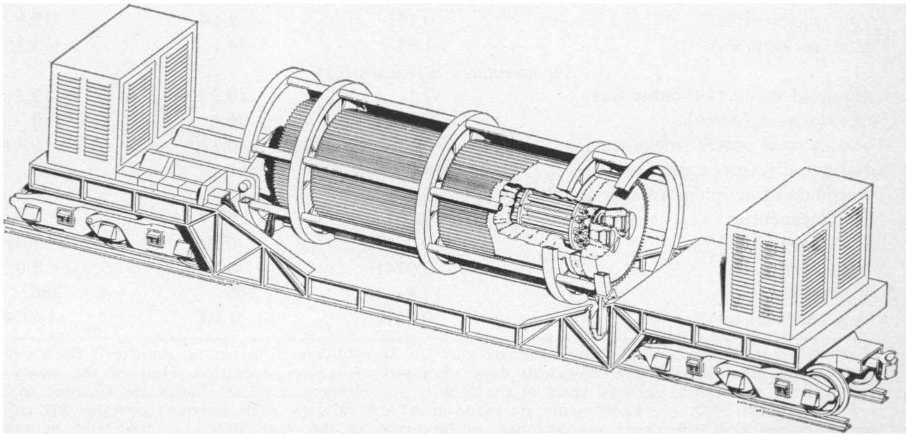

Fig. 3. Liquid metal fast breeder reactor spent fuel shipping cask (18 assemblies).

Waste Disposal

By the year 2000, according to present projections, we shall have to sequester about 27,000 megacuries of radioactive wastes in the United States; these wastes will be generating 100,000 kilowatts of heat at that time. The composition of these wastes is summarized in Table 2.

The wastes will include about 400 megacuries of transuranic alpha emitters. Of these, the ^{239}Pu with a half-life of 24,400 years will be dangerous for perhaps 200,000 years.

Can we see a way of dealing with these unprecedentedly treacherous materials? I believe we can, but not without complication.

There are two basically different approaches to handling the wastes. The first, urged by W. Bennett Lewis of Chalk River (*6*), argues that once man has opted for nuclear power he has committed himself to essentially perpetual surveillance of the apparatus of nuclear power, such as the reactors, the chemical plants, and others. Therefore, so the argument goes, there will be spots on the earth where radioactive operations will be continued in perpetuity. The wastes then would be stored at these spots, say in concrete vaults. Lewis further refines his ideas by suggesting that the wastes be recycled so as to limit their volume. As fission products decay, they are removed and thrown away as innocuous nonradioactive species; the transuranics are sent back to the reactors to be burned. The essence of the scheme is to keep the wastes under perpetual, active surveillance and even processing. This is deemed possible because the original commitment to nuclear energy is considered to be a commitment in perpetuity.

There is merit in these ideas; and indeed permanent storage in vaults is a valid proposal. However, if one wishes to perpetually rework the wastes as Lewis suggests, chemical separations would be required that are much sharper than those we now know how to do; otherwise at every stage in the recycling we would be creating additional low-level wastes. We probably can eventually develop such sharp separation methods; but these, at least with currently visualized techniques, would be very expensive. It is on this account that I like better the other approach which is to find some spot in the universe where the wastes can be placed forever out of contact with the biosphere. Now the only place where we know absolutely the wastes will never interact with man is in far outer space. But the roughly estimated cost of sending wastes into permanent orbit with foreseeable rocket technology is in the range of 0.2 to 2 mills per electric kilowatt hour, not to speak of the hazard of an abortive launch. For both these reasons I do not count on rocketing the wastes into space.

This pretty much leaves us with disposal in geologic strata. Of the many possibilities—deep rock caverns, deep wells, bedded salt—the latter has been chosen, at least on an experimental basis, by the United States and West Germany. The main advantages of bedded salt are primarily that, because salt dissolves in water, the existence of a stratum of bedded salt is evidence that the salt has not been in contact with circulating water during geologic time. Moreover, salt flows plastically; if radioactive wastes are placed in the salt, eventually the salt ought to envelop the wastes and sequester them completely.

