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Irreversibility and multiplicity : two criteria for disposal of nuclear waste

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IRREVERSIBILITY AND MULTIPLICITY: TWO CRITERIA FOR DISPOSAL OF NUCLEAR WASTE

by

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"Del carratere degli abitanti d'Andria meritano di essere ricordate due virtû: la sicurezza in se stessi e la prudenza. Convinti che ogni innovazione nella città influisca sul disegno del cielo, prima de'ogni decisione calcolano i rischi e i vantaggi per loro e per l'insieme della città e dei mondi."[*]

Italo Calvino [1]
Le Città Invisibili

INTRODUCTION

There is a consensus that radiologically hazardous wastes from the nuclear fuel cycle should be separated from the biosphere to a sufficient degree and for a long enough time so that they present no significant risk to life. But this consensus does not extend to the definitions of "sufficient," "long enough," or "significant risk." Our ability to predict material or geological stability over the containment times required for long-lived components has been questioned.[2] Moreover, the impossibility of predicting socially relevant factors over such relatively short periods as a few hundred years precludes accurate estimation of either the probability of an accidental or deliberate breach of containment or the effects of such a breach on society.[3]

Recent attempts to organize technical options for management and disposal of nuclear wastes,[4,5] have been constrained by a number of factors.

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[*] "As for the character of Andria's inhabitants, two virtues are worth mentioning: self-confidence and prudence. Convinced that every innovation in the city influences the sky's pattern, before taking any decision they calculate the risks and advantages for themselves and for the city and for all worlds."

The lack of attention received by the "back-end" of the fuel cycle[6] resulted in periods when waste management research and development were neglected.[7] Utilities have had no incentive to absorb waste management costs.[8] Increased public concern over waste disposal brought pressures to resolve the issue quickly, which in turn tended to restrict consideration to those few methods whose techniques and performance had been relatively well studied.[9] Thus, while criteria, regulations, and techniques for the handling and transportation of wastes after their production have been based on established health and safety standards,[10] solutions for long-term waste management have largely focused on the selection and promotion of an available method or technology.[11]

In the absence of coherent goals or comprehensive regulatory standards, suggested methods of waste management are usually divided into three categories: (1) short-term storage, (2) long-term storage, and (3) disposal.[12] Short-term storage, such as in shallowly-buried metal tanks,[13] requires active maintenance and guarding, and is intended primarily as an interim procedure.[14] Long-term storage, such as emplacement in underground caverns mined in salt,[15] requires little or no active maintenance, but is susceptible to accidental or deliberate breaching of isolation barriers.[16] Disposal, such as ejection into outer space,[17] implies that there are <u>no</u> circumstances that could result in the return of the wastes to the terrestrial environment.[18]

The division of what is properly a continuum of possible waste management methods into three distinct categories is purely arbitrary and appears to have evolved primarily as a way to organize technical thinking in response to political pressures. As each individual waste management method was promoted, heated controversy erupted as to its efficacy. A typical response was to aver that the suggested method was a form of storage, pending the development of an acceptable final disposal scheme.[19] This emphasized the differences between alternative methods rather than the continuity of the problem. The need for perpetual care of a retrievable surface storage facility is difficult to weigh against the probability of re-entry of a space shuttle package or the possibility of an undiscovered water source in a salt formation. In the first case the dominant failure mode is social, in the second case technical, and in the third case informational. Focusing on individual methods and their idiosyncratic deficiencies led to incoherent debate,[20] owing to the absence of a shared basis for comparison. The commonality of the goals and objectives of all waste management methods was obscured.[21]

Two criteria, are suggested here, <u>technical irreversibility</u> and <u>site multiplicity</u>, for use in organizing waste management options in terms of insuring continued isolation from the biosphere in the face of both social and geological uncertainties. They also reflect the possible consequences of technical or judgmental errors. These criteria translate the goals of waste management--public health and safety, ethical and moral responsibilities, obligations to the future, concern over imperfections in present technical and social knowledge--into standards against which the performance of any suggested scheme can be judged.[22] The purpose of the classification is not to substitute quantitative social analysis or purely technical measurements for proper consideration of the ethical and social issues associated with a waste management decision. Rather, it is to provide a clear basis for open and conscious policy choice.

Long-term safety is taken to be the overriding concern. Operational and short-term risks and present costs are held to be of secondary importance in determining an acceptable method,[23] and are to be examined after a desired option has been selected. If this option seems excessively hazardous to present populations, or prohibitively expensive, the next best alternative can then be examined. A minimum ethical requirement is that this choice be made explicitly and self-consciously,[24] and with an open acknowledgement that the well-being of future generations may depend upon our choice. Unexamined or implicit value judgments, ethical choices, and evaluations of risk should be avoided.

WASTES FROM THE NUCLEAR FUEL CYCLE

Radioactive materials of no immediate or foreseeable value are produced at every stage of the nuclear fuel cycle. Collected and contained, they constitute the wastes. Gaseous emissions and liquid effluents, after treatment to remove the more hazardous components,[25] are discharged into the environment and no longer enter as a problem for waste management.[26] Low-level wastes comprise large volumes of material containing low concentrations of radionuclides, and arise from activation or contamination of solids and liquids used in routine operation--gloves, wiping cloths, effluent filters, coolants, etc. The radiological hazard per unit volume is comparatively low, and only a very small concentration of alpha-emitting transuranics is to be allowed.[27] Intermediate-level wastes consist largely of the products of effluent cleanup and of chemical wastes with a higher concentration of fission products and other short-lived radionuclides.[28]

Transuranic-contaminated wastes come primarily from fuel processing and fabrication, where some portion of the actinides being handled is lost as waste in chemical extraction or machining operations. The very long half-lives and very low permissible concentrations of most alpha-emitting actinides requires that these wastes be disposed of by a method that provides long-term guarantees of containment integrity.

The wastes that have most often served as the focus of public debate over long-term containment and disposal are the high-level wastes (HLW) that will originate in the reprocessing of spent reactor fuel.[29] After waiting a few months for the shortest-lived isotopes to decay away, the spent fuel is to be sent to a reprocessing facility where the uranium and plutonium will be chemically extracted. The recovered uranium may be returned to an enrichment facility to be recycled again as fuel. The extracted plutonium can be used directly.[30] The HLW generated as liquid wastes from the solvent extraction process[31] will contain almost all of the non-volatile fission products, a residual percentage of the uranium and plutonium,[32] and the remainder of the actinides.[33] Under present federal regulations, this liquid must be solidified within five years of reprocessing and shipped to a federal waste repository within ten years.[34] Shipment as a liquid is prohibited.[35]

Figure 1 shows some of the constituents of high-level waste as a function of time from reprocessing.[36] The components usually referred to as short-lived have half-lives ranging up to a few tens of years.[37] They decay away sufficiently rapidly so that in times less than or of the order of 10^3 years their contribution to waste activity is comparable to or below background radiation. The long-lived components, on the other hand, have half-lives upwards of 10^3 years. As they are generally emitters of alpha rather than beta or gamma radiation, they present a greater carcinogenic potential per Curie of activity.[38] They must be kept contained and isolated for times up to 10^6 years. This separation according to half-lives is not entirely arbitrary. As shown in Fig. 1, it reflects the character of the waste stream.

From a social or political point of view, it is difficult to think of 10^3 years as a short time. Figure 2 compares the half-lives of some of the radionuclides present in wastes with times of social or political relevance. Recall that many half-lives must elapse before the net activity due to any specific isotope is appreciably reduced. For beta and gamma emitting radionuclides that decay to benign levels in times less than 10^3 years, the decrease in potential risk occurs over times that allow us to at least conjecture about relevant social and political conditions. This is clearly not true for the long-lived transuranics.

