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Disposal of Nuclear Wastes

At an increased but still modest cost, more options can be explored and the outlook can be improved.

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Disposing of radioactive wastes from nuclear fission reactors has been much debated, both in public and in private. The assessments and discussions require rebalancing from time to time, and we attempt this here.

Do the perceived difficulties of the waste disposal problem arise from severe scientific or technological limitations, or from lack of understanding and institutional restrictions? Both contribute, but we think that the latter are dominant: we find several attractive technological options that have been given little consideration, and institutional arrangements that have contributed to premature narrowness of thought. For instance, until late 1971, both the U.S. Atomic Energy Commission (AEC) and the public debated the merits of disposing of nuclear wastes in a salt mine near Lyons, Kansas, almost as if that were the sole option.

Misassessment has led to a nuclear waste disposal program too small to match our needs and has contributed to public debate unworthy of the topic. We believe that a greater but still modest effort should be successful, and that the cost of an adequate program will remain small compared with the overall cost of nuclear power. Since the cost is small an extended range of options can be explored.

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Humanistic and Technological Aspects

Societal problems involving technology, such as radioactive waste management, have features related to present and future costs, perceived benefits, and time scales of concern. Here, for illustration, is one basic dilemma that arises in our problem, somewhat fictionalized for emphasis. Suppose we know that our social structure will persist unperturbed and that we will remain fully responsible up to a time T many years in the future; then society will collapse completely and we will revert to savages. Suppose also that we feel as responsible toward the savages as toward ourselves, and that no reasonable technological option is too expensive for us to afford. (In this hypothetical example, we exclude disposal in space and some other option-terminating stratagems.) Under those circumstances we might choose, until nearly time T, to store irreducible nuclear wastes in surface mausolea built to withstand natural disasters, and to watch them assiduously—each radioactive waste container on its own plinth in a gallery, so to speak. We gain the advantage of preserving technological options, in case anything unforeseen goes awry. But shortly before time T we would transfer those wastes to some subterranean place, chosen, if possible, so that the geologic strata themselves were no special attraction, and there seal them forever as best we could.

The two stratagems entail very different features and trade-offs: the first retains options and provides more safety against both error and disasters, but at a cost of full societal responsibility; the second guards against an irresponsible society at the cost of increased environmental risk. One stresses complete retrievability, the other stresses irretrievability. Deciding which to choose was not a technological matter for that imagined society; it depended on two uncertain things: (i) present assessment of future societal stability, and (ii) depth of responsibility toward future people. Our own choices depend on these two humanistic issues, just as in the caricature above.

Of course technology enters more than that. What mausoleum, and what subterranean disposal? Can the radioactive inventory be reduced or separated into more easily handled materials? Do safe, inaccessible places exist? These questions and more influence the major decisions, and all require study. This article is substantially technological; we will try to present the physical options and estimate the costs and benefits as well as we can. Such an assessment should show the best options in each major category and put matters in the best order for public discussion. These considerations, together with the humanistic ones, help us to decide not only whether we have the "correct" tangible assets for the cost, but also what are the definitions of assets and costs.

Background

A few numbers will help put the following discussion in perspective. First, consider the cost of radioactive waste management schemes compared with that of the nuclear reactor installations themselves. A nuclear capacity of at least 900,000 megawatts has been predicted for the United States by A.D. 2000 (*1*); the nuclear components alone will cast more than $100 billion (at present costs) and the plants over $300 billion. In contradistinction, every nuclear waste disposal scheme which has been discussed (except perhaps shooting the wastes into the sun) costs only a small fraction of that—often less than 1 percent. Thus, public debate on this topic should be viewed somewhat less as bearing on absolute limitations to nuclear acceptance, and more as speculation on the very costly consequences of technical failure of too-cheap disposal schemes.