These arguments were adduced by the National Academy of Sciences Committee on Radioactive Waste Management (*7*) in recommending that the United States investigate bedded salt (which underlies 500,000 square miles in our country) for permanent disposal of radioactive wastes. And, after 15 years of discussion and research, the AEC about a year ago decided to try large-scale waste disposal in an abandoned salt mine in Lyons, Kansas (Fig. 4). If all goes as planned, the Kansas mine is to be used until A.D. 2000. What one does after A.D. 2000 would of course depend on our experience during the next 30 years (1970 to 2000). In any event, the mine is to be designed so as to allow the wastes to be retrieved during this time.

The salt mine is 1000 feet deep, and the salt beds are around 300 feet thick. The beds were laid down in Permian times and had been undisturbed, until man himself intruded, for 200 million years. Experiments in which radioactive fuel elements were placed in the salt have clarified details of the temperature distribution around the wastes, the effect of radiation on salt, the migration of water of crystallization within the salt, and so on.

The general plan is first to calcine the

Table 2. Projected waste inventories at the permanent repository.

	Calendar year		
	1980	1990	2000
	Number of annual shipments		
High-level waste*	23	240	590
Alpha waste†	420	1,200	0
	Accumulated high-level waste		
Volume of waste (cubic feet)	3,170	74,200	319,000
Salt area used (acres)	9	200	900
Total thermal power (megawatts)	1.17	24.4	94.9
Total activity (megacuries)	329	7,030	27,700
^{90}Sr (megacuries)	59.0	1,310	5,290
^{137}Cs (megacuries)	83.1	1,850	7,500
^{238}Pu (megacuries)	0.102	2.34	9.88
^{239}Pu (megacuries)	0.00157	0.0368	0.158
^{240}Pu (megacuries)	0.00400	0.101	0.470
^{241}Am (megacuries)	0.151	3.54	15.3
^{244}Cm (megacuries)	1.58	34.1	133.3
	Accumulated alpha waste‡§		
Volume of waste (10^6 cubic feet)	2.1	10.3	19.3
Salt area used (acres)	20	96	180
Total thermal power (megawatts)	0.0142	0.170	0.476
Total activity (megacuries)	14.2	151	300
Total mass of actinides (metric tons)	1.40	15.8	38.3
^{238}Pu (megacuries)	0.232	2.57	6.02
^{239}Pu (megacuries)	0.0515	0.580	1.41
^{240}Pu (megacuries)	0.0741	0.834	2.02
^{241}Pu (megacuries)	13.8	146	286
^{241}Am (megacuries)	0.0617	1.03	4.74

* Each shipment consists of 57.6 cubic feet of waste in 36 cylinders (6 inches in diameter). Each cubic foot of waste represents 10,000 megawatt days (thermal) of reactor operation. Half of the waste is aged 5 years, and half is aged 10 years at the time of its shipment. Last shipments are assumed to be made in the year 2000. † Shipments are made in ATMX railcars; each shipment contains 832 cubic feet of waste. Last shipments are assumed to be made in the year 1999. ‡ At end of year. § The isotopic composition of Pu at the time of its receipt is 1 percent ^{238}Pu, 60 percent ^{239}Pu, 24 percent ^{240}Pu, 11 percent ^{241}Pu, and 4 percent ^{242}Pu.

liquid wastes to a dry solid. The solid is then placed in metal cans, and the cans are buried in the floor of a gallery excavated in the salt mine. After the floor of the gallery is filled with wastes, the gallery is backfilled with loose salt. Eventually this loose salt will consolidate under the pressure of the overburden, and the entire mine will be resealed. The wastes will have been sequestered, it is hoped, forever.

Much discussion has centered around the question of just how certain we are that the events will happen exactly as we predict. For example, is it possible that the mine will cave in and that this will crack the very thick layers of shale lying between the mine and an aquifer at 200 feet below the surface? There is evidence to suggest that this will not happen, and I believe most, though not all, geologists who have studied the matter agree that the 500-foot-thick layer of shale above the salt is too strong to crack so completely that water could enter the mine from above.

But man's interventions are not so easily disposed of. In Kansas there are some 100,000 oil wells and dry holes that have been drilled through these salt formations. These holes penetrate aquifers; and in principle they can let water into the mine. For the salt mine to be acceptable, one must plug all such holes. At the originally proposed site there were 30 such holes; in addition, solution mining was practiced nearby. For this reason, the AEC recently authorized the Kansas State Geological Survey to study other sites that were not peppered with man-made holes. The AEC also announced recently its intention to store solidified wastes in concrete vaults, pending resolution of these questions concerning permanent disposal in geologic formations.