It has been suggested that HLW, at least, be further separated into long-lived and short-lived components by additional chemical treatment.[39] Such partitioning might simplify some aspects of disposal. The mass and volume of the fraction containing the alpha-emitting transuranics would be reduced considerably, which would facilitate more exotic waste disposal methods such as space and transmutation.[40] The shorter-lived fraction could be handled differently, and some of the isotopes might even be in demand for other purposes as they were separated out.[41]

The definitional problem of determining which components should be treated as wastes and which as potentially recoverable resources is not a trivial one. Present opinions range from the conviction that almost all of the radionuclides have potential value and should be stored retrievably against the day when the need for them is fully developed,[42] to the opinion that any byproduct of the nuclear fuel cycle for which there is no <u>immediate</u> use should be permanently disposed of.[43] Therefore, no fixed definition of isotopic composition or mass is assumed. Where quantities or specific activities of the wastes are determining factors in the operation of a given waste disposal method, they must be taken into consideration when evaluating its feasibility, as both the scale of the operation and the level of risk entailed will be affected.

CRITERIA FOR WASTE DISPOSAL METHODS

All methods for management of nuclear wastes must take into account long-term risks, short-term and operational risks, and cost. In principle, these criteria are empirically determined and then used to establish standards (prescriptive norms) for performance that reflect normative judgments as to safety and affordability.[44] The weighing of the relative importance of each of these criteria when formulating standards is a social decision involving both social and ethical values. Nevertheless, there is a persuasive case for the subordination of both immediate risks and present costs to potential long-term hazards when selecting among alternate options for the disposal of long-lived wastes.

Cost is taken to be least important. It is used here not as a technical determinant for defining an acceptable method, but as an elastic boundary condition to be satisfied. Once a method is selected according to consideration of risks, it is then to be examined to determine the social and economic costs of operation.[45] As these costs are unlikely to be prohibitive,[46] the question is what level of safety society is willing to pay for. Affordability is a flexible social and political decision.

A similar argument is made for subordinating short-term and operational risks to long-term ones. The immediate risks of disposal operations will be borne by the same population that benefits from the nuclear power that generates the waste. It can weigh both risk and benefit and make its own decisions. Waste disposal, however, poses a nearly unique problem in that immediate risks and costs may be decreased by exporting risk to other populations, or to the future.[47] There will be a natural desire to minimize present risk and current costs. The only constraints on doing so at the expense of the future are ethical and moral ones.[48]

I suggest that there are two principles of ethical behavior to be followed. The first is to provide the fullest information possible as to long-term risks and future costs.[49] That the future may be unable to act upon this information in no way absolves the present of the responsibility to provide it. If risks are to be exported, a minimum ethical standard is that this should be done openly. The second principle is to act so as to minimize the amount of irreparable harm that could occur as a result of present decisions.[50] It is certain that every action has uncertain consequences for the future.[51] This does not argue against the right to act, but against the refusal to take responsibility for the consequences.[52] The ethical problem of how to balance the needs of the present against the rights of the future, of justifying the export of risks and costs, is far too large to encompass here. Nor is it clear that there exists a basis on which to resolve it.[53] But to act so as to minimize exported risks, particularly when to do so imposes no great burden upon the present, is the minimum ethical requirement.

Therefore, primacy has been given to minimization of long-term risks in establishing a framework for organizing alternatives for waste disposal. If these risks could be precisely determined, the options could be simply ranked. But there are great technical and social uncertainties as to the integrity of waste containment over the long times that must be maintained. An acceptable method for the disposal of high-level wastes must be proof against technical failures such as corrosion of materials, against scientific failures such as overestimating the efficacy of natural barriers to migration, and against geological changes such as glaciers and earthquakes.[54] Few disposal methods can be confidently guaranteed to be permanent over the hundreds of thousands of years that isolation is needed. A more reasonable condition is that, should the containment fail, the time to return the wastes to the environment is of the same order of magnitude as the time necessary for the toxicity to be reduced to a level equal to or below background radiation at a comparable site. Since even the short-lived components of the wastes will remain hazardous over times that are long on social or political time scales, no guarantee of future ability to repair, clean up, or even recognize a breach of containment can be assumed.

The amount of radioactivity in the waste as a function of time can be combined with technical and scientific estimates of the probability of failure to generate a set of numbers that express the long-term risk in terms of the probable material release in any given year.[55] But to translate these into even a rough measure of social impact requires knowledge as to available pathways and population distributions and habits. Such numbers are too imperfect and incomplete in the face of social, technical, and geologic uncertainties to provide useful guidelines for the evaluation of alternative disposal methods. What I suggest in the next section is a method for extending the risk evaluations into a pair of criteria that reflect not only technical paths for returning the wastes to the environment, but also the possibility of active intervention by more or less intelligent beings. As the impacts of a given release cannot be adequately determined for times far in the future, the focus is on minimizing the probability and quantity of a breach of containment in the face of a wide range of uncertainties as to the causal factors.

TECHNICAL IRREVERSIBILITY

I define technical irreversibility as the degree to which emplaced wastes are resistant to recovery or release either by accident or by the deliberate application of technology. Its significance as a criterion is that the more irreversible a waste disposal method is, the more confident we may be that the wastes will remain isolated in the face of social, technical, and geological uncertainties. If technical irreversibility is high, then neither cataclysmic natural events nor the activities of intelligent and technologically adept beings can readily return the wastes to the environment. Retrievable surface storage, for example, is highly reversible: vulnerable to accidents and easily accessible for recovery. Ejection into deep space is almost completely irreversible.

Melting the wastes into a solid rock matrix would be highly irreversible: a geologic event that would result in large releases of toxic radionuclides would be very improbable; the application of fairly advanced and sophisticated mining technology would be required to deliberately re-extract them from the rock.

Technical irreversibility measures resistance to both social and physical intervention.[56] It does not correlate precisely with scientifically defined irreversibility. Irreversibility can be expressed mechanically, as with a ball rolling down a hill set in the middle of a flat plain. The application of a little intelligence and energy can easily restore the ball to the top of the hill. The irreversibility embodied in the second law of thermodynamics is based on the difficulty of restoring an initial situation in the face of statistical improbabilities, the unlikelihood that a specified event or set of conditions will spontaneously occur if it is but one of a large number of accessible outcomes. The presence of intelligence, however, allows the creation of improbable circumstances;[57] reversibility may be expensive, but it is not in principle impossible.

There are parallel examples of social irreversibility. It is easier to create a bureaucracy than to destroy it.[58] Increases in the perceived quality of our lives are not readily foregone.[59] An example of almost purely social irreversibility that is more to the point here is the fabulous pirate practice of buying a treasure in a remote or obscure location and then killing those who know of it. Mechanically, the burial is very reversible; retrieving the treasure is simple once its location is known.

But it is socially irreversible, since accidental discovery is highly unlikely and a deliberate, but unguided, search has a very low probability of success.

Irreversibility is proposed as a criterion to provide some degree of security against breaching of containment and failure of isolation in the face of unknown social, political, and cultural developments; to provide the greatest possible security against their release or misuse by an agent not equipped to recognize or cope with the dangers.[60] Stability against geological change is a minimum requirement. But the degree of reversibility also depends on the amount of attention that might be drawn to the site by geological features or identifiable artifacts. Intelligent life is notoriously incautious in indulging its curiosity. Construction of a large concrete mausoleum, for example, would almost guarantee that concerted efforts would be made to breach it by intelligent, but uninformed life. On social grounds, such a method is held to be quite reversible. Additional irreversibility cannot be provided by warning messages, symbols, or labels. We cannot assume that even a society that has the technology to undo rather irreversible storage will know enough about radioactivity to proceed cautiously, or that they will be able to decipher a message they cannot read.[61] Indeed, the presence of such an indecipherable message would only arouse additional interest. "Interesting" geological formations such as salt domes are equally likely to draw attention. The society that drills into them may know nothing of radiological hazards, but still be sufficiently advanced technologically and scientifically to be curious about the formation itself and its possible contents.[62]

A condition for site location that aids irreversibility is that it be as uninteresting as possible, and so draw no attention for other reasons.[63]

Table 1 is a preliminary classification of several waste disposal methods according to the degree of technical irreversibility possessed by each, as derived from consideration of both social and technical factors. The categorization is deliberately broad, since a more precise distinction would not only require more detailed analysis, but is limited by technical and social uncertainty. In addition, many of the suggested waste disposal methods could be made more irreversible by a judicious alteration to provide additional technical or social barriers to prevent breaches of the containment and isolation. For example, emplacement in geological formations would be more irreversible if chemical means could be found to immobilize the wastes against uptake into biological systems, since such uptake can both increase waste mobility and provide for subsequent reconcentration of the wastes in the food chain.[64] Disposal on the ocean bottom would be more irreversible if the canisters are randomly placed so that a deliberate and informed search would be necessary to recover them in significant numbers.