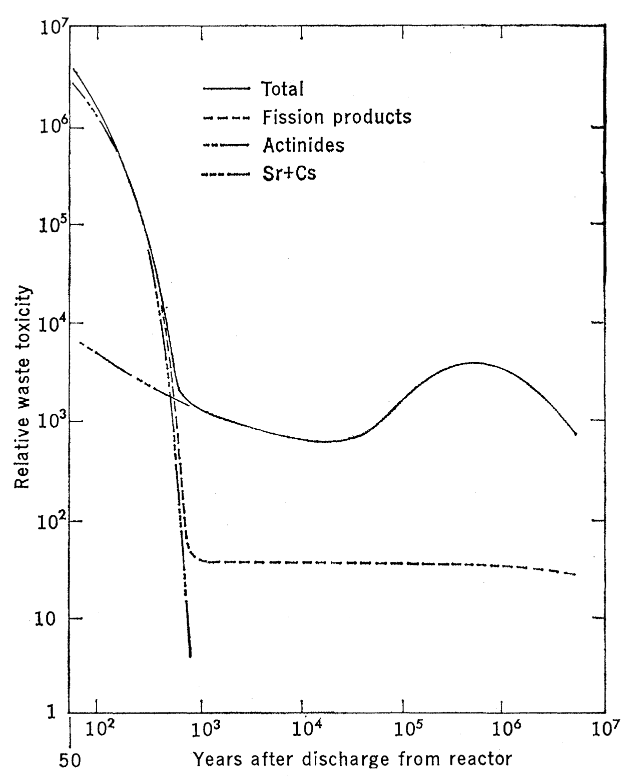
A second set of orienting numbers concerns categories. The major one in terms of short-term radioactivity comprises the fission products, that is, atoms of medium atomic weight formed by fission of uranium or plutonium. Strontium-90, cesium-137, and to a lesser extent krypton-85 are the main culprits; zirconium-93, tellurium-99, iodine-129, cesium-135, and others are much less important. The main ones have half-lives not greater than 30 years (*2*). In 700 years less than one ten-millionth remains, and for this discussion we take 700 years as the end point of practical concern for this category of radioactive wastes.

The other category of radioactive wastes consists of the actinides (the elements actinium, thorium, uranium, neptunium, plutonium, and so on), which are formed not by fission but by neutron absorption into the original uranium (or thorium) fuel. All are very toxic and most have long half-lives—for example, about 25,000 years for plutonium-239, the most abundant transuranium actinide, which is formed either in conventional light water reactors or in proposed liquid metal fast breeder reactors. The actinides cause waste management difficulties at two distinct points in nuclear fuel cycle: some are carried over with the fission products during nuclear fuel reprocessing, with which this article is concerned, but also some highly dilute plutonium wastes will appear from fuel manufacturing plants (*3*). Thus, at the entrance to the waste facility we find a mix of many different transuranic actinides intimately combined with the shorter-lived and temporarily more hazardous fission products. The important things to notice about this category of wastes are that (i) the offending actinides are relatively toxic (*4*), and (ii) although initially far less radioactive than the fission products, they become dominant at 500 years because of their much longer half-lives.

This disparity between the categories, graphically presented in Fig. 1, suggests that it would be advantageous to separate them chemically and adopt different strategies for each kind.

Now we turn to what has been done about the problem. Our present policy, established almost two decades ago, aims for deep underground burial in selected geologic formations; that option seems to have been a logical follow on from waste management practices commenced in the 1940's. At present three major locations are envisaged: the AEC production facilities at Hanford, Washington, in local basalt; the commercial wastes in the salt beds of Kansas; and the salt beds of southern New Mexico, which underlie some largely mined-out potash deposits (*5*). But the underground disposal schemes are opposed by concerned scientists, politicians, and laymen, and the AEC is now reconsidering other options, such as storage in vaults, disposal in space, and so forth.

The present state of waste management policy is based on requirements determined early in the development of commercial nuclear power: (i)



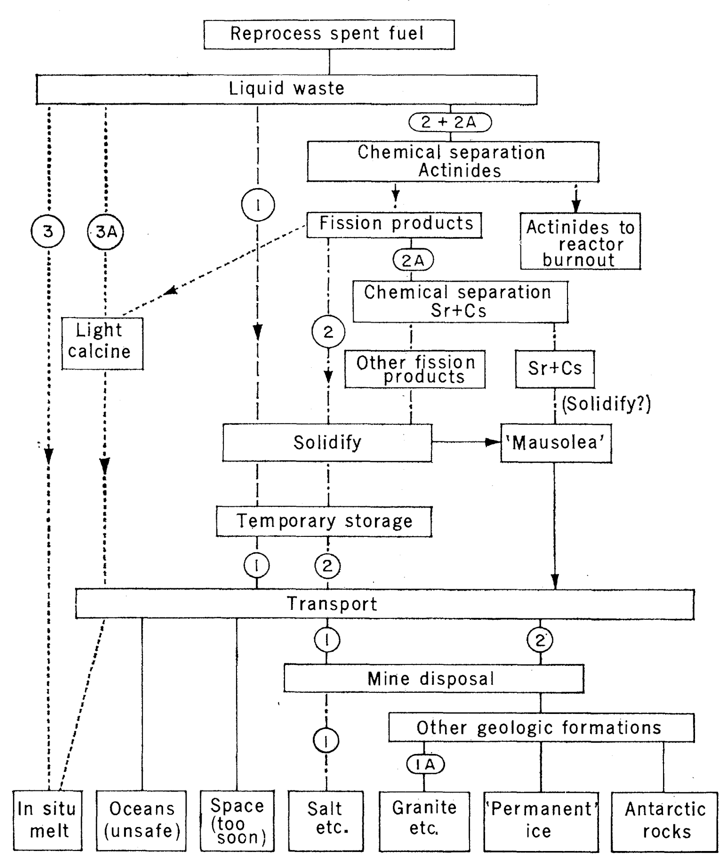


Fig. 1 (left). Toxicity of wastes from light water reactors, for an equilibrium fuel cycle, with 99.5 percent removal of uranium and plutonium. Each metric ton of fuel is assumed to deliver a total thermal energy of 33,000 megawatts × days during its operating lifetime. The turn-up at 10^6 years arises from growth of daughter products not present in the original material, which is not in decay equilibrium. Fig. 2 (right). Taxonomy of nuclear waste disposal options.

