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On the Development of Environmental Radiation Stantards for Geologic Disposal of High-Level Radioactive Wastes

D. C. Kocher

Prepared for the
U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Under Interagency Agreement DOE 40-550-75

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D. C. Kocher

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FOREWORD

The Nuclear Regulatory Commission's (NRC) rulemaking on disposal of high-level radioactive wastes in geologic repositories (10 CFR 60) is intended to be compatible with a generally applicable environmental radiation standard for high-level waste disposal which is being developed by the Environmental Protection Agency (EPA). In developing its final rulemaking, the NRC staff was concerned that publication of the proposed EPA standard might be delayed indefinitely, so that the NRC might need to develop its own environmental radiation standard for inclusion in 10 CFR 60 if the final rulemaking were to be published in a timely manner.

The author was asked by the NRC to provide technical assistance in revising 10 CFR 60 to include an environmental radiation standard. A letter report was prepared for the NRC which discussed the different technical issues which must be considered in developing an environmental radiation standard for high-level waste disposal. Just prior to completion of the letter report, the proposed EPA standard was published in the Federal Register. The NRC then decided to discontinue the development of its own environmental radiation standard for inclusion in 10 CFR 60 and proceeded with publication of the final rulemaking on the basis of the proposed EPA standard.

This report is a revised version of the aforementioned letter report which the author prepared for the NRC. Although the development of an environmental radiation standard for inclusion in 10 CFR 60 was discontinued after preparing the letter report, I believe that the issues discussed herein are worthy of further discussion in the waste disposal community even if the final EPA standard is soon promulgated.

Although preparation of this report was supported by the NRC, the report has not been subjected to any peer or policy review within the NRC. Therefore, the views expressed in this report are entirely those of the author; they do not necessarily reflect the views of the NRC, and no official endorsement should be inferred.

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ON THE DEVELOPMENT OF ENVIRONMENTAL RADIATION STANDARDS FOR GEOLOGIC DISPOSAL OF HIGH-LEVEL RADIOACTIVE WASTES

D. C. Kocher

ABSTRACT

An important issue for geologic disposal of high-level radioactive wastes is the establishment of an environmental radiation standard for the purpose of limiting potential health risks to future generations. Such a standard, which in this country is the responsibility of the Environmental Protection Agency (EPA), provides the basis for all licensing decisions for waste repositories. The purpose of this report is to discuss the different technical issues that must be considered in developing an environmental radiation standard for high-level waste disposal. These issues include the following: (1) defining the acceptable level of risk; (2) specifying the acceptable risk in terms of an operational repository performance standard; (3) formulating the standard so that reasonable demonstrations of compliance can be obtained; (4) determining whether the standard should apply to the protection of maximally exposed individuals, the entire population, or some combination of the two; (5) determining whether the standard applies to unexpected processes and events as well as expected occurrences; (6) determining a time limit for the standard; and (7) specifying certain conditions to be assumed in evaluating repository performance for compliance with the standard. This report also discusses the applicability to a high-level waste standard of principles embodied in previous radiation standards and guidances for other nuclear activities, and it discusses how the proposed EPA standard and other high-level waste standards which have been proposed in the literature address the technical issues of concern.

An important conclusion of this report is that there are not likely to be clear choices on technical grounds alone for resolving the technical issues of importance to the development of a high-level waste standard. The most important general attribute of an effective and workable standard is that it be compatible with the kinds of technical information that will be available for making licensing decisions. Thus, an effective high-level waste standard is likely to be one which recognizes explicitly the subjective and judgmental nature of evaluations of long-term repository performance, and one which allows regulatory agencies an essential degree of flexibility in reaching licensing decisions.

1. INTRODUCTION

An important issue for geologic disposal of high-level radioactive wastes is the establishment of a generally applicable standard for radiation in the environment for the purpose of limiting potential health risks to future generations. Such a standard provides the basis for licensing decisions on high-level waste repositories. The primary purpose of this report is to discuss various technical issues which must be considered in developing an environmental standard for high-level waste disposal and to present an evaluation of the strengths and weaknesses of alternatives for resolving each issue.

The particular type of standard with which this report is concerned is an overall system performance standard for a high-level waste repository. The terms "environmental radiation standard" and "system performance standard" will be used synonymously. In the U.S., the development of generally applicable environmental radiation standards for nuclear activities is the responsibility of the Environmental Protection Agency (EPA), and such a standard for high-level waste disposal has recently been proposed.[1] This report does not consider standards which specify in detail the performance of various components of a repository system for high-level waste disposal. This type of standard is represented by the technical criteria which have been developed by the Nuclear Regulatory Commission (NRC).[2] The NRC technical criteria are intended to be compatible with the proposed EPA standard; i.e., the various quantitative and qualitative requirements in the NRC rulemaking, which pertain to the natural and engineered parts of the repository system, are intended to provide reasonable assurance that the requirements of the EPA standard for overall repository performance will be met.

In my opinion, any discussion of the technical issues that are involved in developing a system performance standard for high-level waste disposal inevitably is quite subjective; i.e., there are not likely to be objective arguments or tests which will lead to a clear resolution of the issues. This type of subjectivity is emphasized throughout this report, and statements which are the opinion of the author will clearly be identified as such.

Perhaps the single most important consideration in developing an environmental radiation standard for high-level waste disposal concerns the problem of formulating the standard so that it is congruent with the kinds of technical information that will be available when licensing decisions are made. This involves the fundamental question of what will constitute reasonable demonstrations of compliance of a repository with the standard. This question will be addressed throughout this report in discussing the various technical issues which must be considered in formulating a standard.

An environmental radiation standard for high-level waste disposal serves two basic functions. First, such a standard defines, either explicitly or implicitly, an acceptable level of health risk to the general public from the activity in question. Thus, even though estimates of risk may be highly uncertain and judgmental, a standard defines how safe is safe enough and provides a focus for the debate over safety. Second, unless the acceptable risk is specified directly, a standard involves a translation of acceptable risk into more operational quantities; i.e., the standard gives secondary goals or limits, such as limits on dose or environmental radioactivity, which must be met in order to obtain acceptable system performance. The specification of secondary limits in a standard is an important consideration because it determines whether the standard is workable (i.e., whether demonstrations of compliance are feasible) and whether meeting the standard will result in actual risks that are compatible with the target level for acceptable risk from which the secondary limits were derived.

There is one important issue of a non-technical nature for the development of a high-level waste environmental standard that is not considered in this report. In order for such a standard to be effective, licensing decisions based on the standard must be acceptable to the general public. This issue more involves public perceptions of the safety of waste repositories and of the licensing process than the particular formulation of the standard itself.

Section 2 of this report discusses characteristic features of high-level waste disposal which must be considered in developing an effective system performance standard. It is my view that the problem of regulating high-level waste disposal is significantly different from the problem of regulating other nuclear activities, because of the largely unique characteristics of high-level waste disposal. Important examples of these unique characteristics include the lack of any repository operating experience prior to the development of standards, the reliance on highly uncertain models for predicting long-term repository performance, and the importance of natural geologic systems in determining overall system performance.

