

Chapter 3

RADIOACTIVE WASTE MANAGEMENT

From chapter 2, we have seen that post-fission radioactive waste is a growing problem with both immediate and long-term ramifications. The problem requires enlightened, far-sighted management.

This chapter, therefore, focuses on radioactive waste management. It does so in a strategic, not tactical sense. We consider key decisions, rather than day-to-day operations. Of course, management involves a decisional process that carries the radioactive waste problem forward from the present into the future. As we shall see, radioactive waste management is a paradigm of decision-making under uncertainty.

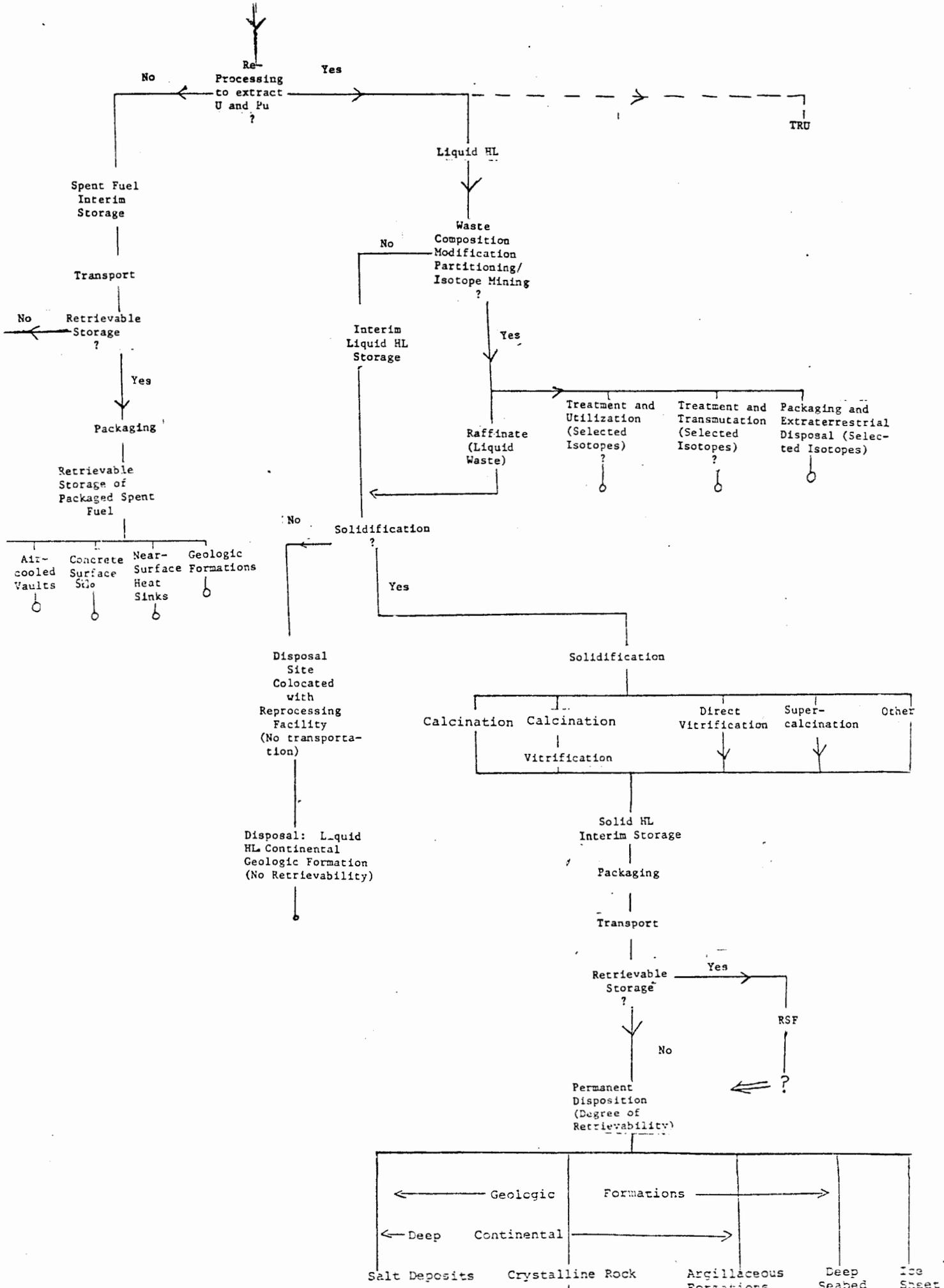
The purpose of this chapter is to present in a coherent manner the strategies that are under consideration for the management of post-fission radioactive waste. The discussion is structured to provide readers with an understanding of how the sequences of key decisions that constitute waste management strategies are inter-related. It is important to determine the constraints each decision imposes on the available technological options. It is also important to consider the risks, costs and benefits associated with the various strategies. Our task is to identify the strategies and the major issues which they raise. We do not attempt quantification. Therefore, the analysis which follows is intended to provide a framework for analyzing the problem that is sufficiently flexible to cope with

the uncertainties involved, yet rigid enough to provide guidance for waste management decision-making.

Overview

The main waste management strategies currently available for commercial and military HL and TRU wastes are shown in figures 3.1 and 3.2. The strategic decisions have been highlighted. The sequences of decisions correspond chronologically to the actual material flows (for example, from reactor spent fuel discharge to permanent disposal of HL waste in salt deposits). This is not necessarily the order in which the strategic decisions need or should be made. The decisional interdependence of waste management planning, unlike the flow of the waste itself, does not move in one direction through time. For example, the selection of a method of permanent disposition may influence the selection of the form of solidified waste and possibly the selection of waste composition. Such decisional interdependence is a recurrent theme.

Military and commercial management are separated. In the short term, the technologies required to deal with these wastes of different origin are significantly different, particularly in the high-level category. Furthermore, a number of important early decisions, starting with the initial decision to reprocess, have already been made in the case of military waste, whereas almost all of the major issues concerning commercial waste generation and management (with the notable exception of the decision to develop a substantial nuclear-electric generating capacity) have yet to be settled.



Because of the future importance of nuclear power and the unresolved nature of the accompanying post-fission waste management decisions, it will be illuminating to consider in the following order the general implications for nuclear power development of reprocessing, the storeaway/throwaway waste management alternative if there is no reprocessing, and the radioactive waste implications of reprocessing. The stage will then have been set for a discussion of the management of commercial HL, military HL, commercial TRU and military TRU wastes.

Reprocessing: Implications for Nuclear Power Development

The first decision is whether to reprocess spent fuel from commercial power reactors. Since the reprocessing decision profoundly affects the whole future development of nuclear power, waste management issues in this context must be kept in perspective and neither exaggerated nor lost from view.

The present economic incentive for reprocessing spent power reactor fuel is to extract uranium and plutonium so that these fissionable materials can be recycled as fuel in commercial power reactors. It is not clear that the value of the fissionable material extracted from spent fuel will outweigh the cost of reprocessing. Uncertainty arises from a number of sources.