safety beyond any reasonable doubt, and (ii) reasonable cost—(that is, it should not hinder appreciably the development of commercial nuclear energy). These criteria, in themselves unexceptionable, receive various interpretations.

Aware of complications, the congressional Joint Committee on Atomic Energy asked the National Academy of Sciences (NAS) on several occasions (and the General Accounting Office as well) to help assess the situation. The NAS concluded in 1957 that, for the near term, salt mine burial appeared most attractive; this assessment was based on the 700-year toxicity of ^{90}Sr and ^{137}Cs. A broader assessment of different disposal schemes has never formally been made, and indeed since 1957 the NAS seems to have been concerned with increasingly fine points of an already-made decision. The concept of long-term storage in vaults near the surface was dropped early as a safe but temporizing solution requiring active surveillance, although a recent AEC announcement (*6*) indicates a return to this concept. Disposal in the oceans seemed unsafe for lack of adequate knowledge about all the consequences of failure—a situation that still obtains. No complete study of disposal in space has been made to date, because of apprehension about the consequences of shortfall. However, there is a growing interest in space disposal. Success for this project depends on the space shuttle to make it economically feasible, and a sophisticated container to survive possible shortfall; both requirements await the successful outcome of the shuttle program, so that prognosis is difficult and likely to be biased by attitudes for or against the space program.

Selective waste management of heat-producing or highly toxic isotopes has been suggested, but never much analyzed because of the costs and added complications of chemical separation. Thus, through the 1960's and into 1971, at a rate of about $5 million a year, research and development focused on deep disposal, including the intermediate step of solidification (*7*). Of that annual commitment, about $500,000 has been applied to developing the salt mine disposal concept, mostly by the Oak Ridge National Laboratory (Oak Ridge, Tennessee); about $2 million has been applied to developing waste solidification processes; and the biggest portion of the remainder has been used to develop a deep underground disposal scheme (now abandoned or at least substantially delayed) for the AEC's Savannah River wastes. This $5-million commitment must be compared to (i) the total waste management budget of the AEC, over $40 million a year in the 1970's, and (ii) the anticipated scale of nuclear operations, as outlined earlier. A waste disposal research and development budget several times $5 million a year seems more appropriate.

Taxonomy of Options

Figure 2 shows what we think are the major options to be considered. Of course, variations exist, and some will be mentioned later. We draw several routes on the map of Fig. 2, so to speak. All start with very radioactive liquid wastes from reprocessing fuels based on either uranium, plutonium, or thorium.

Route 1 is the scheme (until recently in favor) of solidifying the wastes, including whatever actinides were present, and transporting them to a salt mine for permanent disposal. But other types of mines could be used, as shown in route 1A near the bottom of Fig. 2. In routes 2 and 2A various wastes are separated, which ameliorates the disposal problem. With any of these schemes, a temporary visit may be made to near-surface storage facilities with full retrieval capability, which we call mausolea. Several other disposal options of possible interest can follow from the upper segments of routes 1 and 2, particularly the latter. We rule out dumping in the oceans and in space, for the time being, for reasons already given. We are skeptical about the two remaining options, "permanent" ice and Antarctic rocks, for reasons given later.

Routes 3 and 3A, in situ melting, are quite different; the wastes, upon being inserted into a selected underground site, fuse themselves into a permanent glassy mass.

We now discuss each of these options in more detail, giving the advantages, disadvantages, and costs as we see them. The costs and some other details are not always easy to ascertain, and the degree of present uncertainty in our figures varies substantially between options. In this article we present a summary; more detailed justifications can be found elsewhere (*8*).

Simple Mine Disposal and Salt Vaults (Route 1)

The Kansas salt vault project, until recently the AEC's sole commercial option, has proceeded far enough that the major technical and economic uncertainties have been resolved (*9*). The cost would range between 0.045 and 0.055 mill per kilowatt-hour electric (kwhe) for disposal (after 10 years of temporary storage) of solidified, unaltered, high-level radioactive wastes. That is about 0.5 percent of the cost of generating the nuclear power, a negligible increase, small compared even to annual inflation. Retrieval of these wastes from the repository, if it were ever required, grows increasingly problematic as the project passes from demonstration to operation, and finally to a decommissioned state with sealed shafts and backfilled corridors.