In Section 3, previous rulemakings of the EPA and NRC for other nuclear activities and general recommendations of the International Commission on Radiological Protection (ICRP) are reviewed with regard to the potential applicability of their provisions to a high-level waste standard. It is useful to understand these other approaches, because it would be an advantage if a high-level waste standard could use familiar and tested arguments from other regulatory experiences. I believe, however, that the appropriateness of other standards and guidances to a high-level waste standard is somewhat limited, due to the unique characteristics of high-level waste disposal discussed in Section 2. Important features of the EPA's proposed high-level waste standard[1] are also discussed in this section.

With Sections 2 and 3 as background, Section 4 discusses the technical issues which must be addressed in formulating a high-level waste standard. These issues include the following:

[1] defining the acceptable level of risk from high-level waste disposal;

[2] specifying the acceptable level of risk in terms of an operational system performance standard;

[3] formulating a standard so that reasonable demonstrations of compliance with its requirements can be obtained;

[4] determining whether the objective of the standard is protection of individuals in critical groups of the exposed population, protection of the entire population, or a combination of the two;

[5] determining whether the standard applies to expected occurrences or to unexpected processes and events as well;

[6] determining a time limit for the standard; and

[7] specifying certain conditions to be assumed in evaluating repository performance for compliance with the standard.

The discussion in Section 4 presents alternatives for resolving each of these issues and a subjective evaluation of the strengths and weaknesses of the alternatives.

Section 5 presents illustrations of different ways that the technical issues discussed in Section 4 may be resolved in formulating a standard by reviewing system performance standards for high-level waste disposal which have been proposed in the literature. The comparison of the different standards demonstrates that there are no clearly preferable choices on technical grounds alone for resolving the issues outlined above.

The last section of this report presents some concluding remarks which summarize my views on the desirable attributes of a system performance standard for high-level waste disposal.

2. CHARACTERISTICS OF HIGH-LEVEL WASTE DISPOSAL OF IMPORTANCE TO AN ENVIRONMENTAL RADIATION STANDARD

2.1 Introduction

High-level waste disposal has certain characteristics which could have a significant effect on the types of environmental radiation standards that would be effective. These characteristics include the following:

[1] the long time period required for isolation of the wastes from the biosphere;

[2] the lack of any repository operating experience prior to the development of standards;

[3] the necessity of relying on highly uncertain models for predicting long-term repository performance;

[4] the practical inability of taking effective remedial actions should repository performance be significantly poorer than expected; and

[5] the importance of the natural geologic system in determining overall repository performance.

Many of these characteristics have not been encountered in establishing system performance standards for other nuclear activities. Their potential importance to the development of an effective high-level waste standard is discussed in this section.

2.2 Time Period Required for Waste Isolation

Large quantities and high concentrations of high-level waste will be present in a repository.[3] Therefore, the wastes undoubtedly must be isolated from the biosphere for a time period of at least a few thousand years in order to ensure that the risk to the general public will be acceptable. Low-level waste and uranium mill tailings also present a potential health detriment to the general public for thousands of years, but only high-level waste is sufficiently concentrated that radiological impacts much greater than those due to natural background radiation are possible for long time periods in the future. Such impacts clearly would not be acceptable, given the levels of acceptable risk currently embodied in environmental standards for other nuclear fuel-cycle activities (e.g., see Ref. 4).

2.3 Lack of Prior Operating Experience

System performance standards for nuclear activities usually have been developed only after fairly extensive operating experience has been obtained. Examples include standards for reactor operations, low-level waste disposal, and uranium mill-tailings disposal. In each case, prior operating experience provided data for assessing radiological consequences from unregulated practices. In developing an appropriate standard, these data were then used to evaluate alternatives for limiting the potential health detriment from future operations. The existence of prior operating experience has also allowed system performance standards to be based on currently available technology; e.g., this is the basis for the EPA's uranium fuel-cycle standard.[4]

For geologic waste disposal, however, standards must be developed in the absence of operating experience, so that there is no _a priori_ evidence of what level of health risk may actually result from either expected or unexpected releases of radioactivity to the environment. Although a high-level waste standard certainly can be based on the level of risk that is predicted to result from operation of a hypothetical repository, there can be no confirmatory evidence that such performance will actually be achieved. In my opinion, the lack of prior repository operating experience provides one reason why a system performance standard for high-level waste disposal should establish a level of acceptable risk which is less than that for well established nuclear activities. Other arguments for a conservative standard are given in Sections 2.4, 2.6, and 2.7 below.

2.4 Dependence on Models for Performance Assessments

Models of various kinds (i.e., mathematical, physical or analog, and conceptual) must be used to provide predictions of long-term repository performance, basically because of the long time period required for waste isolation and because it is not feasible to perform realistic full-scale tests of a repository system. It is also the case, however, that the model predictions are highly uncertain.[5-7] Because of the impossibility of validating the models, predictions of long-term repository performance may involve a significant degree of essentially unquantifiable uncertainty beyond the level indicated by parameter sensitivity analyses. Therefore, the models themselves are likely to be contentious when they are used as a basis for licensing decisions. The need to resolve disputes over the use of models in demonstrating compliance of a repository with standards may be an important feature of the licensing process, particularly if mathematical models must be used to demonstrate compliance with fixed numerical performance standards. It is not necessarily the case, however, that resolving these disputes will be helpful in making a repository safe.

In demonstrating compliance of a repository with a high-level waste standard, I believe that the most appropriate function of performance assessment models is to provide reasonably conservative estimates of repository performance, rather than to provide realistic predictions taking into account the various uncertainties in models and parameter values. That is, if we can be reasonably certain that repository performance will not exceed the standard, then we need not be particularly concerned with what the actual performance will be. In principle. conservative predictions are more easily obtained than realistic ones, because of the relatively simple models which can be used. In practice, however, it may not be easy to develop reasonably conservative models for repository performance, because of the difficulties in taking all important processes and parameters into account and in determining what constitutes reasonably conservative models and parameter values. Thus, even this approach may be contentious in the licensing process, particularly if model predictions that are widely agreed to be conservative are in violation of the standard and more realistic analyses are then required.

2.5 Inability to Take Remedial Action

For some types of nuclear facilities (e.g., power reactors), violations of environmental radiation standards can be detected by means of environmental monitoring, and corrective actions can be taken on the engineered system to reduce further releases of radioactivity to the environment. Following closure of a geologic repository, however, it is difficult to envision that there can be any such feedback between environmental levels of radioactivity, or other monitorable measures of repository performance, and future releases of radioactivity. First of all, it does not seem reasonable to me to require that environmental monitoring be used to detect violations of a standard over long time periods in the future. Furthermore, even if violations could be detected, it does not seem feasible that any kind of effective remedial action involving the repository itself could be undertaken to prevent further releases of radioactivity. An evacuation of the impacted population or restrictions on the use of food and drinking water are possible in the event of unexpected levels of radioactivity in the environment, but an environmental radiation standard should not, in my opinion, anticipate that this will be done as a matter of course.

In essence, I believe that high-level waste disposal presents a situation in which the long-term radiological impacts on the general public are pre-determined by the design and construction of the engineered system, the properties of the geologic medium in which the repository is located, and the amount and composition of the buried waste. Beyond the use of institutional controls and permanent markers to indicate the presence of the repository and to discourage inadvertent human intrusion, I do not believe that anything reasonable can be done after decommissioning of the repository to reduce whatever the radiological impacts are destined to be. I believe that this line of reasoning provides a strong argument for setting a conservative level of acceptable risk from high-level waste disposal compared with the acceptable risk from other nuclear activities, in case the models on which repository performance assessments are based prove to be faulty and seriously underestimate actual risks.