First, the value of plutonium and uranium recovered through reprocessing depends on the price of natural uranium. At the present time, the extent of uranium ore resources is not well known. Although the selling price of uranium ore has been increasing rapidly, future price trends are highly uncertain and

are likely to be affected by other factors in addition to the availability of uranium ore.

The second major source of uncertainty is the cost of spent fuel reprocessing and the cost of fabricating fuel containing mixed plutonium and uranium oxides. Mixed oxide fuel fabrication is much more expensive than the fabrication of the low-enriched uranium fuel used currently in light water reactors. Two types of uncertainty are associated with these costs: (1) Neither reprocessing nor mixed-oxide fuel fabrication has reached the stage at which it can be called a "mature" industry. Cost estimates for commercial plants have to be made by extrapolation from smaller scale demonstration-type plants. (2) The regulatory requirements for these plants have not yet been established. In particular, the safeguards against theft or diversion that must accompany plutonium through all stages of recycle are undetermined.

Therefore, the calculations often used to estimate the economic feasibility of spent fuel reprocessing and plutonium and uranium recycle cannot provide a conclusive answer to the question of whether or not to reprocess.

To put the decision in perspective, it is necessary to include its long-term implications. Many of the important implications for waste management are essentially long-term and will be dealt with separately. The implications for the future of nuclear power are merely outlined here.

A decision not to reprocess spent fuel, if adhered to, will mean that nuclear power will only play a short-term, interim

role in meeting U.S. energy demands over the next few decades. The duration of that role would be limited by the extent and quality of uranium ore deposits known and yet to be discovered.

The present generation of commercial power reactors, the light water reactors (LWRs), use slightly enriched uranium fuel that contains 2-4 percent uranium-235 and the remainder uranium-238. Fission of uranium-235 in present LWRs is accompanied by the conversion of some of the uranium-238 isotope into plutonium which is easily fissioned, but LWRs are relatively inefficient converters. Without reprocessing, therefore, the possibility of fission is limited to a relatively small fraction of the uranium-235 contained in fresh fuel and that fraction of the plutonium produced from the initial inventory of uranium-238 which fissions before the fuel becomes poisoned with fission products and must be discharged.

If the decision is made to reprocess spent fuel and to allow the recycle of uranium, but not plutonium, then the uranium resource constraint will still basically apply. The recycled uranium would add at most about 20 percent to the energy that could ultimately be produced. If, however, the decision is to permit spent fuel reprocessing and to allow recycling of both uranium and plutonium in existing LWRs, the recycled plutonium would add perhaps an additional 25 percent to the energy output from nuclear power. Thus, reprocessing and widescale uranium and plutonium recycling in the existing type of commercial nuclear power reactors would stretch the lifetime of nuclear fission power perhaps a decade or two, but nuclear power would remain an interim energy option.

The future of nuclear power as a long-term energy option hinges primarily on the successful development and commercialization of a plutonium breeder reactor, and such a breeder necessarily requires large-scale reprocessing of spent fuel. Plutonium breeder reactors use mixed plutonium-uranium fuel surrounded by a uranium blanket. Fission of plutonium in a breeder reactor results, through uranium-238 neutron capture and subsequent conversion, in the production of more plutonium than is consumed. In short, a breeder reactor is a much more efficient converter of plentiful uranium-238 into plutonium than is a light water reactor.

A plutonium breeder of the liquid metal cooled, fast neutron reactor type (LMFBR) is the long-term technological option being currently pursued as the highest priority in the U.S. and by every other country with a major nuclear power program. The breeder reactor development programs in a number of other countries including France, Great Britain, the Federal Republic of Germany, and the Soviet Union are currently on a more advanced schedule than the U.S. program. The U.S. reprocessing decision must be seen in this dynamic worldwide context.

It is possible to construct a strategy in which spent fuel is reprocessed and the plutonium is not recycled to existing LWRs, but rather stored for an interim period and used subsequently in plutonium breeder reactors. This may well occur in Europe because of the earlier introduction of breeders into commercial use. In the short-term, the effect of such a decision on the U.S. nuclear industry would be significantly different from a decision to re-

cycle plutonium immediately to LWRs. In the long term, and particularly in the long-term effect on radioactive waste management, the difference will be quantitatively marginal and qualitatively non-existent.

There is one possible way in which nuclear power might be developed which would avoid both the uranium resource constraint and a plutonium breeder reactor economy. This would involve a fundamental shift from the uranium-plutonium fuel cycle, on which the world wide nuclear power industry has been largely based, to the thorium-uranium-233 fuel cycle. The technical and economic feasibility of such a radical mid-course shift needs further study before it can be seriously considered. If the main reasons for wishing to escape from the plutonium economy are its diversion and routine handling implications, it is by no means clear that the situation would be improved by long-term reliance on a uranium-233 economy. Uranium-233 is a fissionable material which is about as useful for making nuclear explosives as plutonium, and it would be accompanied at all stages in the fuel cycle by uranium-232, an isotope which decays to form isotopes that emit highly penetrating gamma radiation.

The preceding paragraphs have shown that the way in which nuclear fission is most likely to become a long-term energy option is through the successful development of a plutonium breeder reactor. The prospect of a large, mature nuclear power industry based on plutonium raises profound issues for society aside from the energy that will be produced. Very large amounts--tens of thousands of kilograms--of plutonium will emerge annually from

reprocessing plants, flow through fuel fabrication facilities, and be recycled into breeder reactors. Can a reactor which uses liquid sodium as coolant and fast neutrons for fission be made safe? Can toxic plutonium be managed in reprocessing and fuel fabrication operations without undue risk to the health of workers? Can large flows of plutonium--a few kilograms of which are sufficient for a nuclear explosive--be managed so that no significant amounts are stolen?

These issues are in addition to the long-term radioactive waste implications of a plutonium economy. All of them are imbedded in the basic reprocessing decision. With these overarching considerations in mind, we shall now examine in greater detail the waste management implications flowing from the reprocessing decision.

No Reprocessing: The Storaway/Throwaway Alternative

As mentioned earlier, when spent fuel is discharged from a power reactor it is stored at the reactor site in water-filled ponds. The water acts as a heat transfer medium for the radioactive decay heat that must be removed from the fuel, and also provides shielding and a secondary containment barrier for any radioactivity that the fuel cladding fails to contain.

If the decision is made not to reprocess, the spent fuel cannot be left where it is for very long. Water basin storage of unpackaged spent fuel is an unreliable method of isolating the contained radioactivity for periods longer than a few years, primarily because of deterioration in the quality of the containment provided by the spent fuel cladding. Economies of scale are likely to show that long-term storage of spent fuel should be carried out at one or more central locations rather than at each reactor. Hence, after a period of cooling at a reactor site, spent fuel assemblies will be shipped in specially designed casks to these storage facilities. There they will be removed from the casks and specially packaged to provide an extra degree of containment. Possibly this packaging will occur after a further period of interim storage. For spent LWR fuel, there is likely to be a period of 3-5 years between reactor discharge and packaging so that the provision for radiation shielding and heat removal in the package design is made easier.