The long-term safety of the project depends on preventing the intrusion of water into the salt beds by any means. This could occur by natural means such as erosion, failure of overlying or underlying shale beds, boundary dissolution, and by man-induced means such as well borings. The Lyons site had several chiefly man-induced flaws.

The concept has some advantages: salt is easy to mine, it will in time flow plastically to seal the whole midden, and surely the very presence of the salt guarantees that no water was present in the geologic past. But these advantages are two-sided, for the very fragility (vulnerability to water) of the geologic structure is used as an argument in its favor, and the demonstrated stability refers only to past time, and not to the future, when conditions will likely be different. We may mistake an indicator of past quality for a substantive future property.

Arguments like these, related to future uncertainty, now appear in the scientific and public literature. From those discussions, we note that (i) the prognosis is likely to be better in some other salt deposits, and (ii) similar disposal is possible in other geologic structures—other evaporites or granite monoliths, for example—with some advantages and disadvantages (that is, route 1A in Fig. 2).

The extensive beds of salt and some potash of southern New Mexico are now being viewed hopefully by the AEC. The advantages of the site are remoteness from present occupation and a more favorable political climate [due to large AEC commitments to the New Mexican economy at Sandia Base (near Albuquerque) and Los Alamos Scientific Laboratory]. The disadvantages are similar to many discussed for Lyons.

Route 1A leads to disposal in hard rock, whose advantages counter some of the shortcomings associated with salt: the rock is insoluble, ubiquitous, and normally not associated with valuable mineral resources. But there are disadvantages: the rock is brittle and unhealing, and it may be leached by groundwater. The mining cost (less than $1 per cubic foot) almost certainly will be higher, but not prohibitively so. Also, we calculate that the extra expense of transporting unwanted salt or other evaporites to the ocean can equal the extra cost of mining hard rock, which needs no environmental treatment and may actually be salable. At the very worst, the mining cost would be doubled in hard rock (*10*). But the total cost of disposal in hard rock would be only about 25 percent more than for the salt mine repository. This increase is so modest because of the small fraction of the total cost apportioned to the mine facility (either salt or hard rock) compared to the interim storage, solidification, and transportation costs (for burial of 10-year-old wastes in formations where their heat generation limits the concentration; this is the usual case).

Further Chemical Separations (Routes 2 and 2A)

Whatever the final means of disposal may be, using chemical separations to alter the character of the wastes has considerable merit (*11*). As discussed above, removing the actinides turns a million-year problem into a 700-year one, because we envisage burning out the actinides in a reactor; the technology is available now and can be implemented; and the method is not limited to countries with specific geologic formations. Also, at much greater expense, one can remove the principal heat-producing isotopes, ^{90}Sr and ^{137}Cs. Against these advantages we find, as usual, some disadvantages: higher cost, more complex operations, and a reversal of waste management policy that will cause economic dislocations for commercial fuel reprocessors now in operation. Also, what

Table 1. Cost of separating and recycling actinides in wastes from a light water reactor. The three cost categories represent 1.1, 1.5, and 2.0 times the current light water reactor reprocessing costs.

Item	Cost (mill/kwhe)		
	Optimistic	Median	Extreme
Salt mine*	0.045	0.045	0.045
Recycle actinides	.119	.189	.276
Total	0.164	0.234	0.321

* The fission products still require disposal.

to do with the ^{90}Sr and ^{137}Cs is a problem.

Extract actinides only (*route 2*). The extraction of actinides reduces the long-term toxicity (beyond 1000 years) of the wastes by two to four orders of magnitude (see Fig. 3). At present and in the projected future, only plutonium and uranium values are to be extracted from the spent fuels from light water reactors (LWR) and liquid metal fast breeder reactors (LMFBR), and that to only a moderate extent (about 99.5 percent). Even if the extraction were improved to 99.99 percent, the extra reduction in long-term toxicity would be very small, because other actinides are causing the trouble. Curve 1 of Fig. 3 shows that both the 99.5 percent and 99.99 percent extractions of uranium and plutonium are essentially congruent. Thus, extreme extraction of the "usable" values is unhelpful for waste management purposes. Today the technological limit (as opposed to the economic optimum) to the extraction of actinides appears to be 99.9999 percent for actinium through plutonium, and 99 percent for

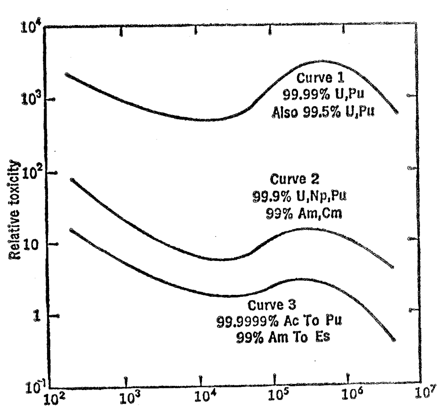


Fig. 3. Toxicity of wastes from light water reactors, for different degrees of actinide extraction. The fuel conditions are the same as for Fig. 1.

americium to einsteinium. If this extreme extraction were accomplished, the wastes would closely approach the "nontoxic" level in 1000 years; at that time the toxicity would be some three to four orders of magnitude less than with the current extraction goals (compare curves 1 and 3 in Fig. 3). A more modest extraction of 99.9 percent of the uranium, neptunium, and plutonium, and 99 percent of the americium and curium (Fig. 3, curve 2) yields substantial benefits compared to the standard extraction, and can be accomplished more cheaply.