Technical irreversibility, then, is defined by a combination of social and physical elements that measure both the size and the sophistication of the technology or natural mechanism that would be necessary to return the wastes to the biosphere in quantities or at rates that would be radiologically significant. It tends to correlate fairly well with the degree of scientific and technical aptitude that would be required for deliberate waste recovery by a society of intelligent beings, and with the size and cost of the necessary effort. The greater the degree of technical irreversibility, the greater the confidence that any failure of isolation and containment will occur only through the intervention of those fully capable of understanding the risks involved. In that sense, it is a useful criterion for establishing standards for waste management that reflect our ethical obligations to the future.

MULTIPLICITY

There will always be a certain amount of uncertainty as to whether a chosen method for waste disposal is technically sound, or as to whether we are capable of thinking through all possible circumstances by which containment might be breached. If a single site, single technique method is used, an appropriate question is: How strong does your basket have to be before you are willing to place all of your eggs into it? The provision of additional baskets has two dimensions--multiplicity of sites and diversity of options. The purpose is, in either case, to provide redundancy as a hedge against error and uncertainty.[65]

For example, the irreversibility of many types of terrestrial geological disposal methods could be increased by making the number of sites very large, reducing the potential risk due to the breach of any single one. This measure can then be augmented by random emplacement in unrecorded locations. The increased probability of accidental discovery must be balanced against the lower radionuclide inventory to see whether this strategy would in fact reduce net risk under a wide range of geological and social factors. An alternate approach would be to collect many years production of waste into a single giant container and then to emplace this so deeply and with such redundant barriers that any breach seems highly improbable. This approach would significantly increase the probable consequences of a release. Under the specified conditions, multiple emplacement is held to confer more technical irreversibility in the face of uncertainty as to social, technical, and geological futures.[66]

Multiplicity of sites does not, of course, provide any security against fundamental conceptual or design errors. It does help to minimize the consequences of such errors if the failures are random and widely spaced in location and time. But if confidence in the performance of a single site is high, multiplicity does not necessarily provide an advantage on technical grounds. Its primary advantage is the reduction of the consequences of the deliberate or inadvertent action of intelligent life.

One aspect is damage limitation. If the opening of a single site causes minimal harm, and if the discovery of one site does not automatically provide the key to uncovering others,[67] catastrophic releases are less likely to occur. Furthermore, this could provide time for effects to be connected to the proximate, if not the ultimate, cause. Given the large uncertainties in predicting future social patterns, such provisions for damage limitation should be a leading factor in considering alternatives even if irreversibility is somewhat compromised. For increased site multiplicity is not necessarily identical to increased technical irreversibility. Although the two tend to correlate for many waste disposal methods, there are some (such as retrievable surface storage) for which the two criteria are nearly independent.

Figure 3 locates a number of waste disposal options on a two-dimensional plot that treats technical irreversibility and site multiplicity as independent criteria.[68] The scale of the axes does not imply any attempt to predetermine their relative importance. It must be emphasized that this is a qualitative map. Not only the absolute but sometimes the relative location of any option is a matter of informed judgment. It is not only difficult but unwise to try and localize any method too narrowly. Even if the axes could be accurately and quantitatively labeled, inherent uncertainties in predicting the future would negate any attempt to pin a given method down precisely.

APPLYING THE CRITERIA

If these criteria are to be useful for organizing alternate approaches to nuclear waste management, they must be translatable into normative standards to guide decisions. A central hypothesis as to the utility of the two criteria and two suggestions for applying them to guide the formulation of waste management policy are offered for this purpose.

The hypothesis is that emphasizing the continuity of goals in formulating waste management policy and doing away with arbitrary classifications (such as short-term vs. long-term storage) increases the possibility for reasoned and ethically sound policy choices. The two criteria were developed and the case for them argued here specifically to facilitate this procedure.

The first suggestion is that both technical irreversibility and site multiplicity are desirable goals for waste management. Given equal uncertainty as to whether two different methods for the management of wastes will suffer from gross conceptual or design faults, the one that maximizes an appropriate weighing of the two criteria is preferable.[69] Although estimating the relative weights is a part of the decision process not to be pre-empted here, Fig. 3 suggests how this might be done. The further into the upper right hand corner a method lies, the greater the reduction of potential future risks in the face of social, technical, and physical uncertainties. Conversely, the greater the confidence in social and physical stability over the time scale during which the wastes must be kept isolated, the closer to the lower left an acceptable method will lie.[70] Note that this method is applicable to all forms of waste.

The joint application of the two criteria provides a crude measure of reduction of risk in the face of uncertainty. But uncertainty increases with time. Using Fig. 3 as an illustrative device, there is an effective containment time scale running from the lower left (reversible, single site) to the upper right (very irreversible, high multiplicity). The shorter lived the wastes, the less the necessary containment time, and therefore the more uncertainty that can be tolerated.

This leads to the second suggestion: <u>for any type of nuclear waste, a set of combinations of the two criteria can be determined that bounds the region of acceptable waste mangement methods</u>. Referring once again to Fig. 3, this suggestion can be graphically interpreted as saying that there are lines of equal preference that can be (fuzzily) drawn upon the diagram to separate the acceptable from the unacceptable regions of performance. As minimization of long-term risk is the dominant concern, the desirability of any given option will be measured by the degree to which it lies beyond the region of minimum acceptability. If there are several equally preferable options, the secondary criteria of reducing operational risk and cost can be freely used to select among them.[71]

It should be kept in mind that technical irreversibility is meant to provide a criterion for choice and not to preempt it. Complete irreversibility that precludes all possibility of recovery may not be the most desirable outcome. It can be argued that our obligation to the future extends to the preservation of options as well as the prevention of harm, that we have an obligation to try to avoid irreversible consequences of our actions.[72] It may then be considered more desirable to dispose of the wastes by a method roughly as irreversible as the dispersal of uranium in present ores. This would at least partially correct the irreversible depletion of natural supplies of fissionable material. The provision of an artificial ore bed is intended to make these materials accessible only to those who understand what they are mining and why. In that regard, the artificial beds could be somewhat more secure against accidental mining than natural beds have been if care is taken to make sure that the wastes are not co-located with other desirable minerals.

On Fig. 4, a locus of minimum acceptability has been plotted, using the same axes as Fig. 3.[73] Assume that this represents emplacement roughly as hazardous as presently mined uranium ores.[74] A second curve has been drawn at somewhat higher values of irreversibility and multiplicity, representing emplacement that is not beyond potential recovery but would entail considerable cost and effort using present technology. Nevertheless, the wastes could be recovered if the need or desire were great enough. By selecting a waste disposal option that lies between these two limits, we could do our best to ensure that the future would be exposed to no more risk than if we had not used the ore for power at all, while still doing our utmost to avoid irreversibility foreclosing future options.