The question of whether to store the fuel retrievably or dispose of it irretrievably arises at this stage. We shall not discuss this issue, except to point out that despite the judgment that produced the original decision not to reprocess, it seems unlikely that an irretrievable disposal method for spent fuel will be chosen in

a society acutely conscious of energy shortages. Irretrievable disposal would deprive future generations of the opportunity to resurrect a long-term nuclear option using the spent fuel inventory of fissile material.

Various methods for retrievable storage of packaged spent fuel have been proposed, including water-cooled basins, air cooled vaults, concrete surface silos, near surface heat sinks and geologic formations. The technological requirements for geologic storage are similar to those for the storage of HL waste in geologic formations. These will be discussed later. Any method adopted must contain the radioactivity in the fuel and protect the fuel against mechanical, chemical or thermal damage. It must also provide a safe, subcritical arrangement for the fuel so that the risk of a fission chain reaction is acceptably low. This environment must be maintained under normal conditions and the storage facility must be designed for a "maximum credible accident", such as the kind of natural catastrophe most likely in the area of the site.

An integral part of the design of the storage facility will be the provision for retrievability. It is unclear as to how long it is feasible for a facility to retain this characteristic. A period of a hundred years is often mentioned as being practical for near-surface or surface engineered storage. However, retrievability is a feature that will not disappear overnight. Instead, inevitable deterioration of the various barriers will gradually make the recovery process more and more difficult. Therefore, in the case of a water-cooled basin, air-cooled vault, concrete surface silo or near-surface heat sink, the spent fuel would need to be removed before storage becomes "irretrievable." For geologic storage concepts,

however, this may not be necessary. It should also be remembered that over the life of the storage facility, the perception within society of what may or may not be retrievable is likely to vary with the levels of technological ability and the incentives for retrieval.

One result of reprocessing and recycling plutonium is that only about one hundredth of the plutonium that would otherwise have to be stored in spent fuel is discharged in the HL and TRU waste. The plutonium in an unprocessed spent fuel assembly would take almost two hundred thousand years longer to decay to any given level than the plutonium discharged in the HL and TRU waste that would otherwise be generated by reprocessing that assembly and recycling the recovered plutonium. The implication sometimes drawn from this is that reprocessing and fissioning of 99.5 percent of the plutonium is advantageous from a long-term waste management perspective. This may be true, but the argument is not so simple. For instance, although at any given time the activity of the plutonium in the spent fuel is about two hundred times greater than that in the HL waste, if the performance of a storage repository is gauged by the length of time for which it can isolate radionuclides from the biosphere, and a period of a million years is set as a suitable "criterion" for HL waste, would we really be significantly less confident about finding a repository that could isolate radionuclides for an extra two hundred thousand years?* The same argument applies to TRU wastes.

*Rephrasing the question slightly, it is valid to ask if there would be more confidence in the ability of a repository to isolate wastes for 1 million rather than 1,200,000 years.

Furthermore, it has already been noted that a decision to reprocess and recycle plutonium would allow nuclear fission to become a long-term energy option. Therefore, rather than making the very long-term comparison on the basis of a single assembly, it would perhaps be more reasonable to compare the implications of storing the spent fuel accumulated during a short-term nuclear option with those of storing HL and TRU waste generated during the deployment of a long-term breeder-based nuclear power industry.

Reprocessing: The Closed Fuel Cycle

Having outlined some of the important issues arising from a decision not to reprocess, we now turn to the radioactive waste implications of the other alternative. The discussion continues under the assumption that a decision to reprocess spent fuel is accompanied by a decision to recycle uranium and, sooner or later, plutonium. From a waste management perspective, this route could be viewed as increasing the complexity of subsequent management operations. Before reprocessing, almost all the fission-product and transuranic radionuclides are retained by the cladding within the spent fuel assemblies. Reprocessing involves chopping up the fuel (with the release of trapped fission product gases), leaching out the spent fuel core material from the cladding hulls with nitric acid, and subjecting the fuel solution to a series of chemical extraction stages designed to recover and purify uranium and plutonium. Each of these operations results in additional dissemination of the radionuclides originally contained in the spent fuel and the consequent generation of many waste streams with different physical forms and chemical compositions. However, it must be remembered that during reprocessing almost all of the by-product plutonium is extracted. Plutonium is extremely radiotoxic, has a half-life of about 24,000 years, and is a major contributor to the long-term risk from post-fission wastes. After extraction it may be recycled and fissioned into less hazardous fission products. Some of the long-term implications of this were mentioned at the end of the previous section.

A brief review of the HL and TRU waste streams generated during reprocessing follows:

After the chopping and leaching, the pieces of fuel cladding

(hulls) remain undissolved. In addition, residual traces of undissolved spent fuel remain on the cladding hulls. Up to 0.1 percent of the fission products and actinides are trapped in this way. The chop and leach operation results in the release of gaseous wastes.

Plutonium and uranium are extracted from the nitric acid fuel leach solution into an organic solvent. The aqueous solution remaining after this first cycle co-extraction of uranium and plutonium is the principal component of the HL waste stream. The major constituents of HL waste are the fission products and the actinides. Over 99 percent of all the non-volatile fission products contained in the spent fuel appear in the HL waste. It is expected that approximately 0.5 percent of the uranium and plutonium originally contained in the spent fuel will not be recovered. Thus it will appear mainly in the HL waste stream, together with almost all of the other actinides (the important ones being neptunium, americium and curium.)

The properties that are important in the subsequent handling of the HL waste stream are the thermal power and the curies of radioactivity generated by decaying fission products and actinides, and the neutron emission rate from spontaneous fission. It should also be noted that the chemical form of the liquid HL waste stream is a nitric acid solution.

Finally, solid TRU waste in addition to the cladding hulls and assembly pieces emerges during the course of reprocessing. This waste may be divided into a number of different categories: combustible trash; non-combustible solids; slurries, sludges and resins from water clean-up, and filters from gas clean-up.*

*Large volumes of low activity aqueous waste are also generated during reprocessing. Only trace quantities of transuranics appear in this waste stream.

At this point, a brief digression is appropriate. Modifications can be made to existing procedures or equipment that facilitate the management of wastes generated during reprocessing. These may not, strictly speaking, be considered as waste treatment technologies since, rather than actually handling waste streams, the waste management problem is affected in its gestation period. The major thrust of improvements currently being considered is to develop "low chemical additive" flowsheets, and wherever possible to avoid unnecessary secondary waste streams. The quantity and variety of wastes generated is thus minimized and the chemical composition expedites subsequent operations.

This general principle -- prevention rather than correction -- may be extended beyond reprocessing to all sources of radioactive wastes in the fuel cycle. It is impossible to avoid completely the generation of waste as long as there is fission, but much can be done to affect the type of waste that is generated.

Commercial HL Waste

Now let us focus on commercial HL waste. The structure of the following discussion corresponds to the decision scheme in Figure 3.1 (on page 3-3). It should be re-emphasized that the order in which these decisions are actually made will not necessarily be the same as the order in which they are presented here.