2.6 Role of Natural Geologic Barriers

The basic rationale for geologic waste disposal is that the natural geologic system by itself will provide an effective barrier against transport of radioactive waste to the biosphere.[8,9] Although current EPA and NRC approaches to regulating high-level waste disposal[1,2] place considerable emphasis on the role of redundant engineered barriers in a repository system, recent analyses of long-term repository performance suggest that the natural geologic barriers should be far more effective than the engineered system in providing isolation of the waste from the biosphere.[10-12] It is important to note, however, that these analyses do not employ a future time limit for evaluating repository performance, and imposing such a time limit increases the importance of the engineered barrier system relative to the natural geologic barriers in achieving waste isolation.

If the natural geologic barriers are indeed an important part of a repository system, then it must be recognized that the natural barriers are not subject to any kind of engineered control and thus, in a sense, cannot really be regulated. This means that there may be very little that can be done to limit the radiological consequences from waste disposal beyond the selection of good sites.

As mentioned in Section 2.4, it may prove difficult to obtain quantitative estimates of radionuclide transport through the geologic media between a repository and the biosphere in which all important uncertainties are reasonably and defensibly taken into account. Therefore, to the extent that the natural geologic barriers are required to contribute to meeting a system performance standard, it may be difficult to demonstrate compliance of a repository with a quantitative high-level waste standard. This will particularly be the case if the requirements on the performance of the natural geologic barriers are quite stringent.

2.7 Conclusion

The development and implementation of an environmental radiation standard for high-level waste disposal probably represents an unprecedented situation for regulatory agencies because of the unique characteristics of waste disposal. The basic problem for the licensing process is that long-term repository performance cannot be verified directly by any means. Therefore, predictions of various kinds of models must be used to demonstrate compliance with a standard; yet, the use of models for this purpose likely will be controversial. Thus, an understanding of the various methods for predicting repository performance and the different means of achieving confidence in the predictions for decision-making purposes (e.g., requiring the use of redundant engineered and natural barriers in a repository system) is quite important for the development of an effective high-level waste standard.

3. APPLICABILITY OF PREVIOUS RULEMAKINGS AND GUIDANCES TO A HIGH-LEVEL WASTE STANDARD

3.1 Introduction

In this section, we consider previous rulemakings and guidances for various nuclear activities which have been developed by the NRC, EPA, and ICRP, in order to determine if the principles embodied therein could be applied to a high-level waste standard. The previous NRC and EPA rulemakings which we consider apply to land disposal of low-level waste[13] and uranium mill tailings;[14,15] these are two other types of radioactive wastes which represent a potential long-term health detriment to the general public. The ICRP recommendations[16] apply to any environmental radiation exposures. It is useful to understand these rulemakings and guidances, because it likely would increase public confidence in a high-level waste standard if the standard incorporated previous regulatory practices to the fullest extent possible.

3.2 NRC Low-Level Waste Rulemaking

The NRC rulemaking on land disposal of low-level waste[13] is intended to provide long-term protection of the general public from radioactivity released to the environment as well as protection of an inadvertent intruder at the disposal site. The rulemaking is not concerned with protection of individuals during deliberate human intrusion.

Long-term protection of the general public is provided in part by limiting the concentrations of different radionuclides that can be buried and by technical requirements on site suitability, site design, facility operation and site closure, and monitoring. Groundwater transport is assumed to be the primary mechanism for long-term, off-site exposures. The system performance objectives for such exposures are expressed as annual dose limits for individuals in critical groups of the population, and the dose limits are numerically the same as those in the EPA's uranium fuel-cycle standard.[4]

Potential radiological impacts on an inadvertent intruder are limited by imposing concentration limits on radionuclides, specifying that the facility be designed to protect such an intruder, and requiring institutional controls for a period of up to 100 years. A numerical performance objective for protection of the inadvertent intruder is not stated explicitly in the rulemaking, but the limits on radionuclide concentrations are consistent with the annual dose limit in the NRC's radiation protection standards for unrestricted areas.[17]

As with the NRC's high-level waste standard,[2] the NRC's low-level waste standard establishes performance objectives which are intended to be compatible with a generally applicable environmental radiation standard to be promulgated by the EPA. An EPA standard for low-level waste disposal has not yet been developed. Nonetheless, certain aspects of the NRC low-level waste rulemaking would seem to be appropriate, at least in principle, to a high-level waste environmental standard. In particular, the individual dose limits established for long-term protection of the general public could be applied to high-level waste disposal as well. It is questionable, however, whether specifying limits on concentrations of different radionuclides would be appropriate for high-level waste disposal. Limits on concentrations or total inventories of radioactivity would result either in larger repository sizes or in an increase in the number of sites, because all of the waste that is produced eventually must be buried somewhere; however, such limits may significantly increase the costs of disposal without a corresponding decrease in long-term health risks to the general public. Finally, it is noteworthy that the specification of dose limits for individuals in the NRC low-level waste standard means that a future time limit for assessing the potential detriment need not be specified explictly.

3.3 Uranium Mill-Tailings Rulemakings

For uranium mill-tailings disposal, both the EPA's environmental standard[15] and the NRC's technical criteria[14] have been established. The EPA standard sets limits on permissible ^{226}Ra concentrations in soil or in other materials on open land, indoor levels of gamma radiation and airborne radon-daughter products, and dose to a maximally exposed individual. The NRC technical criteria focus on methods for controlling long-term radiological impacts on the general public. The rulemaking emphasizes (1) proper siting of tailings piles in order to reduce wind and water erosion without requiring active care and maintenance, (2) limits on airborne emissions of radioactivity by specifying a minimum cover thickness for tailings piles and a limit on the radon emission rate, and (3) siting of tailings piles in semi-arid regions with little groundwater recharge in order to limit groundwater degradation. Human intrusion is not considered explicitly by the NRC, but compliance with the other criteria presumably allows for unrestricted use of the land for farming or grazing.

In my opinion, there are two lines of reasoning used in the EPA and NRC mill-tailings rulemakings which are applicable to a high-level waste standard. First, the primary objective of these rulemakings is to ensure that the tailings are isolated from the biosphere at least to the extent that the potential radiological consequences will be no greater than those from natural radiation from terrestrial sources in the surrounding undisturbed environment. That is, the rulemakings establish the principle that mill-tailings disposal need not be safer than the unmined uranium ore which was used to produce the tailings. (There is, of course, a time delay between the radiological consequences of mill-tailings disposal and those from unmined uranium, except for surface-mined ores, so that this principle also assumes implicitly that there is no discounting of future impacts.) Second, the rulemakings place a greater reliance on proper site selection than on engineered control systems for reducing long-term impacts from tailings piles. Site selection is thus recognized to be more important than efforts to make a given site better.

As with the NRC low-level waste rulemaking,[13] a time limit to which the mill-tailings rulemakings apply is not defined explicitly, even though the potential hazard decays with the 77,000-year half-life of ^{230}Th. The need for a time limit is avoided essentially by specifying the initial state of the disposal system and by focusing on limiting the detriment to maximally exposed individuals. Whether avoidance of a time limit is appropriate for a high-level waste standard is discussed in Section 4.7.