DIVERSITY OF OPTIONS

In the past, waste management policy has consistently been drawn to the search for the single most desirable alternative. The method suggested here facilitates the pursuit of several equivalently desirable options. To return to the previous metaphor, it is of little avail to put your eggs in many identical baskets if they all fail at once. Diversity of options can provide protection against such gross failures.[75]

As with mulitplicity of sites, statistical reasoning alone does not necessarily lead to the conclusion that diversity of options reduces risks.[76] The parallel pursuit of more than one method for waste management is an explicitly normative recommendation, based on the ability of intelligent life to respond to failures. If one of the disposal methods should fail at a time when there is a society capable of understanding what has happened and taking remedial action, it would be extremely important to have at least one alternate storage method that is trusted and immediately usable. If a method has been chosen that has fairly high site multiplicity, and if not all sites fail simultaneously, it is even possible that the transfer could be effected before any large fraction of the stored wastes would be released.[77]

If no other proven method were available, it is far less probable that an acceptable alternative could be developed and proved before the number of site failures increased far past the point at which failure was noted. Furthermore, a society placed in the position of having sites fail with no available alternatives would be more likely to attempt remedial action than to develop new methods with unknown risks.[78] This is as likely to multiply the difficulties as to reduce them. The patched or modified sites may have a risk that would have been unacceptable by the original selection criteria. Patches or repairs may also begin to fail, and the modified system may be much more difficult to correct than was the original.[79]

If the impact of any single release is potentially catastrohpic, it might be preferable to hold to a single waste disposal method to maximize the probability that no untoward events at all will occur during the required storage period. But a properly chosen combination of several multiple-site options would ensure that even a worst case event would not be catastrohpic, particularly for a method with high irreversibility. Furthermore, a most careful monitoring and testing program should be an integral part of waste management procedures to keep track of the condition of the sites and detect early signs of imminent failure.

This social safeguarding will surely not outlast knowledge of the sites, and will not, therefore, compromise their long-term integrity. It is needed because the highest risk would be from gross failure in the early years of storage, and technologies that do fail are likely to give early warning signs. This should not be only a monitoring procedure, but part of an ongoing program of technical and social research to search for and identify procedures and techniques that would increase site integrity and further minimize both the degree and the consequences of uncertainty. Our obligation to the future is not discharged simply by determining the level of risk to which they will be exposed. An ethically sound waste mangement policy will continuously and determinedly seek methods to reduce that risk.

CONCLUSION

Two criteria--technical irreversibility and site multiplicity--have been suggested for use in establishing standards for the disposal of nuclear wastes. They have been constructed specifically to address the reduction of future risk in the face of inherent uncertainty as to social and political developments over required waste isolation times, to provide for safe disposal without requiring a guarantee of future ability to recognize, detect, or repair errors and failures.[80]

Decisions as to how to apply or weigh these criteria in conjunction with other waste management goals rest ultimately with societies and their governments. My purpose has not been to preempt this process, but to construct a framework that facilitates consideration of its ethical and normative components. As with many other human activities, the production of nuclear power entails consequences and risks for future generations who can have no voice in present decisions. On that account, their welfare must be carefully considered. It is not within our power to pass on to the future a world unchanged by our residence in it. Nor do we have an obligation to do so. But, as our every act has the potential to profoundly alter future lives, our minimum ethical obligation is to examine most thoroughly the potential consequences of present actions, to acknowledge them openly, and to minimize the potential for irremediable harm.

This obligation is not satisfied if, in the disposal of nuclear wastes, we impose upon the future an obligation to provide for a stability of social institutions unprecedented in history,[81] if we attempt to transfer the responsbility for accidents from our shoulders to theirs. There is no ethical or moral basis for placing social and technical requirements and obligations on future generations for the sole purpose of protecting them from the consequences of present activities and decisions. The obligation to consider the effects of errors in technology or judgment, to provide for our inability to guarantee future technical performance, social stability, and cultural continuity rests with the present. An ethically sound waste management policy must reflect not only our knowledge and skills, but our limitations as well.

NOTES

1. Italo Calvino, Le Città Invisibili (Giulio Einaudi editore s.p.s., Torino, 1972). Invisible Cities, (Harcourt Brace Jovanovich, New York, 1974).

2. a. P.P. Micklin, "Environmental Hazards of Nuclear Wastes," Science and Public Affairs: The Bulletin of the Atomic Scientists XXX, #4 (April, 1974), p. 36.

   b. A.B. Lovins and J.H. Price, Non-Nuclear Futures, (Ballinger, Cambridge, Mass., 1975).

   c. T.C. Hollocher, "Storage and Disposal of High-Level Radioactive Wastes," in The Nuclear Fuel Cycle, Union of Concerned Scientists, (MIT, Cambridge Mass., 1975)

   d. Transcript of hearings on the California Nuclear Initiative before the California State Assembly Committee on Resources, Land Use and Energy, Nov. 4-5, 1975; summarized as Reassessment of Nuclear Energy in California, May 10, 1976.

3. By "society" is meant both intelligent life and its organized activities. The social costs of evacuation and contamination of land, as well as the effort needed to relocate and decontaminate are rarely assessed in computing the effects of radiological accidents.

4. K.J. Schneider and A.M. Platt, Eds., Advanced Waste Management Studies, High-Level Radioactive Waste Disposal Alternatives, (BNWL-1900, Battelle Pacific Northwest Laboratories, Richland, Wash., 1974); summarized in USAEC, High Level Radioactive Waste Management Alternatives, (WASH-1297, U.S. GPO, Washington, D.C., 1974).
5. U.S. ERDA, Alternatives for Managing Wastes From Reactors and Post-Fission Operations In The LWR Fuel Cycle, (ERDA-76-43, NTIS, Springfield, VA., 1976).
6. U.S. ERDA, The Nuclear Fuel Cycle (ERDA-33, NTIS, Springfield, VA., 1975). The "back-end of the nuclear fuel cycle is defined in this document to consist of spent fuel storage, reprocessing, mixed-oxide fuel fabrication, recycle of plutonium in reactors, and waste management.
7. An analysis of past AEC budgets kindly supplied by D. Metlay (private communication) bears this out. As is also pointed out in ERDA-33 (6), budgets for commercial waste management have been particularly neglected.
8. As operating costs are presumed to be a small fraction of total power generation costs, there has been no open conflict over the assumption that they will be passed on to the utilities and through them to the consumer. But, as pointed out in ERDA-33 (6) and in the testimony of J.L. Liverman in Oversight Hearings on Nuclear Energy Part I--Overview of the Major Issues (Hearings before the Subcommittee on Energy and the Environment, Committee on Interior and Insular Affairs, U.S. House of Representatives, U.S. GPO. Washington, D.C., 1975) at p. 541 ff, the AEC and its successor agencies hold that not only regulation, siting, and the

provision of interim storage and final repositories are the responsibility of the Federal government, but also support of commercial waste management research and development. This policy is held to derive from the requirements of 10 CFR 50, Appendix F (10).

9. An examination of past testimony on waste management at AEC authorization hearings before the JCAE over the period 1960-1974 supports this. For a more concise description of the evolution of AEC waste management policy, see P. Boffey, The Brain Bank of America (McGraw Hill, New York, 1975), Ch. 5.

10. Code of Federal Regulations Title 10, Energy (U.S. GPO, Washington, D.C., 1976). Compare, for instance, the detailed rules and regulations for various isotopes and shipping containers embodied in 10 CFR 71 and 10 CFR 73 with the general and ambiguous definitions set out in 10 CFR 50 Appendix F.

11. A.S. Kubo and D.J. Rose, "Disposal of Nuclear Wastes," Science 182, 1205 (1973).

12. The distinction is that wastes are in principle retrievable from storage, but not from disposal. Recent documents such as ERDA-76-43 (5) have discontinued the confusing use of the term "ultimate storage" for disposal.

13. ERDA-76-43 (5), Section 21.

14. ERDA has not only withdrawn the draft EIS [Management of Commercial High-Level and Transuranic-Contaminated Radioactive Waste, WASH-1539, USAEC, Washington, D.C., 1974] on the RSSF (letter from R.C. Seamans, Jr. to the Hon. John O. Pastore, April 9, 1975) but has also indicated that

it does not intend to proceed further on it at this time; see Nuclear News, April, 1976.

15. Siting of Fuel Reprocessing Plants and Waste Management Facilities (ORNL-4451, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1970). See also ERDA 76-43 (5), Section 25.