Radioisotope Extraction

After reprocessing, the next strategic decision is whether or not to alter the chemical composition of the HL waste that emerges. Any operation which changes the waste composition will take place in the liquid phase. This step will therefore almost

certainly precede waste solidification, since performing further radioisotope extraction operations directly after reprocessing seems more sensible than first solidifying the waste, subsequently redissolving it and then changing the waste composition.* However, in the future a revised sequence may, for as yet unknown reasons, become attractive.

Both radioisotope extraction and solidification will occur at the reprocessing plant site since the transportation of liquid HL waste is prohibited for safety reasons. Such a prohibition is appropriate since the risks of transport in liquid form outweigh the gains, if any, of waste treatment off-site.

Why should the HL waste composition be altered after it emerges from the reprocessing plant? Two different rationales are proposed. First, the removal of certain radioisotopes from the waste may facilitate subsequent waste storage and disposal. Extraction for this purpose is generally referred to as "waste partitioning." Second, the waste contains isotopes that could be recovered and used in other applications. Extraction for this purpose may be called "isotope mining." Of course, waste partitioning and isotope mining are not mutually exclusive, since an isotope might, for example, be partitioned to reduce long-term risks from the waste and might also have commercial value.

With respect to partitioning, we observe that spent fuel reprocessing technology is governed by the law of diminishing returns. With available technology, it is not likely that it will pay to extract more than about 99.5 percent of the uranium and plutonium from

*It may be necessary to store the liquid HL waste temporarily to allow further radioactive decay before the extractions take place.

the spent fuel. The extra cost of more efficient extraction will probably more than offset the value of the energy in the fuel material recovered by the effort. Therefore, as previously noted, the HL waste contains about 0.5 percent of the plutonium and uranium contained in the spent fuel as well as almost all of the fission products and transuranic actinides apart from plutonium. In general, the actinides take a very long time to decay to harmless levels -- on the order of a million years, whereas the fission products lose almost all of their radioactivity after about a thousand years. This is an oversimplified picture, since some fission product isotopes (principally iodine-129 and technetium-99) have extremely long half-lives and thus remain a potential hazard for as long as the actinides.

The rationale for partitioning is as follows: if HL waste can be divided into fractions according to half-life, the flexibility of subsequent waste storage and disposal operations will be increased, since it will then not be necessary to isolate all the waste from the biosphere for the length of time dictated by the toxic lifetime of the longest-lived radionuclide present in the unpartitioned stream. Therefore, if the actinides and perhaps the long-lived fission products can be partitioned from the HL waste, the residual fission product waste will probably need to be isolated from the biosphere only for about one thousand years. This is a long time in human history, but a relatively short time in geologic terms. It is short enough to be confident about the continuing integrity of the geologic formation in which the waste is stored.

The long-lived fraction partitioned from HL waste might then be eliminated. Transmutation and extra-terrestrial disposal have been proposed as elimination methods. The former essentially would

convert long-lived radionuclides into shorter-lived ones, and the latter would provide an isolation method of cosmic proportions. Both alternatives are still in an early stage of development and are not likely to play more than a peripheral role in waste management planning in the near future.

Strontium-90 and cesium-137 have also been suggested as candidates for partitioning from HL waste, since these isotopes contribute about 90 percent of the activity in the spent fuel after a few years of cooling and continue to dominate for the first several hundred years. During this time they are the most important heat emitters, dictating the thermal design of the waste storage repository. However, removal would not materially reduce the potential hazard posed by these radioisotopes since it is impractical to apply either nuclear transmutation or extra-terrestrial disposal methods to them.

Methods to partition the long-lived radionuclides with sufficiently high extraction efficiencies have not yet been demonstrated, but the indications are that if they are feasible they will also be expensive. The same holds for the additional fuel cycle operations that would be necessary for the partitioning/transmutation option and the space technology required for extra-terrestrial disposal. Furthermore, these new steps would introduce new short-term, operational risks and would also generate new secondary waste streams.

Assessment of the partitioning/transmutation and partitioning/extra-terrestrial disposal options will be a difficult task, since it involves comparing the potential benefits of a reduction in risk that will not begin to take place for almost a thousand years with the increased costs and short-term risks of the technologies that must be implemented if this is to be achieved.

Turning to isotope mining of HL waste, the production of isotopes as by-products of the nuclear power program will far exceed the amounts required for applications in most cases. The management of the residual waste will be effectively unchanged. Furthermore, use of the radioactive isotopes that are mined defers, but does not eliminate, their contribution to the waste problem, since they must eventually be disposed of unless they have decayed to harmless levels during the period of their use. Indeed, waste management may be complicated further, since the radiotoxicity (and sometimes the chemical toxicity) of these isotopes requires their use to be tightly controlled.

Waste Solidification

Whether or not some isotopes are extracted after reprocessing, the liquid HL waste stream is a hazard if it is not handled and processed properly. Solidification immobilizes the waste and reduces its volume, thereby diminishing the potential hazard in liquid HL waste.

Current regulations require solidification to take place no later than five years after the liquid HL waste is generated at a commercial reprocessing plant. A number of different types of solidified product are proposed, each of which can be prepared by a number of different chemical processes. Despite this proliferation of means and ends, solidification technology is already quite well developed, and some of the processes have been extensively applied. Calcination has been used to solidify some U.S. military HL waste for over a decade. Calcined waste is, however, quite leachable. For this reason it is probably unsuitable for long-term waste disposition. Methods to produce

vitriified waste have therefore been developed. The final product of vitrification is a glassy matrix containing waste. It is highly leach resistant and is regarded as being well-suited for long-term isolation of waste. The technology for other solidified waste forms, for example, supercalcine, metal matrix, glass ceramic and coated pellet, is at an earlier stage of development.

It has been suggested that, instead of solidification, HL waste might be disposed of simply by injecting it in liquid form into suitable rock formations. The decay heat from the waste would be sufficient to melt the surrounding rock. As the waste continued to decay, the molten rock-waste mixture would eventually solidify, thus immobilizing the waste in a stable, non-leachable form. This in situ melting concept for liquid HL waste disposal could only be utilized if the reprocessing plant was sited above a suitable geologic formation, unless the present regulations are changed to permit transport of liquid HL waste. The concept is not generally favored, perhaps because it is so unequivocally irretrievable from the outset. It is worth noting at this stage that the in situ melting concept has also been proposed for the disposal of solid HL waste. Similar considerations apply, except that in this case, colocation of the reprocessing plant and disposal site would not be required.

Retrievable Storage

The next major decision concerns retrievable storage of solid HL waste in surface or near-surface storage facilities. After the waste is solidified and suitably packaged, it can be transported either to a permanent storage or disposal site directly, or first to an interim storage facility and then, at some later date, to a

final resting place. Retrievable storage concepts place the responsibility for waste isolation on man-made systems maintained under appropriate surveillance. As noted previously for storage of unprocessed spent fuel, "interim" generally is used to mean a period of up to 100 years.

The idea of retrievable storage of HL waste has had a checkered history. The present situation is that an earlier decision to construct an interim surface storage facility for the waste has been reversed and it is now planned to transport solidified HL waste directly to a permanent storage/disposal site. However, the retrievable storage concept may still be revived. Water-cooled basin, air-cooled vaults and concrete surface silos have all been proposed as storage methods.