We propose that the troublesome extracted actinides are to be recycled through a reactor (*12*), which we consider in this article to be a LWR. This is the most disadvantageous reactor for such a task, having a deficiency (for this purpose) of high energy neutrons, but there are no data at present for evaluating recycling through a fast breeder reactor. Thus, the economic figures are pessimistic. The remaining wastes would be processed for "conventional" disposal (for example, in a mine or a mausoleum).

The anticipated costs for using route 2 in this way are given in Table 1; these are more uncertain than the route 1 costs. The three categories—optimistic, median, and extreme—are based on reprocessing costs 1.1, 1.5, and 2.0 times the current LWR reprocessing costs. In all cases the reactor fuel was slightly and appropriately enriched to compensate for the actinides, and the fuel manufacturing costs were increased also.

For a LMFBR, the added costs should be much lower, for several reasons: (i) a less pure actinide product should be recyclable without degrading the reactor's neutron economy, which would reduce the need for extreme separations of chemical groups; (ii) there would be a smaller fuel manufacturing penalty, since the whole system is full of highly toxic gamma-emitting plutonium already; and (iii) more actinides are naturally present in an operating LMFBR, so the addition of more actinides affects it less. We estimate informally that the recycle cost would be 0.020 mill/kwhe if the actinide extraction cost could be reduced to 110 percent of the currently anticipated cost, and that the overall disposal cost would be about 0.065 mill/kwhe (if the fission products go to a salt mine).

Admittedly, these estimates are premature, but they do indicate that nuclear transmutation of the actinides would cost between 0.065 and 0.320 mill/kwhe. This is a nontrivial fraction of the total fuel cycle cost (about 8 to 9 mill/kwhe) of nuclear electric energy, but in our opinion it is promising enough to be worth further study.

In shortening the period of concern about the waste repository by a factor of at least 1000, extraction of the actinides represents a real safety improvement.

Extract actinides, strontium, and cesium (route 2A). Removing these key isotopes reduces the long-term toxicity, as in the previous case, and also the waste thermal power. Strontium and cesium account for the major portion of the waste thermal power during the interim period, 1 year to about 100 years after discharge from the reactor, the precise fraction depending on reactor type. The thermal contributions of key groups of elements are shown in Fig. 4.

Waste thermal power is the prime disrupting force that jeopardizes the storage of wastes underground. Reducing the waste thermal power by removing strontium and cesium has two advantages. With a reduced heat load, the waste containers can be packed closer together, which reduces the mining cost by about a factor of 30. More important, it decreases the thermal stresses that work against the safety of (say) the salt disposal project, so that the remaining wastes can be buried in salt or similar structures within the year after fuel reprocessing. The cesium and strontium would be stored in a mausoleum until the space disposal scheme is operational or some future disposal scheme is developed, say in 50 years. The stripped actinides would be recycled to a LMBFR as before (cost estimates based on a LWR are given in the preceding section). The disadvantages of the scheme are that no method of disposal is available yet for strontium and cesium and that the in situ melt option is precluded (because of marginal energy in the residual wastes). The costs for route 2A are estimated in Table 2 for the following assumptions: (i) the actinides are recycled as before; (ii) strontium and cesium are extracted at \$0.01, \$0.05, and \$0.10 per curie for the three cases; (iii) strontium and cesium are stored at 0.8, 1.0, and 2.0 times the expected cost of long-term storage of wastes in a mausoleum.

Table 2. Cost of separating strontium, cesium, and actinides and recycling actinides. The cost of recycling actinides is the light water reactor estimate.

Item	Cost (mill/kwhe) Optimistic	Median	Extreme
Extract Sr and Cs	0.071	0.142	0.710
Store Sr and Cs	.020	.025	.050
Recycle actinides	.119	.189	.276
Salt disposal	.025	.025	.025
Subtotal	0.235	0.381	1.061
Disposal of Sr and Cs	?	?	?
Total	?	?	?

Considering the problem of what to do with the strontium and cesium, the option would be attractive only if it promised a substantial societal advantage.