16. See, for example Hollocher (2c) California Transcripts (2d), Boffey (9).

17. ERDA-76-43 (5), Section 26; a more comprehensive discussion of the prospects and problems is given in BNWL-1900 (4).

18. ERDA-76-43 (5) classifies transmutation and space disposal as "elimination" to distinguish them from terrestrial disposal. This introduces another new category and suggests that other disposal is not "ultimate."

19. See, for example, the statement of F.K. Pittman: ERDA Authorizing Legislation Fiscal Year 1976, Hearings before the JCAE, Feb. 1975, Part 2 (U.S. GPO, Washington, D.C., 1975) at p. 1258.

20. California transcripts (2d).

21. D. Metlay (private communcation) has pointed out that the AEC originally set the problem up well in 1959, but succumbed to the notion that technical fixes could resolve the problem. The initial approach was to take two tacks for dealing with hazardous materials: dilute and disperse; concentrate and contain. See, for instance, the testimony of J.A. Lieberman in Industrial Radioactive Waste Disposal, hearings before the JCAE, Jan. 29, 1959 (U.S. GPO, Washington, D.C., 1959) at p. 989.

22. This approach is in marked contrast to the usual organization of waste management alternatives by one or another technological parameter. For examples of the traditional approach, see (4) and (5); for a less traditional but still primarily technical approach, see (11).

23. In the November, 1975 report of a survey conducted by the Human Affairs Research Center of Battelle Memorial Institute, the attitudes of 465 persons from five regions of the United States towards waste disposal were analyzed by means of a poll. The respondents were then aggregated into six groups: environmentalists; high school students; nuclear technologists; public utility employees; university students; church and civic group members. The opinions of five of the six groups were in agreement with the rank ordering by importance suggested here. Only the nuclear technologists rated short-term above long-term safety. All groups rated costs as being the least important consideration.

24. That is, an action is a candidate for moral choice only if it is voluntary and based on all available information. See, for example, Aristotle, Nichomachean Ethics, Book III, Sections 1-5.

25. At the present time, the more hazardous effluents from the back-end of the fuel cycle are considered to be H-3, C-14, Kr-85, and I-129. Their classification as "potential hazards" involves not only activity and half-life, but the quantities to be released and the available pathways to humans.

26. Although the NRC has presumptive statutory authority over all gaseous and liquid radioactive effluents, only constituents confined on site by filters or as trapped liquids fall under waste management regulations.

27. Some difficulty has been encountered in attempts to define the level of contamination that distinguishes ordinary from transuranic-contaminated low level wastes, and in establishing procedures for dealing with the latter. The currently proposed standard of treating all wastes with an

alpha-activity exceeding 10nCi/gm as transuranic contaminated and shipping them to a Federal repository within five years as set out in WASH-1539 (14) is in dispute between the NRC and the industry.

28. The distinction between low and intermediate level wastes is not specified by quantitative guidelines. One common interpretation is that wastes that are safe to handle without special precautions are low-level, and vice-versa.

29. Few, if any, industry or government sources are prepared to consider spent fuel as a waste. It is held to be a valuable (if unnatural) resource, owing to the large inventory of fissile material contained.

30. U.S. AEC., Draft Generic Environmental Statement, Mixed Oxide Fuel (GESMO) (WASH-1327, USAEC, Washington, D.C., 1974).

31. 10 CFR 50 Appendix F defines high-level liquid wastes to be "those aqueous wastes resulting from the operation of the first cycle solvent extraction system, or equivalent, and the concentrated wastes from subsequent extraction cycles, or equivalent, in a facility for reprocessing irradiated reactor fuels.

32. Draft GESMO (30) states that about 0.5% of the uranium and plutonium in the spent fuel will be lost to high-level wastes. There will be additional losses to other than high level wastes at the reprocessing plant and at other facilities.

33. Primarily neptunium, americium and curium (at present fuel burns).

34. 10 CFR 50 Appendix F.

35. The container must meet the specifications of 10 CFR 71 and 10 CFR 73.

36. Adapted from ERDA-76-43 (5).

37. There are also very active components that decay away in times of only a few months to a few years. At present, the spent fuel is stored for a long enough time for these decays to occur. For some waste management schemes, such as deep rock melt, it is necessary to ship and reprocess the fuel very quickly to preserve these short-lived isotopes. This may significantly alter the balance between short-term and long-term risks.

38. That is, under specific exposure conditions, such as inhalation of insoluable fine powders.

39. U.S. NRC, The Management of Radioactive Waste: Waste Partitioning as an Alternative (NR-CONF-001, NTIS, Springfield VA., 1976).

40. See, for example, Kubo & Rose (11).

41. The thermal power of wastes that have been aged for the requisite several years is comparatively small, and cannot be recovered without an effective energy subsidy roughly an order of magnitude greater than the usable output. For a summary of possible beneficial uses of radioisotopes, see: G.P. Dix, "The Beneficial Uses of Nuclear Waste Products," in Waste Management 75, R.G. Post, Ed. (Univ. of Arizona, Tucson, 1975).

42. For an analysis of the present (unfavorable) economics of extracting usable isotopes, see the testimony of F.K. Pittman in ERDA Authorizing Legislation, FY 1976 (op. cit.) at p. 1304. Taking aside the hazards of storing these materials, carrying charges will add greatly to their price.

43. This could conceivably be extended to include all spent fuel for which there is no currently available reprocessing capacity. But see (29).

44. I follow here the general outline of the analysis by W.W. Lowrance, <u>Of Acceptable Risk</u> (W. Kaufman, Inc., Los Altos, Cal., 1976).

Matters of empirical fact are:

Risk--the measure of adverse effects;

Efficacy--the measure of beneficial effects;

Cost--both internalized and external;

Distribution of the above.

These translate via personal and social values into normative measures:

Safety--the degree to which risks are acceptable;

Benefit--the degree to which efficacies are desirable;

Affordability--the degree to which costs are reasonable;

Equity--perceptions of just distributions.

Criteria are taken to be based upon empirical data. They provide only the quantitative basis for choice. Standards are used to screen for acceptability, and therefore are based on the normative factors. Thus the maximum permissible concentration for a given radionuclide in air or water may be expressed in empirical terms such as (Ci/m^3), but are determined both by pathways to life, and by decisions as to safety and equity that are not entirely based on technical data.

45. With the exception of the civil liberties implications of safeguards, potential social costs of either successful operation or of failure have rarely been considered in analyzing the nuclear fuel cycle. Among the factors that need consideration are patterns of employment and land use, the consequences of evacuations and other dislocations, and anxieties and fears raised by both real and potential accidents. See, for example,

R. Budnitz and J. Holdren in Annual Review of Energy I (Annual Reviews Inc., Palo Alto, 1976).

46. There appears to be widespread agreement by all parties that operating costs for any presently conceivable waste managmeent method will be so small, on a percentage of power costs basis, that safety considerations should predominate in the decision. See also (23).

47. It is assumed here that nuclear electric power is a common good--one that distributes its benefits over all persons in a society by virtue of their participation in it--as well as a private one. Similarly, the risks and costs of waste management may be described as common "bads." In this context, exporting risk means exposing persons who derive neither individual nor common benefits. These may be persons in the future or members of other contemporary societies.

48. M.P. Golding and D. Callahan, "What is Our Obligation to Future Generations?", Working Paper Series, #2, (Hastings Center Institute of Society, Ethics, and the Life Sciences, Hastings-on-Hudson N.Y., 1972).

49. K. Arrow, "Social Responsibility and Economic Efficiency," Public Policy XXI, 303 (1973). Arrow argues that provision of full information as to potential costs and risks is the minimum ethical obligation of the seller. H. Jonas (53) argues further that modern technology has conferred the power to have such enormous impacts that traditional ethics will not suffice. Given that uncertain outcomes can destroy the very context in which ethics operates, ignorance can no longer serve as an alibi. The ethical obligation thus extends to making the search for knowledge a prime duty.