The performance objectives in both the low-level waste and the uranium mill-tailings rulemakings are based in part on analyses of so-called base-case scenarios, which are essentially the predicted radiological impacts from operating experiences prior to the development of the regulations. As previously mentioned in Section 2.3, this type of analysis is not appropriate for high-level waste disposal because of the lack of prior operating experience.

3.4 Recommendations of the ICRP

In Publication 26, the ICRP recommends a system of dose limitation for environmental exposures in which it is necessary to assess the detriment to maximally exposed individuals and to the population.[16] One first assesses population dose for the purpose of optimizing exposures, and then assesses individual dose to ensure that exposures of critical groups in the population remain within appropriate limits. Optimization of radiation exposures involves the concept of ALARA (As Low As Reasonably Achievable) and the use of cost-benefit analysis. The ICRP also recognizes explicitly that assessments of long-term population dose for the purpose of optimizing exposures may involve significant uncertainties.

Again, the use of individual dose limits in a high-level waste standard is reasonable, at least in principle. In my opinion, however, it is not reasonable in this case to apply population dose assessments to the optimization of radiation exposures, even though application of the ALARA principle to environmental exposures is currently required by the EPA for some operations of the nuclear fuel cycle.[4] The problems with applying the ALARA principle and cost-benefit analysis to nuclear activities which potentially involve long-term radiological impacts have been discussed in connection with the NRC's uranium mill-tailings rulemaking[18] and elsewhere.[2,19] The difficulties arise primarily from (1) the highly subjective choice of the future time period over which the population detriment is to be estimated, (2) the highly subjective judgments involved in assigning a monetary value to future health effects, (3) the large uncertainties involved in predicting future health effects as well as the purely hypothetical and probably conservative nature of any such predictions, and (4) the inability to obtain a unique correlation between repository performance and costs. An additional problem for high-level waste disposal is that optimization of performance is applicable only to controlled sources of radioactivity (e.g., nuclear power plants) and not to uncontrollable sources such as a waste repository. Therefore, even though the proposed EPA high-level waste standard contains an ALARA requirement,[1] it is difficult to see how this principle can be applied effectively to the performance of a waste repository. On the other hand, optimization would appear to be a relevant concept for site selection.

3.5 Summary of Previous Rulemakings and Guidances

Certain features of previous rulemakings of the EPA and NRC on low-level waste and uranium mill-tailings disposal and of the ICRP recommendations for radiation exposures of the general public may be appropriate for a high-level waste environmental standard. These rulemakings and guidances emphasize a limitation on the detriment to individuals in critical groups of the population, and this is certainly a possibility for a high-level waste standard. The mill-tailings rulemakings seem to be particularly appropriate for high-level waste disposal in their emphasis on site selection rather than engineered controls as the most effective way of ensuring long-term safety of the general public and in their definition of acceptable performance on the basis of the unavoidable risk from the natural, undisturbed environment.

Other aspects of the previous rulemakings and guidances seem to be less appropriate for a high-level waste standard. These aspects include limitations on initial release rates or concentrations of radioactivity, as in the low-level waste and mill-tailings rulemakings, and the application of the ALARA principle and cost-benefit analysis to system performance, as recommended by the ICRP.

3.6 Comments on Proposed EPA High-Level Waste Standard

This section presents some subjective comments on the proposed EPA standard for high-level waste disposal.[1] Aspects of the standard which are emphasized here either represent a significant departure from most previous rulemakings for other nuclear activities or are likely to be particularly controversial.

The proposed EPA standard for long-term repository performance is quite different from standards for other nuclear activities in that it is based on limiting the population detriment only. This principle is expressed by specifying limits on cumulative releases of different radionuclides to the so-called accessible environment. The EPA's rationale for this type of standard is basically as follows: (1) a limit on individual detriment may not be appropriate when one considers the potentially large doses to an inadvertent intruder compared with doses to other exposed individuals from normal groundwater transport to the biosphere; and (2) it is significantly more difficult to demonstrate compliance with an individual dose standard than with a standard based on population detriment, because the former requires estimates of release rates and environmental concentrations whereas the latter depends only on the total amounts of radionuclides that are released to the biosphere. It should be recognized, however, that the EPA standard implicitly limits the detriment to most individuals by setting a very low level for acceptable population detriment. It is only for unusual types of intrusion scenarios involving a very few individuals, such as drilling into a repository, that meeting the EPA release limits could still lead to large individual doses.*

The specification of limits on releases of radionuclides in the proposed EPA standard is not an entirely new approach. The EPA's uranium fuel-cycle standard[4] also establishes release limits for certain long-lived and/or mobile radionuclides, but these limits are in addition to the annual dose limits for individuals from all emissions. Furthermore, the release limits in the fuel-cycle standard are based on considerations of best available control technology, not on the potential population detriment.

A particularly controversial aspect of the proposed EPA high-level waste standard is its specification of radionuclide release limits for accidental ("very unlikely") as well as normal ("reasonably foreseeable") occurrences and the specification of numerical probabilities to distinguish between releases in these two categories. In particular, there likely will be considerable debate over the importance attached to human intrusion scenarios in the EPA's analyses of repository performance and expected health effects,[1,21] and the determination of probabilities of disruptive events may be highly uncertain and contentious. A somewhat peculiar feature of the EPA standard is that the levels of acceptable risk for normal and accidental occurrences are not the same, with the acceptable risk from reasonably foreseeable releases being generally the greater.

The release limits in the EPA standard apply to a time period of 10,000 years, and there are no restrictions on releases of radioactivity to the accessible environment beyond that time. The EPA believes that meeting the requirements for 10,000 years will also limit implicitly the potential health risks beyond that time, and this is certainly desirable if a time limit is specified. The EPA argues that 10,000 years is a reasonable time limit because it is sufficiently long to encourage the selection of sites with desirable geochemical properties for retarding

* In revising its proposed standard, the EPA is considering an individual dose limit over a 1,000-year time period from use of contaminated groundwater (see Ref. 20), in addition to the limits on cumulative releases of radionuclides to the accessible environment. Such a provision is intended to protect individuals who inadvertently drill into an aquifer near the repository.

radionuclide migration in groundwater, but it is sufficiently short that disruptive natural geologic processes are not likely to be important.[1,22] In my opinion, however, there is considerable arbitrariness in the EPA's choice of a time limit. This issue is discussed further in Section 4.7.

Another aspect of the proposed EPA standard that is important but potentially controversial is the definition of the "accessible environment," which specifies the boundary at which repository performance is to be evaluated for determining compliance with the release limits in the standard. In the subsurface lithosphere, the accessible environment is defined as a hypothetical boundary located ten kilometers from the repository.* While hypothetical boundaries for consequence analyses are an important feature in regulating other nuclear activities (e.g., the use of a hypothetical "fencepost man" in estimating dose to maximally exposed individuals from nuclear reactor emissions), the EPA's choice of a fixed generic boundary for evaluating the performance of a high-level waste repository seems somewhat illogical. In my opinion, a sensible definition should attempt to distinguish between regions where human exposures are relatively likely or unlikely. Although specifying such a boundary in the subsurface lithosphere is admittedly somewhat arbitrary, because of the need to consider the possibility of well drilling into aquifers, it seems reasonable to me that the definition should allow for site-specific considerations. A fixed numerical definition of this boundary, as in the EPA standard, appears to remove any incentive for choosing sites with long groundwater travel paths to the biosphere. On the other hand, perhaps it can be argued that compliance of a well chosen site with the EPA standard would result in actual releases to man's exposure environment which are much less than the release limits in the standard.