Engineered Near-Surface Structures (Mausolea)

Using a mausoleum or storage vault is really storage with the option, if not the explicit intent, of future retrieval. Present estimates of the cost of long-term storage are inaccurate and scanty, because the waste management policy has been oriented toward disposal. However, research at Oak Ridge National Laboratory on interim storage for periods up to 30 years indicates a cost of about 0.015 mill/kwhe. For a 50-year storage period, a cost of approximately 0.025 mill/kwhe seems reasonable. The use of mausolea (if storage for future recovery of isotopes is neglected) is a temporizing measure. All countries currently using this concept intend to use some other method of disposal when new technology is developed or the wastes are more manageable.

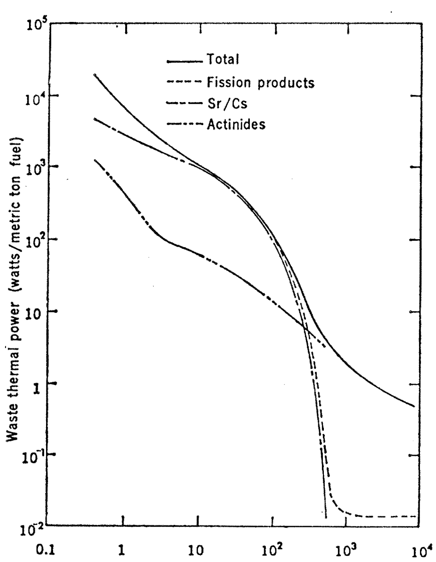


Fig. 4. Thermal power from light water reactor wastes. The conditions are the same as for Fig. 1.

The optional flexibility of near-surface storage is acquired at the expense of extensive surveillance, and could leave the wastes vulnerable to extremes of nature (such as earthquakes) and the irrationality of man (for example, war, sabotage, and neglect).

Such a temporizing solution would make sense if new technology is likely to be available later. If the present-worth concept of money is employed, at even as low a discount rate as 5 percent per year, 8.7 cents today would purchase services worth \$1 at the end of a 50-year storage period. This might be attractive if expensive technological solutions, such as space disposal, were imagined to be the ultimate choice. Of course, if nothing turns up such schemes appear as procrastination.

Antarctic Rocks and "Permanent" Ice

These options have features in common and both start from solidified waste (*13*). First, we present the favorable points of view.

Two difficulties that exist with conventional hard rock disposal are the possibility that groundwater might leach out the wastes, and the possibility that people might come across the material in some future age when markings have vanished. These difficulties can be circumvented, at least in large part, by disposal at great depths. But both would be overcome by burial at modest depth in Antarctic rocks. To a depth of about 1 km, all groundwater is frozen in the Antarctic; thus, insertion of the wastes might be arranged to cause only warm inclusions in the totally frozen surround. Also, none but scientifically well-prepared civilizations are likely to come upon the area.

Another scheme might apply to wastes from which the actinides had been extracted. The residual wastes could be suitably contained (in stainless steel, perhaps) to last for thousands of years in fresh water. Their activity ceases for all practical purposes after a few thousand years. It might be possible to place the residuals in deep holes in one of the long-lasting ice sheets, such as Greenland or Antarctica. The volume of ice that could be melted by all the wastes generated between now and A.D. 2000 is about 0.04 km^3 (0.01 cubic mile) which is not very much. The bottom of the Greenland ice sheet is bowl shaped and below sea level. Thus, it appears that nuclear wastes with a 700-year half-life would be secure there.

One of the major difficulties is that frozen ground—either permafrost or Antarctic rocks—is not really cold enough at depth. The temperature ranges from $-5°C$ at -150 m to $0°C$ at -300 m, which leaves little room to maneuver. Rocks beneath the Antarctic ice cap are colder but inaccessible.

Ice-cap disposal has several drawbacks. First, wastes still containing actinides require extremely long periods of storage; for example, if the original concentration of ^{239}Pu is 10^6 times the permissible concentration in drinking water and no credit is allowed for insolubility, dilution, or adsorption, the required period of isolation is 500,000 years, and the ice may not be that permanent. Even if the actinides were removed, an area problem remains: to preclude appreciable heating at the ground-ice interface (and hence increased ice flow), the heat generated from the wastes must be a small fraction of that appearing via the geothermal gradient—1 percent would be 63 kw/km^2. Wastes from the United States aged 10 years before burial, if accumulated and spread out in Antarctica to give that heat load, would cover 10^6 km^2 by A.D. 2025, that is, 25 percent of the area that has ice with an anticipated lifetime exceeding 10,000 years.

Finally, transportation and working conditions in the Antarctic are difficult and hazardous, and at present the Antarctic is kept free of nuclear wastes by international treaty.