50. Golding and Callahan, (48).

51. "Action" is used here in the sense of H. Arendt. In contrast to labor and work: "Action, the only activity that goes on directly between men....corresponds to the human condition of plurality, to the fact that men, not Man, live on the earth and inhabit the world. While all aspects of the human condition are somehow related to politics, this plurality is specifically *the* condition....of all political life." *The Human Condition* (University of Chicago Press, Chicago, 1958) at p.7. To act is to set something into motion in the context of human plurality, and because of this plurality every action is a beginning whose process is irreversible and whose outcome in unpredictable.

52. The future is by definition uncertain. Attempts to find a substitute for action and avoid the frustration of unpredictable outcomes must lead to either the suppression of human plurality through tyrannical control or the insistence that one's activity is "worldly" or self-contained, rather than political and interactive. The former reflects the refusal to allow consequences, the latter the refusal to acknowledge them. See H. Arendt (51) Ch. 5.

53. H. Jonas, "Technology and Responsibility: Reflections on the New Task of Ethics," *Social Research* 40, 31 (1973). See also, H. Arendt (51) at p. 232.

54. Imperfections in human knowledge and the fundamental uncertainties associated with the probabilistic distribution of the frequency and severity of cataclysmic events can be somewhat compensated for by the provision of secondary barriers that ensure slow diffusion and return of the wastes to the environment even if the primary containment is breached.

55. This much, at least, is within the scope of mathematical risk analysis.

56. A good example of such mixed irreversibility is dropping a cracker spread with peanut butter and jelly face down on a sandy beach. In principle, the effects can be reversed. In practice, both social and physical costs are usually too high. I thank R. Budnitz for this example.

57. In fact, the continued existence of intelligent life requires it.

58. See, for example, H. Kaufman, Are Government Organizations Immortal? (Brookings Institution, Washington, D.C., 1976).

59. Note that only the perceived quality of life is referred to. This makes clear the political nature of the assertion. Translated to economic terms, this is equivalent to the price elasticity of demand being greater for falling prices than for rising prices. At times of great stress, such as during major wars, perceived quality of life may be sacrificed willingly. At other times, changes in perception are simpler.

60. This argument could be extended as follows: Knowing what we do of the dangers of nuclear weapons, we should not leave any fissionable materials for the future, on the assumption that we have been lucky and they could easily do far worse. This presents an ethical problem of even greater complexity than those set out in this article.

61. Arthur Evans excavated the first of the Mycanaean tablets inscribed in Linear B at Knossos in the year 1900. More than 50 years elapsed before they were deciphered. See J. Chadwick, The Decipherment of Linear B (Cambridge University Press, Cambridge, 1970). The 3,500 years that have elapsed since the inscriptions were made is only about

one-seventh of the half-life of Pu-239. Yet, almost all the information as to the culture and language of Minos had been lost.

62. If we deplete existing beds of uranium ores, a future society will, in all probability, develop to a fairly advanced industrial stage before discovering the existence of natural radioactivity.

63. One of the advantages of seabed disposal in the center of the North Pacific plate is that the site is not only geologically stable, but barren of resources and scientifically boring. (W. Bishop and C. Hollister, private communication).

64. E. A. Martell, "Actinides in the Environment and Their Uptake by Man" (NCAR-TN/STR-110, National Center for Atmospheric Research, Boulder, Colo., 1975).

65. M. Landau, "Redundancy, Rationality, and the Problem of Duplication and Overlap," Public Administration Review 29, 346 (1969).

66. More detailed method-specific analysis is needed to examine this somewhat intuitive conclusion.

67. That is, by other than informed and sophisticated actors who know just what it is they are seeking and for what purpose it is to be used. Under these conditions, we can be fairly certain that they would be aware of the risks.

68. Technical irreversibility and site multiplicity are taken to be independent variables. It is assumed that for each method of waste disposal there is what amounts to a functional equation that expresses the interrelationship of the variables for that specific method.

69. In the absence of contrary information, *a priori* equal probability of gross failure is assumed.

70 It should be kept in mind that Fig. 3 is a conceptual and heuristic device, not a quantitative map. The significant information is the relative, not the absolute, position of any given option.

71. This is, of course, only one of the possible ways to select an option. The major point here is the bounding of a region that contains the unacceptable methods, so that they may be discarded.

72. D.E. Boeyink, "Finitude and Irreversibility: The Duty to Avoid Irreversible Consequences," ms. presented at an AAR regional meeting, April 1975. Irreversible consequences are to be distinguished from irreparable harm. The former involves uncertainty as to the harm or good of our actions in the face of imperfect knowledge and a moral finitude. Note that it is the irreversibility of consequence that is suggested as being avoidable. All action is inherently irreversible. But see H. Arendt (51).

73. Waste dipsosal methods have been deliberately omitted from Fig. 4 to avoid even the appearance of preempting social choice. The placement of the indicated regions relative to the various options is not purely a technical problem.

74. That is, 0.2% sandstone ores.

75. See, for example, M. Landau (65).

76. Assume that all methods chosen have equal rates from a failure. If two options are selected, and the probability of a certain release during the required storage time is 1/2 for each of the methods, the probability that both will have such a release is 1/4. For three methods, the probability would be 1/8. This is advantageous only if the release in

question is small enough so that this constitutes effective damage limitation. But suppose that this release would result in a catastrophic hazard. In that case, the selection of three methods at the stated probabilities results in a 7/8 assurance that at least one such catastrophe will occur. For two methods, the probability decreases to 3/4, and for only one method to 1/2. For any combination of methods there will be a distribution of failures in time and a distribution of radionuclide inventory. It would be most instructive to have some strategies played out by mathematical analysis to examine over what period the hazards entailed are actually increased by diverse options in the absence of remedial action. For long times, damage limitation is expected to dominate.

77. The inforamtion needed for monitoring the sites and locating them if necessary will not compromise the requirement of technical irreversibility if properly done. It would be required as part of the original design consideration to provide for the storage and handling of emplacement data and the monitoring of disposal areas in such a way as provide inaccessibility of both sites and information to a naive actor.

78. This is particularly true if remedial action can be rapidly effected, since a thorough program to develop a new method from scratch would take a minimum of several years.

79. For example, potential leakage from corroding carbon steel tanks at the Hanford reservation was prevented by solidifying the contained wastes into salt cake. There is no existing method for removing the solidified wastes without risking a potentially serious spill, as the tanks can no longer be checked for integrity. As ERDA itself put it in <u>Creating</u>

Energy Choices for the Future (ERDA-48, U.S. GPO, Washington, D.C., 1975): "If it is determined that the salt cake must be removed from these tanks before the level of radiation decays substantially (several hundred years), unique fully remote techniques for removing the salt cake from the storage tanks will have to be developed." ERDA-48, Vol. II, at p. 119.

80. To the extent that one holds the contrary belief that social stability is more assured than present technological aptitude, it would be better to store the wastes in a small number of accessible sites so that performance could be monitored and errors corrected. Of course, this assumes that future technologies will be an improvement and that operational errors such as that discussed in (_79_) will be avoided.

81. A. Weinberg, "Social Institutions and Nuclear Energy," _Science_ _177_, 27 (1972).

82. The comments of T. Bradshaw, D. Metlay, B. Schiff, K. Smith, and P. Windham are gratefully acknowledged. I thank T. La Porte and A. Middleton for their advice and support.

TABLE 1

TECHNICAL IRREVERSIBILITY OF SELECTED METHODS FOR THE MANAGEMENT OF HIGH-LEVEL WASTES.