Finally, the EPA standard specifies that performance assessments which are used to determine compliance of a repository with the standard shall consider realistic projections of the performance of all parts of the repository system. It is difficult for me to understand what

* The revised EPA standard may include a reduction to one mile in the distance from the repository to the accessible environment (see Ref. 20).

"realistic" means given the likelihood that there will be many orders of magnitude of uncertainty associated with the quantifiable aspects of repository performance (e.g., see Refs. 23, 24) and that uncertainties in some important aspects of repository performance may be essentially unquantifiable.[5-7] As discussed in Section 2.4, I believe that models for demonstrating compliance of a repository with standards should focus on conservative rather than realistic assumptions.

Additional comments on the proposed EPA standard are presented throughout Section 4.

4. TECHNICAL ISSUES FOR A HIGH-LEVEL WASTE STANDARD

4.1 Introduction

This section discusses the various technical issues which, in my opinion, must be considered in developing a generally applicable environmental standard for high-level waste disposal. Various alternatives for resolving each of the issues and their strengths and weaknesses are described, and reference is made to the approach adopted by the EPA in their proposed high-level waste standard.[1]

The technical issues for developing a high-level waste standard which are discussed in this section include the following:

[1] defining the acceptable level of risk;

[2] specifying the acceptable level of risk in terms of an operational system performance standard;

[3] formulating a standard so that reasonable demonstrations of compliance can be obtained;

[4] determining whether the standard is to be based on the protection of individuals, protection of the population, or some combination of the two;

[5] determining whether the standard applies to normal occurrences only or to unexpected events as well, including human intrusion;

[6] determining a time limit for the standard; and

[7] specifying certain conditions to be assumed in evaluating repository performance, e.g., the definition of the boundary of the accessible environment.

In discussing the various issues outlined above, it will be evident that my primary concerns with regard to a high-level waste standard are related to the problems of (1) demonstrating compliance and (2) writing a standard that focuses on issues which are believed to be important for limiting the risk from geologic waste disposal. It will also be clear that I regard the solution to many of the technical issues discussed in this report as largely a subjective matter; i.e., I do not believe that there are clear choices based on technical considerations alone.

4.2 Acceptable Level of Risk

The fundamental purpose of a high-level waste standard is to establish an acceptable level of risk to the general public from geologic waste disposal. The choice for an acceptable level of risk could be based on one or more of the following: (1) some fraction of the unavoidable risk from natural background radiation; (2) some fraction of the natural cancer incidence or mortality rate; (3) the unavoidable risk from unmined uranium ore; (4) the risk from nonnuclear industrial activities which are generally regarded as safe; (5) the acceptable risk associated with previously established standards for nuclear activities, such as the NRC's radiation standard for unrestricted areas[17] or the EPA's uranium fuel-cycle[4] and drinking-water[25] standards; and (6) best available technology. The different choices are discussed in the following paragraphs.

4.2.1 Natural background radiation

It is appealing to base an acceptable level of risk for high-level waste disposal on some fraction of natural background radiation, because risks of this nature are unavoidable and variations in natural background usually do not influence an individual's choice of where to live. Use of the standard deviation of the geographical distribution in natural background, which is about 20 mrem/y, as a basis for radiation protection of the general public has been proposed by Adler and

Weinberg.[26] The American Physical Society study group also has recommended that population exposures from high-level waste disposal be kept small compared with the variation in natural background.[9]

There is a difficulty with using natural background as a fundamental basis for defining acceptable risk, in that people are generally not aware of variations in natural background when they decide where to live. If people knew that living near a waste repository could given them an additional dose of 20 mrem/y, for example, then perhaps they would decide that the risk is unacceptable and either veto the facility or move elsewhere. It is difficult to argue that ignorance of variations in natural background can be equated with acceptance of that amount of additional exposure.

4.2.2 Natural cancer incidence or mortality rate

The acceptable risk for high-level waste disposal could be based on some fraction of the natural cancer incidence rate or total mortality rate in the general population. However, this seems to me to be a rather weak approach, because the chosen fraction may appear to be largely arbitrary unless it can be related clearly to some known risk from specific and familiar activities. In addition, the acceptable risk would be expressed most conveniently in the standard in terms of either incremental risk to individuals or total deaths. Particularly if the risk were expressed in a standard as an acceptable number of fatalities, then even a small incremental risk to an average individual may not be accepted by the general public.

4.2.3 Unmined uranium ore

Using the risk from unmined uranium ore as a basis for defining acceptable risk in a high-level waste standard seems to me to be a particularly strong line of reasoning, at least in principle. In this case, the acceptable risk from waste disposal would be based on the unavoidable risk from an equivalent amount of unmined uranium ore. The additional risks from uranium mill tailings over the time period required for the parent ^{230}Th ($T_{1/2} = 7.7 \times 10^4$ y) to decay would also need to be taken into account. Cohen has been an active proponent of the idea that mining uranium ore, burning it in reactors, and burying the waste in deep geologic formations will save a substantial number of lives in the future,[27,28] primarily because the mined uranium ore is much closer to the earth's surface than the buried waste. Maxie et al.[29] have proposed an ore-body comparison as a basis for acceptable risk from geologic waste disposal; this proposal is discussed in Section 5.2.

Even though a high-level waste standard based on the risk from unmined uranium ore is quite attractive, implementing such a standard may be difficult because of the need to define a reference ore body. Uranium ore deposits vary greatly in their distance from the ground surface, which affects radon emissions at future times as a deposit is uncovered by erosion, and in the rates and future times of discharge of uranium and radioactive daughter products to surface waters. The EPA has estimated, for example, that population risks from unmined ore bodies can vary by several orders of magnitude.[1,30] The largest estimates give a predicted incremental death rate of 1,000 per year, and an incremental risk of this magnitude for waste disposal would probably be unacceptable to the general public. Measured radium concentrations in surface waters[31] also indicate that the risks from some uranium ore bodies are unacceptably high.

Attempts have been made to compare the radiological impacts of specific ore deposits with those of buried high-level waste, and the predicted impacts for the two are generally comparable when uncertainties in the calculations are taken into account.[31] In addition, Cohen has estimated an upper bound for the risk from geologic waste disposal on the basis of the behavior of an average atom of uranium in the earth's crust between the surface and the depth of a repository.[32,33] Nonetheless, no one has yet to my knowledge made a formal proposal for the characteristics of a uranium ore body which would serve as a basis for defining acceptable risk in a high-level waste standard.

4.2.4 Risks from nonnuclear industrial activities

It would be possible to base a high-level waste standard on risks to the general public from nonnuclear industrial activities which are generally regarded as safe. The difficulty with this choice, however, is that the public would not necessarily accept the same risk from a relatively unfamiliar nuclear activity as from a more familiar nonnuclear activity.