Man's intervention complicates the use of salt for waste disposal; yet by no means does this imply that we must give up the idea of using salt. In the first place, such holes can be plugged, though this is costly and requires development. In the second place, let us assume the all but incredible event that the mine is flooded—let us say 10,000 years hence. By that time, since no new waste will be placed in the mine after A.D. 2000, all the highly radioactive beta decaying species, notably ^{90}Sr and ^{137}Cs, would have decayed. The main radioactivity would then come from the alpha emitters. The mine would contain 38 tons of ^{239}Pu mixed with about a million tons of nonradioactive material. The plutonium in the cans is thus diluted to 38 parts per million; since plutonium is, per gram, 10,000 times more hazardous than natural uranium in equilibrium with its daughters, these diluted waste materials would present a hazard of the same order as an equal amount of pitchblende. Actually, the 38 tons of ^{239}Pu is spread over 200 acres. If all the salt associated with the ^{239}Pu were dissolved in water, as conceivably could result from total flooding of the mine, the concentration of plutonium in the resulting salt solution would be well below maximum permissible concentrations. In other words, by virtue of having spread the plutonium over an area of 200 acres, we have to a degree ameliorated the residual risk in the most unlikely event that the mines are flooded.

Despite such assurances, the mines must not be allowed to flood, especially before the ^{137}Cs and ^{90}Sr decay. We must prevent man from intruding—and this can be assured only by man himself. Thus we again come back to the great desirability, if not absolute necessity in this case, of keeping the wastes under some kind of surveillance in perpetuity. The great advantage of the salt method over, say, the perpetual reworking method, or even the aboveground concrete vaults without reworking, is that our commitment to surveillance in the case of salt is minimal. All we have to do is prevent man from intruding, rather than keeping a priesthood that forever reworks the wastes or guards the vaults. And if the civilization should falter, which would mean, among other things, that we abandon nuclear power altogether, we can be almost (but not totally) assured that no harm would befall our recidivist descendants of the distant future.

Social Institutions—Nuclear Energy

We nuclear people have made a Faustian bargain with society. On the one hand, we offer—in the catalytic nuclear burner—an inexhaustible source of energy. Even in the short range, when we use ordinary reactors, we offer energy that is cheaper than energy from fossil fuel. Moreover, this source of energy, when properly handled, is almost nonpolluting. Whereas fossil fuel burners must emit oxides of carbon and nitrogen, and probably will always emit some sulfur dioxide, there is no intrinsic reason why nuclear systems must emit any pollutant—except heat and traces of radioactivity.

But the price that we demand of society for this magical energy source is both a vigilance and a longevity of our social institutions that we are quite unaccustomed to. In a way, all of this was anticipated during the old debates

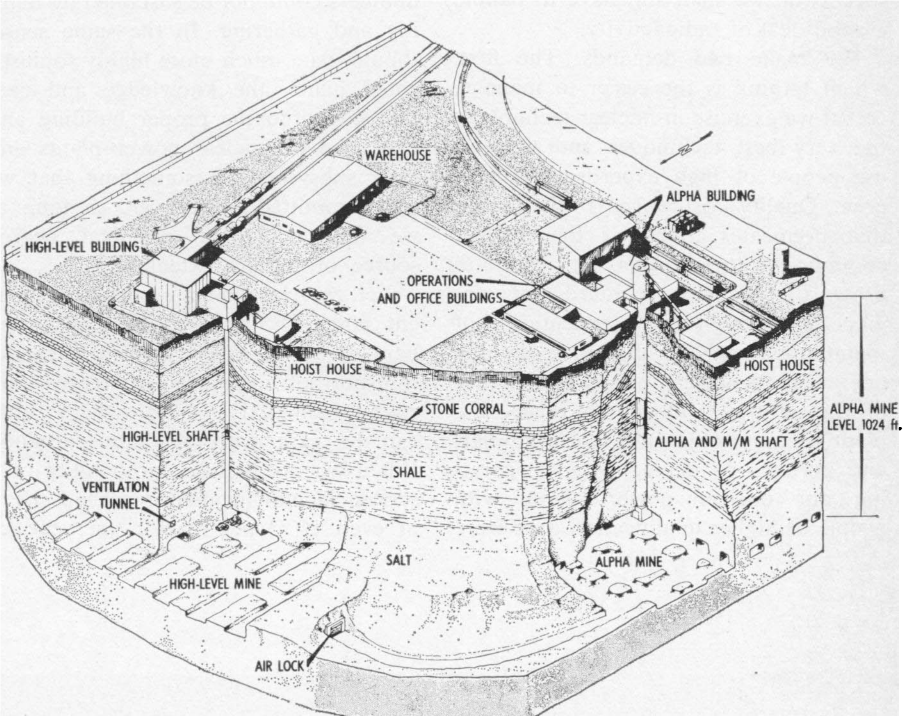

Fig. 4. Federal repository.