Retrievable storage of HL waste allows time for the development of new, improved permanent disposition technologies. Actinide partitioning-elimination schemes could also be developed during a period of interim storage. If the stored wastes are in solid form, however, subsequent redissolution for the purposes of partitioning could prove to be either technically unfeasible or too costly.

It is argued by some that, apart from the development of partitioning which would reduce the time required for waste isolation, scientific and technological progress that will take place during a period of interim storage will not reduce significantly the long-term risk of permanent disposition in geologic formations. If this is true then the incentives for a period of retrievable storage are greatly reduced. Furthermore, it is argued that even if significant progress is made during the interim period, society as that point may be unable to find the resources to retrieve the

waste and store it permanently, if this is then regarded as desirable. The prospect of societal collapse is also invoked in this context. There is no reason to expect such social disintegration to wait until the permanent disposition of radioactive waste has been completed.

Others feel that the hubris of a decision made now to select and implement a final disposition method -- a decision based on the supposition that current knowledge is adequate and unlikely to be improved significantly in the future -- must be avoided. They argue that, despite the additional responsibility that is involved, future generations would prefer to be in a position to make waste management choices of their own, rather than to witness passively the irreversible consequences of a previous decision. This point of view is sometimes expanded to propose the viability of a "permanent" retrievable storage option. Because of the limited time for which a single storage facility can retain its retrievability property, 'permanent' retrievability can only be retained by continual renewal and replacement of the systems used to isolate the waste -- a burden that is justified, in the minds of the proponents, by the fact that in a sense all options continue to remain open in successive generations.

The trade-off between the essentially irretrievable option of permanent geologic disposition and 'permanent' retrievable storage centers on the question of where reliance should be placed: on our existing ability to predict the evolution of geologic history over the next million years or so; or on the ability of future generations to manage the waste safely? From a different perspective one might argue that in the case of permanent retrievable storage, primary reliance is placed on the present and continuing ability to predict

the evolution of human history over much shorter periods. In this case, because of the periodic renewal of storage facilities that would be necessary, the time scales for prediction are measured in hundreds rather than millions of years.

It would be misleading to imply that 'permanent' retrievable storage concepts have received anything approaching the attention that has been given to permanent geologic disposition. Nevertheless, a direct comparison such as this helps to crystallize issues that may otherwise have been obscured if the discussion had focused solely on the "mainstream technological options."

Permanent Disposition of HL Waste

Many persons with diverse backgrounds believe that the most important decision to be made in developing a radioactive waste management system is the choice of a permanent disposition method. It is easy to understand why. The waste must be isolated from man and the environment for as long as it will present a potential radiological hazard. Without reprocessing, the isolation period will be more than a million years; with reprocessing it will be about two hundred thousand years less; with reprocessing and effective partitioning it will be at least one thousand years.

Unfortunately, one characteristic of choosing a permanent disposal method is that we can never know whether we have chosen safely, since such a long period of time is likely to elapse before errors in judgment or mistakes in implementation are likely to show up. This feature of decision-making regarding permanent waste disposition appears more extraordinary than it really is, however. Most major social decisions are made under large uncertainty and they effect a separate distribution of benefits, costs and risks within a society geographically and/or economically, if not across long stretches of time.

Here, we are concerned with what may be done to minimize the risk that something actually will go wrong.

A technical consensus appears to have been reached to the effect that the best place to isolate HL waste is under the earth's surface. The major debate concerns which areas of the earth's surface and which underground geologic formations are the most suitable. Continental land masses, the ocean floor, and polar ice caps are proposed as suitable areas. Since these three areas together include most of the surface of the earth, we must be more specific.

On land, a number of different geologic formations are being considered. Rock salt has been a candidate for over two decades. HL waste disposal in salt formations continues to be the favored alternative within the U.S. government. Hard, insoluble crystalline rock formations such as granite and basalt are in some ways preferable to plastically flowing, water-soluble salt, but in other respects they are less desirable. The same applies to formations of shale or sandstone.

More than two-thirds of the earth's surface is covered by the oceans. Some areas of the ocean deep seabed are geologically and seismically stable, are remote, and are biologically relatively unproductive. These areas are, moreover, separated from man's immediate environment by huge volumes of a diluting medium. Thus, the deep seabed contains possible sites for HL waste repositories. The disposal concept is not ocean dumping, but rather controlled emplacement of solidified, packaged, HL waste in either the argillaceous sediment or the underlying basaltic bedrock. The engineering capability to perform the required ocean floor operations is quite highly developed. Therefore, seabed disposal appears technically feasible. However, more knowledge is needed concerning the physical, chemical and biological mechanisms by which radionuclides in HL waste could be released from the repository and transported through the seabed and into the marine environment.

HL waste storage or disposal in or under the Antarctic ice sheet is an alternative that is currently not considered as attractive as deep continental or seabed disposal. Most of the schemes envisioned would allow the waste to melt its way through the icesheet, eventually coming to rest either at the ice-rock

interface or within the bedrock itself. Other concepts include the construction of an interim surface storage facility which, after decommissioning, would become covered with snow, and subsequently sink through the ice towards the bedrock.

The previous discussion has focused on the technological implications of the decision sequences involved in the implementation of various commercial HL waste management strategies. Some of the more important risks, costs and benefits arising from these decisions have been identified. An in-depth comparison, based on detailed and comprehensive studies, will be necessary to provide the foundation for choosing which particular strategy or strategies should be implemented.

Military HL Waste

This section discusses the military HL waste situation, and various ways in which it might be handled in the future. First, we discuss what may be done with the waste that has already accumulated. Then we consider the alternatives available for managing military HL waste generated in the future. The majority of the future waste will come from the continuing plutonium production program. The division is somewhat artificial, since management policy for waste in prospect is heavily influenced by previous practices. Nevertheless, by structuring the discussion this way, it is easier to focus on the important waste management issues. Figure 3.2 (on page 3-4) shows diagrammatically the management strategies currently applicable for military HL waste.

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Existing Waste Treatment

In chapter 2, the quantities of existing military HL waste were briefly outlined. This information will now be augmented.

By the early 1980s, it is estimated that approximately 65 million gallons of HL waste will exist in solid form. An additional 9 million gallons will be "in process" as liquid that is being allowed to decay before solidification and liquid that cannot be solidified with present technology. At the present time, 72 percent of the military HL waste is stored at Hanford, 25 percent at Savannah River, and 3 percent at Idaho Falls. These ratios will not change appreciably by the early 1980s.

At Savannah River and Hanford, with the exception of the HL waste produced in the very early reprocessing plants that have long since been shut down, all HL waste is originally generated in acid form. Acid liquid HL waste must be stored in stainless steel tanks. In the immediate post-World War II years stainless steel was expensive and not easy to obtain. The decision was therefore made to neutralize the wastes. This increases the waste volume by about 60 percent and causes some of the more radioactive isotopes to precipitate out in a sludge. Nevertheless, neutralized waste can be stored in carbon steel tanks. These were (and still are) cheaper than stainless steel tanks, and were therefore used for storing the sludge and liquid after generation. The lifetime of carbon steel tanks was shorter than expected and leaks occurred.