4.2.5 Risks from other nuclear activities

The use of existing environmental radiation standards for other nuclear activities as a basis for defining acceptable risk from high-level waste disposal seems reasonable, because the dose, release, or concentration limits for the other activities have already been accepted. This approach could enhance the appearance of consistency in regulating a wide variety of nuclear activities. However, one would also need to take into account that the ALARA principle allows for differences in acceptable risk from different nuclear activities. Furthermore, as emphasized in Section 2, there may be valid reasons for setting an acceptable risk for high-level waste disposal that is much less than the accepted risk for other nuclear activities. The most important reasons are the large uncertainties in predicting repository performance and the inability to reduce radionuclide releases to the biosphere should repository performance be poorer than expected.

4.2.6 Best available technology

Best available technology has been used previously by the EPA as the basis for the uranium fuel-cycle standard.[4] This approach has also been used as the primary basis for defining acceptable risk in the EPA's proposed high-level waste standard.[1] This is a reasonable approach if the public accepts the predicted risk from the assumed technology and the costs associated with achieving that risk.

4.2.7 An approach for defining acceptable risk

I believe that the best approach in defining the acceptable level of risk for a high-level waste standard would be to use as many of the bases discussed above as are applicable. This approach perhaps would lead to a greater degree of public acceptance of the standard. If one uses several bases for defining acceptable risk, then there is a distinction to be made between the fundamental bases and the other bases which are used, in essence, to support the choice of acceptable risk. This type of reasoning has been used in developing the proposed EPA high-level waste standard.[1] This standard is based primarily on a best available technology which is expected to result in a very small number of health effects per repository compared with the natural mortality rate. The EPA then supports the choice of acceptable risk by arguing that it is less than the risks due to variations in natural background radiation and to most uranium ore bodies and that it is much less than those allowed by other standards for nuclear fuel-cycle operations. This type of approach to establishing and justifying acceptable risk for a high-level waste standard appears to me to be quite sound.

4.3 Operational System Performance Standards

Once an acceptable level of risk for high-level waste disposal has been established on the basis of considerations such as those outlined in the previous section, the primary risk standard may need to be expressed in more operational terms by specifying secondary system performance standards which are believed to be compatible with the acceptable level of risk. This will be the case unless the standard specifies the acceptable level of risk directly. In general, secondary performance standards which are derived from an acceptable level of risk may be expressed as numerical limits on quantities such as release rates or cumulative releases of radionuclides to the biosphere, doses to maximally exposed or average individuals, or environmental concentrations of radioactivity. But particular types of standards may also involve other considerations. For example, a standard based on the risk from a uranium ore body would need to consider the definition of the reference ore body.

The determination of the basis for acceptable risk and the specification of secondary performance standards to express that risk are closely related, because the former may lead naturally to preferred forms for the latter. For example, a standard based on some fraction of natural background radiation as an acceptable risk would be expressed most conveniently as an annual dose limit for either maximally exposed or average individuals.

It may not be necessary to quantify the acceptable level of risk (e.g., in terms of incremental health risk to individuals or number of deaths in a population) in order to express that risk in a standard. For example, if variations in natural background radiation were chosen as the basis for acceptable risk, then one can derive a dose limit without consideration of what the risk corresponding to that dose actually would be. Similar considerations also might be appropriate for a standard based on the risk from a reference uranium ore body. The potential advantage of this type of approach is that it avoids unresolvable arguments over the risk from very low levels of radiation, particularly for alpha-particle irradiations where the commonly used linear no-threshold dose-response relation may not underestimate actual risks.[34] It seems to me that the public can accept an activity as being safe without knowing what the actual risk is, as long as the risk is low and there is some basis for relative comparisons of risk with those of other familiar activities or occurrences. This type of reasoning may be particularly useful for high-level waste disposal, because the risks are expected to be very low but any estimates of risk will be highly uncertain.

One way of considering the use of secondary performance standards to express the level of acceptable risk is as follows. During the process of developing an environmental radiation standard and then using it as a basis for licensing decisions, the entire spectrum of issues related to the risk from geologic waste disposal will need to be addressed. This spectrum of issues includes the quantity of waste to be buried, the performance of the engineered and natural geologic barriers of the repository system, environmental transport and human exposures, dose, and the health risk per unit dose. In formulating the standard, one is deciding in essence which of these issues will be resolved in setting the standard and which will be considered in the licensing process. At one extreme, for example, the environmental standard could be expressed directly as a numerical limit on acceptable risk. The rationale for this approach is that risk limitation itself is the objective of the standard and that the models for relating risk to secondary performance standards, such as dose or environmental radioactivity, do change with time as our state of knowledge increases. In this approach, the only issue for establishing a standard is to decide what the acceptable level of risk is; all other issues related to risk estimation are then relegated to the licensing process. At the other logical extreme, one could consider an environmental standard which limits the quantity of waste to be buried in a repository. In this case, all issues associated with estimating the risk from high-level waste disposal would be resolved in the process of establishing the environmental standard. Possible disadvantages with this approach are that complying with the standard may result in actual risks which are very different from the level of acceptable risk from which the standard is derived and that the risk per unit quantity of buried waste may be highly site-specific. On the other hand, for a site with very good hydrologic and geochemical properties, the risk may indeed be proportional to the quantity of a few very long-lived radionuclides in the waste, such as ^{129}I and ^{238}U. Thus, in the absence of a time limit for the standard, limiting the quantities of waste to be buried may be the only really effective means of limiting potential risks.

I believe that the soundest approach to dividing risk-assessment issues between standards development and the licensing process is to include in standards development those issues which are primarily generic in nature and relegate to the licensing process those issues which are primarily site-specific or involve engineered parts of the repository system. Thus, I believe that the approach embodied in the proposed EPA standard[1] of expressing acceptable risk in terms of allowable releases of radioactivity to the accessible environment is, at least in principle, a reasonable one. In this case all issues related to environmental transport of radioactivity, human exposures, dose, and health risk are resolved in standards development. This is reasonable for the dose per unit exposure and the health risk per unit dose, because these quantities are site-independent. Estimates of environmental transport and human exposures, on the other hand, will be somewhat site-specific. However, possible variations in these quantities between different sites probably will be insignificant compared with potential site-specific variations in the performance of the natural geologic barriers, due primarily to the long half-lives of most of the radionuclides that could be released to the biosphere. Thus, in my opinion, it would be reasonable in standards setting to define generic environmental transport and exposure models for application to any site in a manner similar to the approach currently used by the NRC in assessing radiological consequences from nuclear reactors.[35] Another justification for the approach used by the EPA in formulating an environmental standard is that uncertainties associated with predicting the radiological consequences per unit release of radioactivity to the biosphere are expected to be much less than uncertainties in predicting the long-term performance of the engineered and natural barriers in a repository system.[7,36] With the EPA standard, the licensing process would focus on the important issues related to the performance of the repository system itself, and the other risk-related issues of lesser importance would be resolved in developing the environmental standard.

The choice of a secondary system performance standard for expressing an acceptable level of risk involves a certain degree of removal from the target level of risk unless the performance standard is expressed directly as the acceptable risk. For example, a dose limit based on an acceptable risk is one step removed from the target risk itself, because the derivation of the secondary performance standard involves only a single model for the risk per unit dose. A limit on releases or environmental concentrations of radioactivity is even farther removed from the target level of risk, because the derivation of the secondary standard also involves models for environmental transport, human exposures, and dose per unit exposure. The farther removed the secondary performance standards are from the acceptable risk, the greater the discrepancy likely will be between the actual risk associated with the performance standards and the target risk itself. This may not be a serious problem when one considers the relative importance of different sources of uncertainty in predicting the risk from geologic waste disposal and the need to demonstrate compliance with the system performance standard, particularly if the models used to derive the secondary performance standard are not likely to underestimate actual risks. However, this idea is worth bearing in mind in deciding how to express a standard for acceptable risk.