DESCRIPTIONS ADAPTED FROM ERDA-76-43 (5)

Disposal Method	Physical Irreversibility	Social Irreversibility	Technical Irreversibility
Retrievable surface storage	very low for water cooling to moderately low for above ground convection cooling	very low	very low
Sealed Mausolea	low to moderate	very low	low to very low
Mined caverns in salt	moderately low	low	low
Drilled or solution mined cavities in salt	depends on ground water; low to moderate	low for domes to moderate for bedded salt	low to moderate
Seabed, emplacement in bottom sediments	moderate, depends on nature of sediments	moderate to moderately high	moderate to moderately high
Mined rock cavity, partial melting	moderately high	moderate to moderately high, (away from other minerals)	moderate to moderately high
Mined rock cavity, complete melting	moderately high	moderately high (away from other materials)	moderately high
Seabed emplacement in basement rock, no melting	moderately high to high, depends on geologic activity	high	moderately high to high
Deep rock melt, drilled hole	high; depends on geologic activity	high (located away from other minerals)	high
Deep rock melt, self-descending capsule	high to very high, depends on geologic activity and sinking depth	high to very high	high to very high
Space disposal, outer space mission	very high to complete	very high to complete	very high to complete
Transmutation	complete	complete	complete

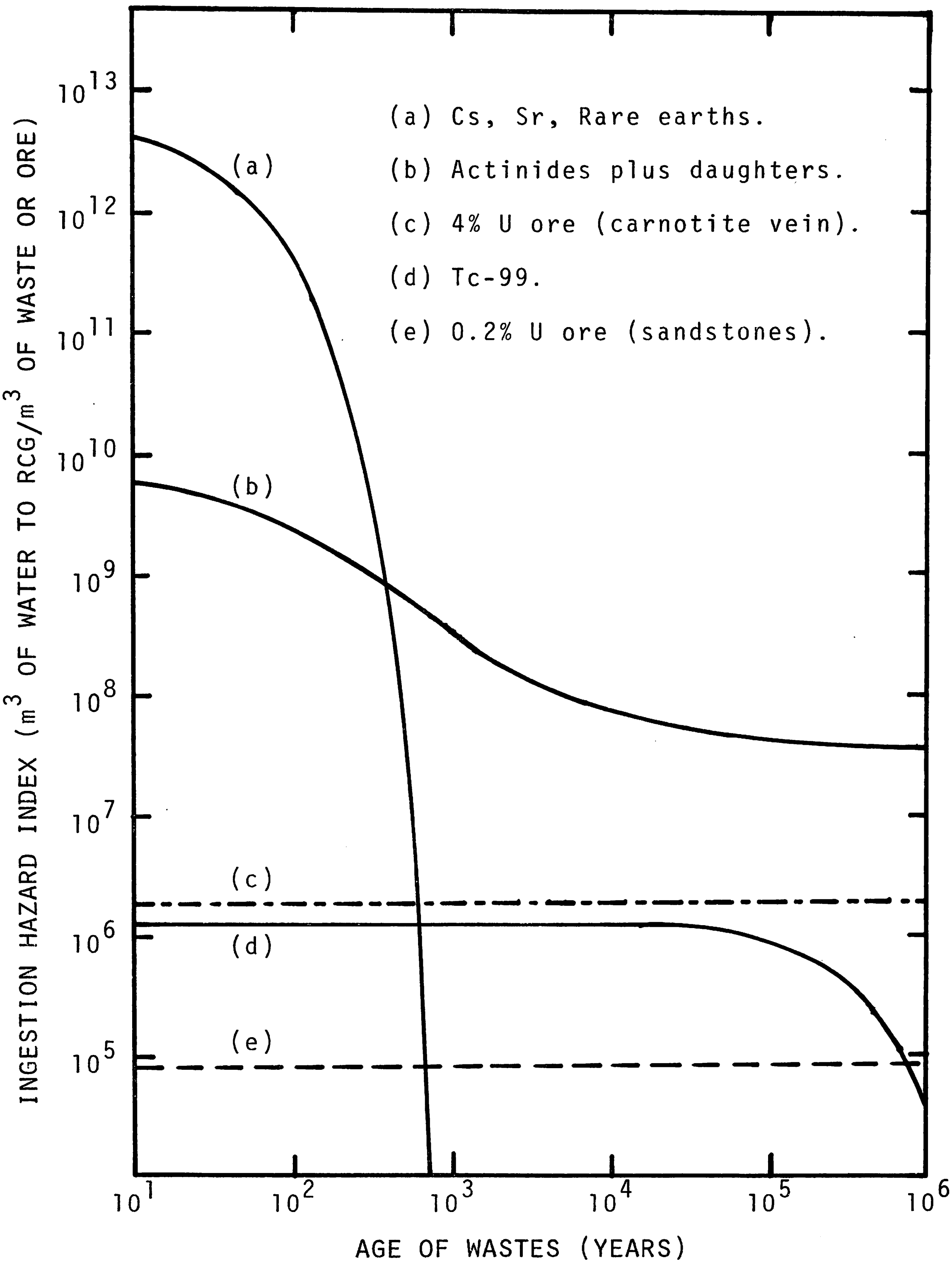

Figure 1

Ingestion Hazard Index (volume of water to dilute to RCG levels/ volume of waste or ore) for solidified high-level wastes from reprocessed light-water reactor U fuel. 99.5% of U and Pu, and all Kr and I removed. Colorado carnotite vein ores and typical commercial sandstone ores included for comparison.