In situ Melt (Routes 3 and 3A)

This scheme was originally proposed at Lawrence Livermore Laboratory (*14*). A hole is bored beneath the waste processing plant, and a nuclear bomb is set off in the hole. Then the radioactive waste is poured into the subterranean cavity so formed, over a 25-year filling period. The wastes heat up through their own activity, boil dry, and eventually melt themselves and some surrounding rock into a glassy ball. The cost is quite uncertain but was judged to be extremely attractive —0.011 to 0.016 mill/kwhe if government financing is used. But there are substantial technical difficulties with the scheme in its present stage of planning. (i) During the boiling phase isotopes could migrate from the disposal site. (ii) Stress reversal will occur as the transient temperature field moves radially from the disposal site. (iii) Faulting or earthquakes might shear the feed and steam lines which join the disposal site to the surface facility. (iv) Groundwater might eventually leach out the wastes. (v) An excavation procedure should be developed which does not involve the originally proposed nuclear explosive, and which can make a cavity at greater depth.

According to the original proposal, the fuel reprocessing plant would be at the waste disposal site. This is a severe restriction that protends an undesirable proliferation of disposal sites. But the concept can be modified so that lightly calcined wastes are transported from fuel reprocessing facilities to a federally controlled central repository for in situ melt (this is alternate route 3A in Fig. 2). The wastes are slurried and pumped down to the prepared cavity. The waste boiling period would be reduced from the proposed 25 years to less than 1 year if adequate wastes

Table 3. Summary of waste disposal options. The routes refer to the diagram in Fig 2.

Route	Option	Cost (mill/kwhe)	Advantages	Disadvantages
1	Salt mine	0.045–0.050	Most technical work to date; plastic media with good thermal properties occur in seismically stable regions	Corrosive media; highly susceptible to water; normally associated with other valuable minerals; difficult to monitor and retrieve wastes
1A	Granite	0.050–0.055	Crystalline rock; low porosity if sound; comparable to salt in thermal properties; retrievable wastes	Nonplastic media; presence of groundwater; difficult to monitor
2	Further chemical separation; recycle actinides	0.065–0.320	Reduced long-term toxicity; technology feasible; increases future options	Additional handling and processing; more toxic materials in fuel inventory; waste dilution due to processing; fission products remain
2A	Further chemical separation; remove Sr and Cs; recycle actinides	0.140–1.100	Reduced long-term toxicity; reduced short-term thermal power; some reduction of fission product toxicity; increases future options	Additional handling and processing; more toxic materials in fuel inventory; waste dilution due to processing; storage and disposal of Sr and Cs extract; fission products remain
3	Melt in situ	0.011–0.016	In situ creation of insoluble rock-waste matrix; no transportation; reduced handling	Highly mobile wastes during 25-year boiling phase; presence of groundwater; irretrievable wastes; proliferation of disposal sites; difficult to monitor
3A	Melt in situ, central repository	0.031–0.036	In situ creation of insoluble rock-waste matrix; short boiling period; no proliferation of sites	Presence of ground water; irretrievable wastes; difficult to monitor
2	Antarctic rocks		Immobile water	Very narrow temperature limits; not a permanent geologic feature; difficult environment
2	Continental ice sheets		Immobile water	Cannot dispose of actinides; limited amount of ice; not a permanent geologic feature; difficult environment

were stored on site and charged in one operation. Solidifying and transporting the wastes would introduce an added cost, which we estimate at 0.020 mill/kwhe, and would bring the total to roughly 0.031 to 0.036 mill/kwhe. This is less expensive than the salt mine concept, and if it can be shown to be technically safe the project might be practicable. Of course, retrieval is impossible for any of these variations; chemical separation of actinides (route 2) can be incorporated, probably to advantage.

In situ melt suffers from lack of any detailed assessment, but the modified idea seems worthy of analysis comparable to that given the salt project.

Summary

For the present and the foreseeable future the following options appear to be either usable or worth further exploration: mausolea; disposal in mines of various sorts, and perhaps in ice; in situ melt; and further chemical separations. The options are interdependent.

It is too early to assess disposal in space, and disposal in the oceans remains unsafe for lack of adequate knowledge. Table 3 is a summary of the main ideas for which we have worked out (sometimes uncertain) costs.

For the short term, ultimate disposal in deep mines is the best-developed plan. However, the related concept of in situ melt has significant advantages and should be realistically appraised. Further chemical separation with subsequent recycling of the actinides in a LMFBR should be investigated and implemented, for it would be universally beneficial; on the other hand, additional removal of strontium and cesium does not seem attractive. Thus, for the near future we make the following recommendations:

1) Provide temporary storage facilities to ensure that the projected commercial high-level wastes do not become a public hazard. The AEC adopts this view, and has stated an intention to construct such facilities. But because of the capriciousness of man and nature, a workable ultimate disposal scheme must be developed soon.

2) Fund other ultimate disposal schemes at the same rate as the salt mine project—say $1 million a year or more—to sharpen the technological issues, so that a decision can be reached in the next few years. The schemes should include (i) in situ melt, and the variation with a central repository; (ii) burial in mines other than salt mines (including Antarctic rocks and permanent ice); (iii) further chemical separation of actinides and recycling actinides in a LMFBR.