If one chooses to express performance standards as numerical requirements, then one must decide upon the numerical values. Again, I believe that the necessity of relying on highly uncertain models for performance assessments and the inability to take remedial action if the repository system should malfunction argue strongly in favor of setting a standard which is considerably more conservative than current standards for other nuclear fuel-cycle activities. Just how conservative a standard should be is an important matter for debate, and societal acceptability of a standard will be an important part of the process. However, one should beware of assuming, for example, that a reduction in a dose limit by a factor of two will reduce the actual risk from geologic waste disposal by the same factor. There are too many qualitative and judgmental aspects involved in assessing repository performance for this line of reasoning to be valid.

4.4 Demonstrations of Compliance

An environmental standard for high-level waste disposal (or any other type of standard) is effective only to the extent that it is possible to demonstrate compliance with the performance objectives contained therein. Again, in my opinion, a key issue for high-level waste disposal is that repository performance can be "measured" only by means of various kinds of predictive models which are highly uncertain. Furthermore, the validity of these models for predicting risks from geologic waste disposal has not yet been demonstrated, even when uncertainties in model input parameters are taken into account.

There are basically two kinds of uncertainties associated with predictions of mathematical models. The first kind involves uncertainties in model output due to uncertainties in model input. Such uncertainties are amenable to a statistical treatment. The second kind of uncertainty involves the possibility that the models may treat some processes incorrectly or leave important processes entirely out of account. Such uncertainties are not, to my knowledge, amenable to quantification and, furthermore, may be an important feature of models for predicting long-term repository performance.

Performance objectives for an environmental standard which are expressed as fixed numerical limits would seem to force the use of mathematical models for demonstrating compliance. If we assume that these models describe the processes affecting repository performance correctly, then the only source of uncertainty arises from uncertainties in the input data. Stochastic analyses based on currently available information give predicted distributions of repository performance which encompass many orders of magnitude,[23,24] and it is this type of distribution of possible outcomes which is to be compared with a fixed performance standard. I believe that the development of repositories at specific sites will not significantly reduce the uncertainties due to model input data because of the limited data which are likely to be obtained in the far-field region. The question then arises as to what part (percentile) of the predicted probability distribution of repository performance is to be compared with the standard. While a numerical specification of the appropriate percentile may not be practicable, some specification which is at least qualitative would be needed. It is because of the need to deal with uncertainties and distributions of possible outcomes that it is difficult for me to understand how the EPA's emphasis on "realistic" projections of repository performance and fixed numerical performance objectives[1] is an effective way of formulating a high-level waste standard. On the other hand, perhaps the use of expressions such as "reasonable expectation" in the standard[1] would allow one to exercise appropriate qualitative and subjective judgments in the decision-making process.

Because of the large uncertainties associated with mathematical models of repository performance and because of the possibility that the models may leave important processes affecting waste isolation out of account or treat them improperly, I believe it is reasonable to require conservative demonstrations of compliance. Conservatism can be expressed in qualitative and judgmental terms, such as requiring "reasonable assurance" that a performance objective will be met.[2] While it may be true that one needs to be careful that requiring conservative performance assessments in conjunction with conservative standards leads to an unreasonable degree of conservatism, I do not believe that this approach will make it impossible to license repositories. The degree of conservatism in the standard itself probably will not be extreme; i.e., the standard will probably define a level of acceptable risk which is no more than two or three orders of magnitude below current levels embodied, for example, in the EPA's uranium fuel-cycle standard.[4] This degree of conservatism will be less than the magnitude of uncertainty associated with "best-estimate" repository performance assessments. Thus, in my opinion, raising or lowering a system performance standard by only a few orders of magnitude does not necessarily make it appreciably easier or harder to demonstrate compliance of a repository with the requirements. The important step is to decide, at least conceptually, what constitutes a reasonable degree of compliance with a fixed numerical standard given the significant uncertainties, both quantifiable and unquantifiable, in repository performance assessments.

The desirability of incorporating conservatisms in waste disposal manifests itself both in standards development and in the licensing process. I would argue that setting conservative standards is an appropriate way of taking into account that the models used in performance assessments might be faulty and that there is no possibility of controlling repository performance after decommissioning. Then, focusing on reasonably conservative parameters in the performance assessment models would be appropriate for the licensing process.

Given the various sources of uncertainty in predicting repository performance, a requirement of multiple barriers is probably the most sensible approach in developing a repository system. The important step, then, is to define acceptable performance of the different parts of the system (i.e., the engineered and natural barriers) in such a way that their performance can be characterized in a reasonable way. I believe that the key to repository licensing is to develop means of being confident that waste disposal is safe without having to be concerned in detail with how safe the system really is. In other words, I do not believe that focusing exclusively on specific numerical performance requirements necessarily makes waste disposal safe compared with focusing on more qualitative goals for important components of a total waste-isolation system. For example, I believe that the specification in the NRC's technical criteria[2] of qualitative conditions that would be either favorable or unfavorable for waste isolation, in addition to the quantitative requirements for certain parts of the system, is quite helpful in providing a reasonable basis for licensing decisions.

4.5 Protection of the Individual or the Population

An environmental standard will be based either on protection of the individual, protection of the population, or some combination of the two. For example, most radiation standards in this country are based on protection of the individual, and the population detriment is considered only in applying the ALARA concept.

I believe that the issue of formulating a high-level waste standard in terms of protecting the individual, the population, or both is not as important for waste isolation as some of the other issues discussed in this report. Nonetheless, high-level waste disposal may have certain attributes which tend to favor some choices over others.

4.5.1 Limitations on individual detriment

In choosing to base a standard on protection of the individual, we are concerned with protecting the so-called maximally exposed individual. This term does not refer to the single individual receiving the largest dose. Rather, it involves a more hypothetical concept involving population subgroups. That is, limitations on individual detriment apply to so-called critical groups of the population, which are groups receiving higher exposures than the rest of the population,[16] and it is the maximum of the average detriment in the critical groups which is to be compared with a standard for protection of individuals.

It is important to distinguish between the maximally exposed individual and the average individual exposure. If one would choose to formulate a standard in terms of protection of the average individual, then this is essentially the same as limiting the population detriment because the two differ only by a constant factor which is the total number of exposed individuals.

Limitations on individual detriment could be specified in a standard by limiting the individual risk directly, by individual dose limits, or by limits on environmental concentrations of radionuclides. Thus, this type of standard would encourage waste disposal schemes which dilute radioactivity in the biosphere.