One possible way to deal with the leaks would have been to reduce the working lifetime of the tanks. This could be done by building new ones and periodically transferring waste from one tank to another. An alternative procedure would be to solidify the waste.

The leaks would be stopped. Furthermore, since solidification reduces volume, extra storage space would be created in existing tanks. The latter alternative was cheaper, and it was selected.

Solidification of neutralized liquid HL waste is achieved by evaporating it down to a damp salt cake. Evaporation does not solidify all of the liquid, however, and there is always a quantity of residual liquor remaining. (Before solidifying the Hanford waste it is necessary to partition most of the Sr-90 and Cs-137. These isotopes are encapsulated and currently stored in water basins.) The solidification program will not reach a steady state until the early 1980s, by which time there will be approximately 450,000 tons of residual solids in the tanks.

What should be done with these solids? Should they remain where they are or should they be removed?

One possible course of action is to leave them where they are without further treatment. It is practically certain that such a plan would be deemed unacceptable. Salt cake is extremely soluble, the carbon steel tanks are corroding, and the arrangement would provide reliable containment for no more than a few decades. Another alternative is to leave the solids in the tanks and treat them further. The salt cake might be converted into a form less susceptible to leaching. Then the tanks might be covered with asphalt or concrete to make them more inaccessible to water and living organisms.

If the solids are to be removed from the tanks, the problem of extraction must be faced. Two methods are currently being considered. Neither seems very attractive. High-pressure water jets might be used to sluice out the partially dissolved solids. Such

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a procedure would not be suitable for the many tanks (particularly at Hanford) that are cracked because dissolution of the salt would reopen the previously blocked cracks and cause still more leakage. Alternatively, the solid salt cake might be dug out of the tanks -- a risky procedure made more difficult because access to the tanks is limited to a few narrow vent pipes. Furthermore, the excavation work would increase the risk of airborne radioactivity.

After it is removed, what should be done with the salt cake? It will probably require further treatment to produce a solid form that is more suitable for permanent disposition. The technology required for this step is not yet developed. It is not clear whether there is a form that fulfills the dual requirements of long-term stability and the ability to be produced from salt cake.

Finally, the costs of treatment and removal of existing military HL waste from tanks at Hanford and Savannah River must be mentioned. Cost estimates vary over a wide range from \$2 to \$20 billion dollars just to prepare the existing military HL waste inventory at Hanford and Savannah River for permanent disposition. Two conclusions seem appropriate: (1) The cost of managing military HL Waste is likely to be greater than the cost of commercial waste management for quite some time to come. (2) In radioactive waste management, the longer term consequences of decisions made only on the basis of short-term considerations can be enormous. It should also be remembered that "longer term" here means about 50 years -- a very small fraction of the toxic lifetime of the waste.

The situation at Idaho Falls with regard to existing solid HL waste is significantly different from Hanford and Savannah River. At this site, the acid waste has not been neutralized. Instead, it

has been stored temporarily in stainless steel tanks. Since the opening of the waste calcination facility in 1963, it has been processed to form a dry granular solid called waste calcine. The calcined waste is stored in stainless steel bins partially underground. The lifetime of these bins is estimated to be several hundred years.

Calcined waste, however, is relatively leachable. Bin storage cannot therefore be relied upon to provide adequate isolation for the toxic lifetime of the waste. Thus the question of when to begin removal will have to be settled. Unlike the situation at Hanford and Savannah River, the removal of solid wastes from storage bins will not be a very difficult technical operation. In view of the technical similarity between the waste produced at Idaho Falls and that from the commercial power reactor program, (they are both retained in acid form, and then calcined), the waste management decisions made for each should presumably be consistent. For example, it would not seem consistent to decide upon an extended period of storage for calcined waste in bins at Idaho Falls and also decide that retrievable engineered storage is not suitable for commercial HL waste.

Management of Future Wastes: Short-Term

Major modifications to existing management practices for HL waste at Idaho Falls do not appear necessary in the immediate future. The important decisions yet to be taken concern the post-calcination steps and apply equally to existing and future waste.

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This is not the case at Hanford and Savannah River. The root of the present problem, and its magnitude is considerable, seems to have been the initial decision to neutralize the acid waste. This practice continues. The issue is: should future acid HL waste be neutralized? At this stage, it is helpful to briefly compare a neutralized waste/salt cake system with an acid waste/calcine system.

As discussed previously, the initial decision to neutralize was based on the availability and cost of carbon steel compared to stainless steel. The former is still cheaper than the latter, but it should also be remembered that neutralization results in a significant increase in volume so that the tankage required for acid storage is less than for storage as a neutralized solution. The lifetime of stainless steel tanks is longer than that of carbon steel tanks for waste storage purposes.

Solidification technology is different for the two systems. Calcined waste, although not suitable for long-term storage because of its leachability, is a satisfactory base from which to produce glasses and other more suitable forms. Calcination of acid waste has taken place routinely since 1963. On the other hand, it is not possible to calcine neutralized wastes with present technology, and the evaporation/crystallization method used to solidify waste at Savannah River and Hanford is not entirely satisfactory. In addition, salt cake is more soluble than calcine, and is clearly not suitable for long-term storage. A method for converting it into a less leachable form such as glass has not yet been demonstrated on a commercial scale, and it will be a difficult problem to solve.

The volume of salt cake per unit of spent fuel reprocessed is significantly greater than the corresponding volume of calcine produced by an identical amount of spent fuel. Finally, calcined waste in bins at Idaho is much more retrievable than salt cake, especially the material in the flawed tanks at Hanford.

With this comparison in mind, we may consider the question of whether or not to continue to neutralize future HL waste at Hanford and Savannah River. At Hanford, the military production of plutonium is gradually being phased out. Of the nine production reactors that have operated at one time or another over the past thirty years, only one is still functioning, and that one will probably be shut down within a few years. Therefore, in view of the relatively small quantity of HL waste that is still to be generated at Hanford, a switch to an acid waste management system at this stage may be uneconomical. The Savannah River plant is now the major plutonium production facility in the U.S., and will continue to generate HL waste in relatively large quantities for as long as plutonium is required for nuclear weapons. In this case, it may be preferable to convert to an acid-calcine system. Nevertheless, a recent assessment, based upon economic estimates to 2000, indicates that it will be cheaper to continue with an improved neutralization-salt cake system than it would be to convert to an acid-calcine system.

Permanent Disposition: Existing and Future Waste

It is sometimes suggested, or charged by critics of government management, that existing military HL waste, in salt cake form, can be left in existing tanks, more or less permanently. Enough has been said previously to indicate that such a solution is clearly unsafe.

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Regrettably, further procrastination is possible and perhaps likely in view of the costs involved.