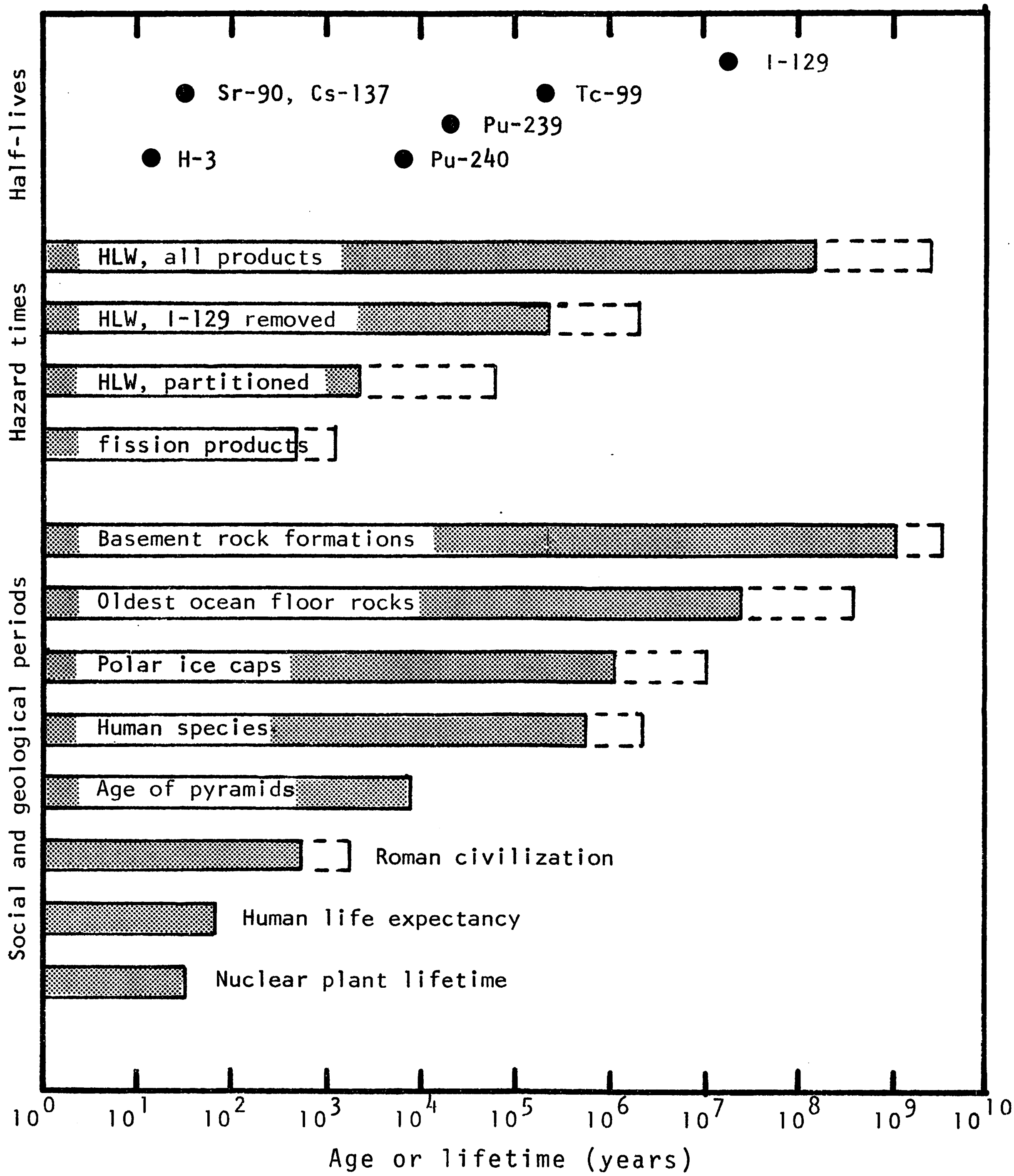

Figure 2

Duration of hazards from various nuclear wastes, and half-lives of the constituents, compared to times of social or geological relevance. Spent reactor fuel has roughly the same hazard time, arbitrarily defined as the time for the wastes to decay to the same RCG dilution volume as 4% vein U ores, as HLW with all products included. Partitioning is assumed to remove 99% of the transuranics from the HLW.

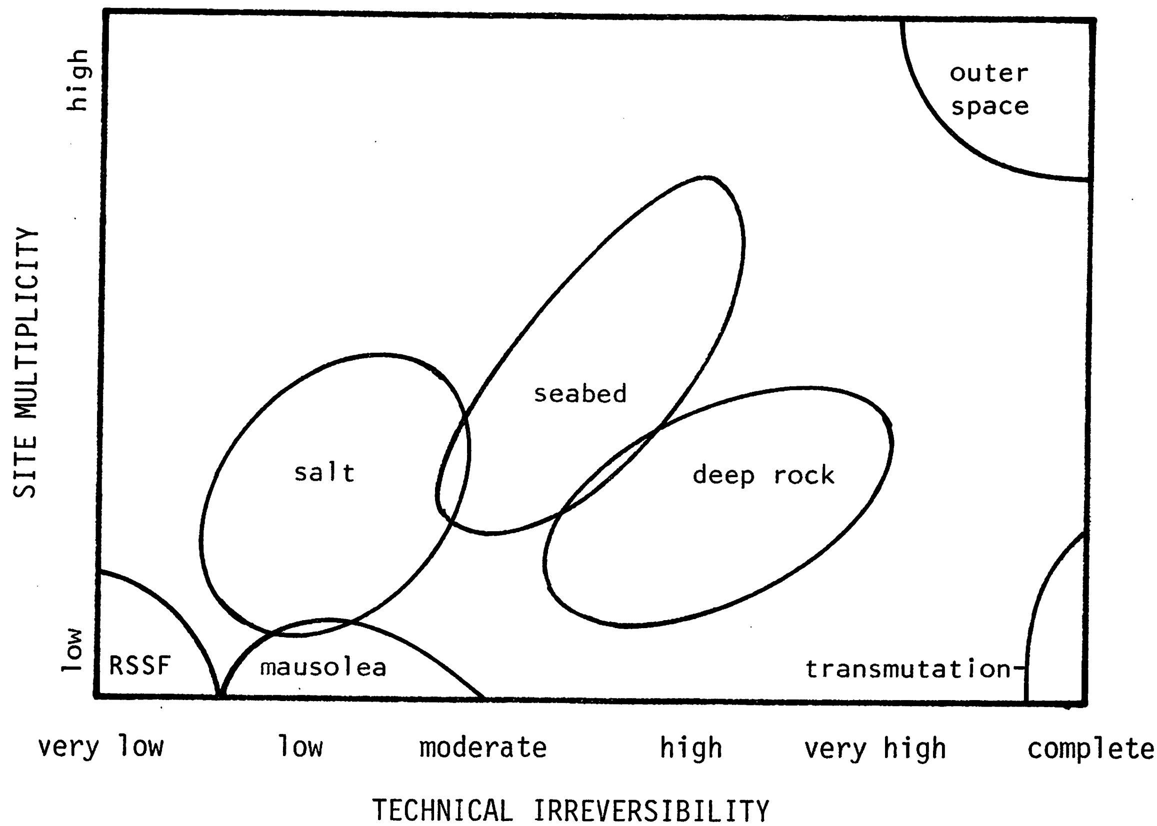

Figure 3

Various waste disposal methods classified by site multiplicity and technical irreversibility. For an explanation of the criteria see Table 1. The salt and deep rock categories as displayed on this figure include all of the various methods for these geological formations.

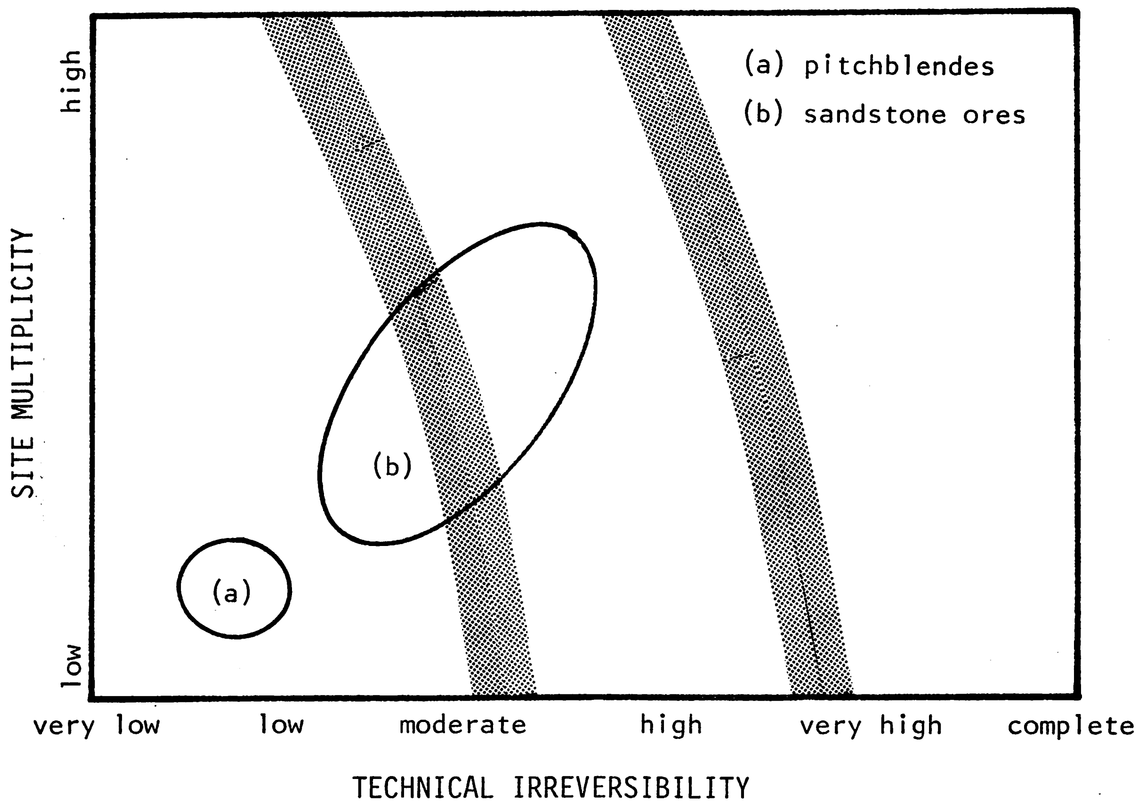

Figure 4

A suggestion for loci of equal preference in choosing among alternative methods for disposal of nuclear wastes. The curve at lower values of irreversibility approximates roughly the natural emplacement of presently mined 0.2% sandstone U ores. The two types of ore, various sandstones and 40%-60% pitchblendes, are indicated on the figure for purposes of comparison.