3) Maintain liaison with the developing space shuttle technology to insure that no opportunity is lost.

The AEC has a commitment to hold safety foremost in its waste management program, but budget considerations and management priorities have downgraded the program. Past funding levels and management emphasis have yet to produce, after a decade and a half, one operational long-term storage facility—a sign of both commendable caution and inadequate work. If nuclear power is to resolve our energy needs in the coming decades, its benefits should not be delayed for lack of a viable management program for high-level wastes.

References and Notes

1. "Potential nuclear power growth patterns," *U.S.A.E.C. Rep. Wash. 1098* (December 1970).
2. Excepting ^{129}I, which has a half-life of 16 million years and is therefore very weakly radioactive. Eventually (after many centuries) its buildup in the environment could become a problem; but the amount to be released in the present technological age is insignificant.
3. We do not discuss here the fuel manufacturing wastes and other solid objects contaminated with plutonium, commonly referred to as alpha wastes. This does not imply that alpha wastes are less important, for about as much plutonium is lost there as is sent to waste at the fuel reprocessing facility. But some of our option analyses can apply to those wastes too.
4. Relative toxicity is an important concept which, while still unofficial, finds increasing use; it is used here to compare hazards of nuclear wastes with those of naturally occurring substances. For each hazardous species, a maximum permissible concentration (MPC) in water has been defined by federal regulations [*Code of Federal Regulations, Title 10* (Government Printing Office, Washington, D.C., 1973), regulation 20 for the substances discussed here, for unrestricted discharges]. Thus, for any initial concentration, a water dilution factor can be specified, to dilute the substance to MPC. We define relative toxicity as the ratio: (volume of water required to dilute a mass of solidified waste to MPC)/(volume of water required to dilute an equal mass of uranium ore to MPC). The ore is assumed to contain 1.4 percent U_3O_8 by weight; the solidified fission wastes are assumed to be concentrated to 4.14 kg per 1000 megawatt-day (thermal) burnup.
5. Disposal in gneiss at the AEC facility on the Savannah River, South Carolina, was considered, but on 17 November 1972 the AEC announced that the Savannah River Bedrock Project was indefinitely postponed.
6. This announcement appeared in *Nucl. News* **15** (No. 7), 55 (1972).
7. The discussion of AEC budgetary actions is based on various hearings on AEC authorizing legislation, particularly: U.S. Congress, Joint Committee on Atomic Energy, *Hearings before the Subcommittee on Legislation* (88th Congress, 1st session, 9, 10 April and 2 May 1963) on the 1964 budget; *Hearings before the Subcommittee on Legislation* (88th Congress, 2nd session, 22, 23, 27 January and 3, 4, 7 February 1964), part 1, on the 1965 budget. Also, *Nucl. News* **15** (No. 3), 26 (1972) on the 1973 budget; H. F. Soule, private communication. Additional material on the program for fiscal years 1968 to 1971 is contained in: Comptroller General of the United States, *Progress and Problems in Programs for Managing High Level Radioactive Wastes* (Document G 164052, General Accounting Office, Washington, D.C., 28 January 1971).
8. A. S. Kubo, thesis, Massachusetts Institute of Technology (1973).
9. There are many salt mine references, but the basic ideas are covered in: "Siting of fuel reprocessing plants and waste management facilities," *Report ORNL-4451* (July 1970); U.S. Congress, Joint Committee on Atomic Energy, *AEC Authorizing Legislation, Fiscal Year 1972* (92nd Congress, 1st session, 9, 16, 17 March 1971), part 3; R. L. Bradshaw and W. C. McClain, Eds., *Report ORNL-4555* (April 1971); A. Boch, *Report ORNL-4751* (December 1971).
10. J. J. Perona, R. L. Bradshaw, J. O. Blomeke, *Report ORNL-TM-664* (October 1963).
11. D. Ferguson and H. C. Claybourne, private communications. For Cs and Sr removal: D. E. Larson and P. W. Smith, paper presented at the 66th national meeting of the American Institute of Chemical Engineers, Portland, Oregon, 24–27 August 1969; H. L. Caudill, J. R. LaRiviere, H. P. Shaw, *Report ARH-SA-41* (Atlantic Richfield Hanford Co., Richland, Washington, undated).
12. An analysis of this possibility is given by H. C. Claiborne, *Report ORNL-TM-3964* (1973).
13. These ideas have been promoted in, for example, E. J. Zeller, D. F. Saunders, E. E. Argino, *International Radionuclide Depository (INTER RAD) Report 72-1* (Center for Research, Inc., University of Kansas, Lawrence, 1972).
14. J. J. Cohen, A. E. Lewis, R. L. Braun, *Nucl. Technol.* **13** (No. 1), 76 (1972).