After HL solid waste has been removed from the tanks and converted into a different form, it is necessary to decide on a site for final disposition and then to package and transport the waste to the site chosen. (Retrievable interim storage is also a possibility, but it would be an additional costly stage in an already very costly program, and, depending on the performance of the existing temporary storage facilities over the next few decades, it might also be unnecessary.) The location could be either on or off the tank storage site. On-site disposition seems most unlikely. Earlier AEC efforts to establish the feasibility of on-site geologic disposal of the solidified HL waste at both Hanford and Savannah River have been suspended indefinitely. The alternative off-site permanent disposition methods for solidified military HL waste are similar to those for solidified commercial waste. However, alternatives that are international in scope, specifically deep seabed and ice sheet disposal, may not be available for military waste disposal if other governments raise political and legal objections.

Demonstration of Permanent HL Waste Repository

The U.S. government presently plans to have begun a "demonstration" of a permanent HL waste repository by 1985. Based on the results of site selection and R & D programs that are already underway, the demonstration is believed to be necessary as one of a series of actions to "close" the nuclear fuel cycle (i.e. to begin commercial reprocessing and plutonium recycling in LWRs). 1985 is the target date for the initial waste repository demonstration to begin because that is the earliest date that solidified HL waste from a

commercial reprocessing plant will be received for permanent disposition. The logic of the schedule -- reprocessing plant; interim storage of liquid; solidification; transportation; disposal -- assumes that all stages are developed in a timely and orderly manner.

The demonstration will begin with the establishment of a pilot facility which is ready to receive waste in 1985, to be followed by expansion, and then, if nothing unforeseen has occurred and the demonstration has been successful, conversion into a full-scale federal repository after about ten years, or about 1995. The change from an expanded pilot plant to a full-scale federal repository will be characterized by the conversion of retrievable storage facilities into irretrievable disposal. Six sites for repositories will be established on a staggered basis, with the first two in salt and the next four in formations other than salt.

In 1985 there will be no absolute necessity for a federal repository for the ultimate disposal of HL waste. The absence of such a repository would not result in a technical inability to generate nuclear electric power. Moreover, such a repository is not the only way to prevent harmful health or environmental effects arising from the HL waste. So, we must look elsewhere for the reasons behind the existing schedule for the demonstration and creation of a permanent waste repository.

What are the technical benefits from the operation of a pilot-scale permanent repository for about ten years? Experience will be gained: in the handling of packaged solid waste; in the construction and operation of surface and underground facilities for receiving waste; in the emplacement of wastes in the geologic formation; and in the measurement of the physical effects of waste emplacement. It will, of course, be impossible to "demonstrate" with

any reasonable assurance of validity, the capability of the repository to contain HL waste over the period for which it constitutes a potential radiological hazard. What can be demonstrated is the ability to receive and emplace solid waste in the repository.

What are the possible non-technical benefits from the demonstration? It seems generally acknowledged that one of the major obstacles to public acceptance of nuclear power is concern that there is no safe solution to the radioactive waste problem. It is believed by many that this concern is derived, at least in part, from the absence of a demonstrated permanent waste repository. It seems reasonable to conclude that one of the most important purposes intended by the waste repository demonstration "on a timely basis" (i.e., by 1985) is to increase public confidence.

But what worries the public about the disposal of radioactive waste? It is the concern that, in pursuit of our objectives of providing ourselves with energy and security, we might also be responsible for harm inflicted on one or more generations far into the future by failing to provide adequate isolation of this radiologically hazardous material.

Assuming the demonstration is successful within its limitations, what will it help to achieve in public confidence? It is possible that a demonstration will satisfy the public that the task of radioactive waste management can be dealt with safely. But if this occurs, the demonstration will have created an "illusion of certainty" (to quote Kenneth Boulding's phrase). Even those who have great confidence in the ability of our society to dispose of radioactive waste in a safe manner would not claim that the operation of a waste repository for a few years will, in itself, provide substantial evidence to support a conclusion that the waste is very unlikely

to harm man or the environment thousands of years in the future. Should we proceed on the basis of such an illusion of certainty in the public mind, even if the illusion is not shared by those in authority?

Another possibility is that the general public becomes more sophisticated in its ability to make judgments on the basis of technical and probabilistic information, and the predominant view will be that the risks of radioactive waste disposal are acceptable. If such a development actually takes place, the public will not regard the demonstration as being very significant as an input into a long-term decision-making process. A third possibility is that there will be a public reaction against what is seen as an attempt to manipulate opinion with the demonstration. In this event, the obstacle which the radioactive waste problem poses to public acceptance of nuclear power will become even greater.

It may be concluded from this discussion that it would be unwise to rely heavily on the successful demonstration of a pilot permanent waste repository to obtain public acceptance of the waste management program. Therefore, all the uncertainties associated with the various nuclear waste management strategies discussed previously in this chapter should be fully aired. Indeed, the tendency of many of those involved in the resolution of nuclear issues to interpret current public sensitivity to waste management issues as public pressure for quick resolution may be misguided. An alternative argument is that the current ill-defined sensitivity will eventually articulate itself into a clearly stated desire for slower but surer resolution.

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Commercial TRU Waste

Under existing ERDA standards and proposed NRC regulations, TRU waste is defined as low-level waste which is presumed to contain more than ten nanocuries of long-lived transuranic radioactivity per gram. This definitional limit is currently being studied and may be revised upward.

Low-level, transuranic contaminated waste (TRU waste) will require more careful management than other kinds of low-level waste because of the very long time for which it will remain a radiological hazard. Indeed, assuming that reprocessing and recycling are introduced using existing process methods, more than half of the plutonium released in nuclear fuel cycle wastes will be contained in low-level waste streams. However, although TRU waste contains at least as much plutonium as HL waste, the plutonium concentration is very much lower. Nevertheless, quantities of long-lived radionuclides rather than their concentrations should probably be given more weight in basic policy decisions.

TRU waste streams of three types--non-combustible solid, combustible solid and liquid--are generated by three stages of the commercial fuel cycle--reprocessing, the conversion of liquid plutonium nitrate to solid plutonium oxide and mixed oxide fuel fabrication. Measured by the amount of plutonium contained in TRU waste per unit of electric power produced, TRU waste is created in these three stages at roughly the same rate. In similar units, each type of TRU waste--combustible and non-combustible solids and liquid--is produced at approximately the same rate. These two facts imply that all TRU waste streams from all TRU waste producing stages of the fuel cycle should receive equal attention.

With this brief introduction in mind, we will discuss the major TRU waste management decisions. As with HL waste management, all decisions are interdependent.

The management of TRU waste can be affected by operational changes at the points of generation. As in the case of HL waste management, this concept is one of prevention rather than correction. For instance, the efficiencies of plutonium recovery at the reprocessing plant* and plutonium utilization at the mixed oxide fuel fabrication plant could both be improved, so that less plutonium is lost in the TRU waste streams. The argument used earlier for plutonium recovery from HL waste involving the law of diminishing returns applies here. It may be economic to remove part of the plutonium contained in some TRU waste and recycle it to reactors. But in order to obtain a significant reduction in the long-term environmental risks from these wastes, it will be necessary to achieve a higher recovery efficiency. The cost of these operations will not match the value of the extra fuel obtained as a result. It therefore seems likely that the reprocessor and fabricator would require some form of encouragement--a government subsidy as a carrot or regulatory standard as a stick--if these improvements are to be achieved. Similar considerations apply to the flowsheet modifications that could be made at reprocessing and mixed oxide fuel fabrication plants to make the physical form and chemical composition of the TRU wastes more suitable for subsequent waste management operations.