over nuclear weapons. As matters have turned out, nuclear weapons have stabilized at least the relations between the superpowers. The prospects of an all-out third world war seem to recede. In exchange for this atomic peace we have had to manage and control nuclear weapons. In a sense, we have established a military priesthood which guards against inadvertent use of nuclear weapons, which maintains what a priori seems to be a precarious balance between readiness to go to war and vigilance against human errors that would precipitate war. Moreover, this is not something that will go away, at least not soon. The discovery of the bomb has imposed an additional demand on our social institutions. It has called forth this military priesthood upon which in a way we all depend for our survival.

It seems to me (and in this I repeat some views expressed very well by Atomic Energy Commissioner Wilfrid Johnson) that peaceful nuclear energy probably will make demands of the same sort on our society, and possibly of even longer duration. To be sure, we shall steadily improve the technology of nuclear energy; but, short of developing a truly successful thermonuclear reactor, we shall never be totally free of concern over reactor safety, transport of radioactive materials, and waste disposal. And even if thermonuclear energy proves to be successful, we shall still have to handle a good deal of radioactivity.

We make two demands. The first, which I think is the easier to manage, is that we exercise in nuclear technology the very best techniques and that we use people of high expertise and purpose. Quality assurance is the phrase that permeates much of the nuclear community these days. It connotes using the highest standards of engineering design and execution; of maintaining proper discipline in the operation of nuclear plants in the face of the natural tendency to relax as a plant becomes older and more familiar; and perhaps of managing and operating our nuclear power plants with people of higher qualification than were necessary for managing and operating nonnuclear power plants: in short, of creating a continuing tradition of meticulous attention to detail.

The second demand is less clear, and I hope it may prove to be unnecessary. This is the demand for longevity in human institutions. We have relatively little problem dealing with wastes if we can assume always that there will be intelligent people around to cope with eventualities we have not thought of. If the nuclear parks that I mention are permanent features of our civilization, then we presumably have the social apparatus, and possibly the sites, for dealing with our wastes indefinitely. But even our salt mine may require some small measure of surveillance if only to prevent men in the future from drilling holes into the burial grounds.

Eugene Wigner has drawn an analogy between this commitment to a permanent social order that may be implied in nuclear energy and our commitment to a stable, year-in and year-out social order when man moved from hunting and gathering to agriculture. Before agriculture, social institutions hardly required the long-lived stability that we now take so much for granted. And the commitment imposed by agriculture in a sense was forever: the land had to be tilled and irrigated every year in perpetuity; the expertise required to accomplish this task could not be allowed to perish or man would perish; his numbers could not be sustained by hunting and gathering. In the same sense, though on a much more highly sophisticated plane, the knowledge and care that goes into the proper building and operation of nuclear power plants and their subsystems is something that we are committed to forever, so long as we find no other practical energy source of infinite extent (*8*).

Let me close on a somewhat different note. The issues I have discussed here—reactor safety, waste disposal, transport of radioactive materials—are complex matters about which little can be said with absolute certainty. When we say that the probability of a serious reactor incident is perhaps 10^{-8} or even 10^{-4} per reactor per year, or that the failure of all safety rods simultaneously is incredible, we are speaking of matters that simply do not admit of the same order of scientific certainty as when we say it is incredible for heat to flow against a temperature gradient or for a perpetuum mobile to be built. As I have said earlier, these matters have trans-scientific elements. We claim to be responsible technologists, and as responsible technologists we give as our judgment that these probabilities are extremely—almost vanishingly—small; but we can never represent these things as certainties. The society must then make the choice, and this is a choice that we nuclear people cannot dictate. We can only participate in making it. Is mankind prepared to exert the eternal vigilance needed to ensure proper and safe operation of its nuclear energy system? This admittedly is a significant commitment that we ask of society. What we offer in return, an all but infinite source of relatively cheap and clean energy, seems to me to be well worth the price.

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