*For convenience, the nitrate-oxide conversion facility will now be considered as part of the reprocessing plant. In practice, the two functions, reprocessing and conversion, will essentially be combined into one process flowsheet.

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The issue of improved plutonium recovery is related to the HL waste partitioning question. The ability of waste partitioning to reduce the long-term risk of HL waste management has already been discussed. Since the amounts of long-lived radionuclides in unpartitioned HL waste and untreated TRU waste are similar for each unit of electricity produced, it is argued that a decision taken to partition HL waste, if consistent, would have to be accompanied by a decision to remove enough of the transuranics (mostly plutonium) from the TRU waste to achieve a corresponding reduction in long-term risks.

Transuranic recovery from TRU waste would precede or follow a number of other treatment steps. For instance, sorting and shredding followed by incineration of combustible waste produces a residue (or ash) that can be processed for plutonium recovery. An incentive for incineration (or some other method of combustion) is the volume reduction that is achieved. Reduction factors varying between 20 and 50 are claimed for the different processes. Mechanical compaction can also be used to reduce the as-generated volume of both combustible and non-combustible solids.

In view of the great variation in TRU waste streams generated in reprocessing and mixed oxide fuel fabrication plants, it is not surprising that there are a great many different treatment technologies. Some of them are still at an early stage of development, probably because the commercial nuclear industry has not begun to generate TRU waste in significant quantities, and until recently TRU and non-TRU low-level wastes were not distinguished in management operations involving military and research and development waste. Others are equally applicable to TRU and non-TRU wastes, and certain

of these have been used routinely for some time. A substantial proportion of these generally applicable non-high-level waste treatment technologies have not yet been introduced into commercial waste management systems.

Nevertheless, all of these technologies are designed to achieve one or more of the following objectives: the creation of a waste form with good long-term storage properties; volume reduction; the reduction of short-term risks. In all cases, the importance of minimizing secondary waste stream production is clear, since each operation involving the handling of radioactive materials tends to disseminate the radionuclides in the feed stream among a number of different cut-put streams.

The final two stages in TRU waste management--each of which bears directly on the long-term risk posed by this waste--are immobilization and final disposition. They must combine to prevent the migration of radionuclides from TRU waste to the biosphere. Again, in view of the wide variety of TRU waste forms, there will be a number of applicable immobilization technologies.

It is becoming increasingly likely that the long-term isolation criteria that will be applied to HL waste will also be applied to TRU waste. The logic behind this trend is based on the realization that the amounts of long-lived radioactivity in these two waste categories are comparable, although the concentrations are, of course, significantly different. Decisions concerning the permanent disposition of HL and TRU wastes will be closely related, and the options presented in the section on HL waste are applicable.

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Military TRU Waste

Military TRU waste comes principally from two sources--plutonium separation from irradiated plutonium production reactor fuel and the fabrication of nuclear weapons. Information concerning the latter is classified. As has already been mentioned, until 1970 TRU waste under the jurisdiction of the old AEC (most of which had a military origin) was emplaced in shallow burial grounds with no provision for retrieval. Since then, TRU waste at ERDA (formerly AEC) burial sites has been stored retrievably above ground.

Taking the long-term perspective, particularly with regard to permanent disposition, it seems unjustifiable to manage the military and commercial TRU wastes so that the risks posed by one will be greater than those posed by the other. The waste must be managed consistently, regardless of origin. In the case of the weapons fabrication waste this may present security-related problems. But these difficulties can be solved administratively, and they should not obscure the fundamental waste management issue--the long-term nature of the risk.

Conclusions

From the preceding discussion of radioactive waste management strategies, the following conclusions are drawn:

1. The decision whether or not to reprocess commercial power reactor fuel has fundamental importance for the future development of nuclear fission as a source of energy. Nuclear fission will be a long-term energy option only with reprocessing and successful breeder reactor development. Either the uranium/plutonium, or the thorium/uranium-233 fuel cycle, or a combination of both, are possible as long-term fission energy options, but the uranium/plutonium

fuel cycle is the more likely to mature first. With reprocessing and plutonium recycling in existing commercial LWRs only, the short lifetime of the fission energy option based on the uranium/plutonium fuel cycle is only marginally extended.

The reprocessing decision may be delayed and spent fuel discharged from LWRs may be stored pending the outcome of breeder reactor development and demonstration efforts now underway. If, however, reprocessing is ruled out permanently, then the costly breeder reactor development program should be promptly stopped and the funds and manpower currently devoted to it should be allocated to development of other long-term energy options instead of nuclear fission. From another perspective, the continued top priority assigned to plutonium breeder reactor development and the expenditure of resources in support of that priority in the U.S. (and every other country with a major nuclear power program) imply that the decision in favor of reprocessing has already been made in principle, and that the remaining issues are when and on what conditions reprocessing should begin.

2. Radioactive waste management is an important, though not in itself decisive, issue in the reprocessing decision. If commercial spent fuel is not reprocessed, over the long-term it will be a major waste management problem. Some form of reprocessing may eventually be necessary as a waste treatment measure, if not to recover uranium and plutonium for use as fuel. If commercial spent fuel is reprocessed for the purposes of fuel recycling, then HL and TRU waste streams which emerge principally during reprocessing and uranium/plutonium mixed oxide fuel fabrication will be interrelated long-term waste management problems.

3. The decision whether or not to reprocess military fuel was made at the outset of the U.S. nuclear weapons program in order to obtain plutonium for use in weapons. From past military plutonium production, the legacy of liquid and solid accumulations of HL waste in temporary tanks constitutes a multi-billion dollar treatment problem before the waste can be safely placed in a permanent repository.

4. Radioactive waste management operations are interdependent. The risks and costs of permanent disposition methods affect and are affected by waste partitioning and solidification or other treatment methods. In view of the long-term risks, essentially all HL and TRU waste, regardless of its commercial or military origin, should be eventually destined for one set of government-managed radioactive waste repositories.

5. Decisions regarding every phase of radioactive waste management must be made under uncertainty. Research and development can narrow technological uncertainty. Short-term demonstrations of permanent waste repositories can show that radioactive waste can be safely emplaced in geologic formations, but little more.

6. Radioactive waste management requires comprehensive strategic planning. A key issue in such planning is the distribution of risks and costs through time. In radioactive waste management, quality of thought is more important than timeliness in decisions because the current costs of delay are likely to be much less than the future costs of error. This reasoning runs counter to the strong pressure, which currently exists, for an early "solution" to the radioactive waste problem.

7. From a technological standpoint, radioactive waste operations require a fully integrated management framework. The management framework should be vertically integrated so as to include all operations from temporary waste storage, through treatment and transport to permanent disposition. The framework should be horizontally integrated to include post-fission HL and TRU wastes of commercial and military origin.

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Radioactive waste management will be a continuing challenge for government throughout the nuclear age, and perhaps for many centuries beyond.