Basing a standard on protection of the individual has the possible advantage that it directly expresses concern for each person, and this could enhance societal acceptability of a standard. This choice also provides an implicit limitation on the population detriment; i.e., the population detriment cannot exceed the detriment to maximally exposed individuals times the number of individuals in the population. The converse is not necessarily true; i.e., specifying a limitation on population detriment does not necessarily limit the detriment to maximally exposed individuals. However, for normal operations of a waste repository, I believe that the doses to the maximally exposed and average individuals are not likely to differ by many orders of magnitude, and individual dose rates are not likely to vary significantly over a person's lifetime. This follows from the expectation that normal releases of radioactivity via groundwater flow will be quite constant over an individual's lifetime and will become widely dispersed in the environment before radioactive decay occurs, due to the long half-lives and mobility in the environment of the radionuclides which would be released. Therefore, if the limits on population detriment for normal operations of a waste repository were set sufficiently conservatively, then the critical groups probably would also be protected. This may not be the case for unexpected releases which are acute and localized, such as releases via human intrusion into contaminated groundwater near the repository, because a few individuals could receive doses which are much larger than the dose to an average individual. Thus, limitations on individual detriment for such special exposures may need to be specified separately from the limits on expected exposures of off-site populations.

If one decides to set limits on individual dose, as in the EPA's uranium fuel-cycle standard,[4] then I believe that one should take into account that a given dose to different body organs gives different risks of cancer induction. The use of "total body" or "whole body" dose as a measure of detriment is no longer used by the ICRP. Rather, the ICRP recommends a risk-based effective dose equivalent which is a weighted average of dose equivalents to several body organs.[16] Thus, the EPA's approach[4] of specifying three different annual dose limits — 25 mrem to whole body, 75 mrem to the thyroid, and 25 mrem to any other organ — is logically weak because these doses do not correspond to the same expected cancer risk.

If one chooses to limit individual detriment for normal operations of a waste repository, then I believe that the dose limit for the maximally exposed individual should be set no higher than a value which would be acceptable to the average individual, because many persons will likely receive doses at or near those for the critical population groups. Because of the expected weak time dependence of dose rates over an individual's lifetime, it makes little difference if a standard for normal operations specifies an annual or a lifetime dose limit.

4.5.2 Limitations on population detriment

Basing a standard on limiting the population detriment, rather than explicitly protecting the maximally exposed individual, has been an infrequent practice in regulating nuclear activities. As described in Section 3.4, this is not the approach that is recommended by the ICRP.[16]

Limits on population detriment could be expressed as limits on the number of health effects or on the incremental risk to an average individual, limits on population dose or dose to an average individual, or limits on quantities of radionuclides which can be released to man's exposure environment. Thus, this type of standard would encourage waste disposal schemes which isolate the radioactivity from the biosphere.

Setting limits on population detriment may present a potentially significant advantage for high-level waste disposal compared with limiting individual detriment, when one considers performance assessments and demonstrations of compliance of a repository with a standard. If all individual detriments are sufficiently low that nonstochastic radiation effects would not occur, then the population detriment depends only on the total amounts of the different radionuclides that are released to man's exposure environment and are essentially independent of the spatial and temporal variability of the releases. Predictions of the total amounts of activity released may be much more credible than the predictions of release rates and environmental concentrations which are required for assessing the detriment to maximally exposed individuals. It also seems to me that natural analog models are more easily applied to repository performance assessments if limitations on population detriment are used in a standard, because analog models usually involve a physical system in which we observe the cumulative effects of processes integrated over time rather than the time-dependence of the processes and their effects.

Another possible advantage of limiting population detriment in a standard arises from the expectation that releases of radioactivity from normal operations of a waste repository likely will occur over long periods of time. Thus, one conceivably could specify limitations on the population detriment on the basis of the detriment that would be acceptable to our generation if all future impacts were to occur in our generation's lifetime. The detriment to any future generation from normal operations then would probably be much less than this.

A possible disadvantage of a standard based on population detriment arises from the customary assumption of a linear, no-threshold dose-response relation in assessing the detriment. In my opinion, this assumption presents a fundamental problem when a given detriment is obtained by accruing very small individual detriments over very large populations, which likely will be the case in assessing the consequences of routine releases of long-lived radionuclides in high-level waste. It is difficult for me to accept, for example, that giving 10^{10} persons a dose of 1 mrem each is worthy of the same concern as giving 10^{6} persons a dose of 10 rem each, even though the linear, no-threshold hypothesis predicts the same number of radiation-induced cancers in either case. Individuals usually are concerned more with their own risk, and the expected individual risk differs by a factor of 10^{4} in these two hypothetical cases. If one chooses to use the linear, no-threshold hypothesis in setting radiation standards or in evaluating population risks from low-levels of exposure, then I believe it must be recognized that this is primarily a mathematical exercise with little scientific basis and that the actual risks may be quite different from, and probably much less than, the predicted risks.

The logical difficulties with using the linear, no-threshold dose-response hypothesis in setting limits on population detriment, or in using population detriment to evaluate ALARA, possibly can be avoided by using the concept of _de minimis_ dose or risk for individuals.[37] A _de minimis_ level corresponds to the largest dose or incremental risk which would be of no concern to an individual. In essence, the _de minimis_ approach sets a level of risk which is effectively zero, i.e., a threshold for the dose-response relation, because it is a risk that is too low to be of concern. Thus, the concept of _de minimis_ dose or risk can be used to establish a cutoff for accruing calculated effects among individuals in the exposed population. This would avoid the problem of possibly obtaining a significant number of predicted health effects from insignificant individual detriments. An example of the use of a _de minimis_ dose in applying the ALARA principal to waste disposal is given in Section 5.3.

A practical difficulty with estimating health risks in a population is that one must assume a relation for the cancer risk as a function of dose. The cancer risk is highly uncertain at low dose levels, and it may be difficult to establish consensus on a conservative upper limit for the risk from internal irradiation by alpha particles. This problem perhaps could be avoided by basing the standard on acceptable dose or exposure to an average individual rather than acceptable risk. Again, it would be desirable to avoid unresolvable arguments over just how safe an activity would be if the standard were met.

4.5.3 Approach in the proposed EPA high-level waste standard

In resolving this issue, the EPA has chosen to base its proposed high-level waste standard[1] on limiting the population detriment only, rather than the usual practice of limiting individual detriment. The EPA's choice was based on (1) the difficulty of applying a limit on individual detriment to certain types of accidental releases (e.g., human intrusion via drilling) for which only a few individuals could receive doses larger than any reasonable limit and (2) the increased difficulty in demonstrating compliance of a repository with individual exposure limits compared with demonstrating compliance with cumulative radionuclide release limits. Even though the EPA's approach involves use of the linear, no-threshold hypothesis for estimating health risks from releases of radioactivity to the biosphere, I believe that limiting population detriment is a more suitable approach for a high-level waste standard than limiting individual detriment, primarily because of the greater problems associated with demonstrating compliance with a limit on individual detriment.

4.6 Application to Normal and Accidental Occurrences

An important and potentially controversial issue for high-level waste disposal is whether the environmental standard should apply to normal or expected occurrences only (e.g., releases via groundwater flow through a repository located in hard rock) or to accidents and inadvertent human intrusion as well. The proposed EPA standard[1] clearly intends to include accidental releases.

One argument in favor of including accidents within the domain of the standard is that this would force a certain completeness of performance assessments and would result in a greater public acceptance of both the standard and the licensing decisions based on the standard. On a more practical level, there are some processes that could lead to releases of radioactivity which cannot be categorized clearly as either normal or accidental. For example, a shaft-seal failure or some failure of the natural geologic system which allows water to reach the waste would have to occur for any radioactivity to be released from a salt repository within 10,000 years.[21] Such events, while they would be regarded as accidental, are clearly important to a performance assessment in this case.

A difficulty with including accidents explicitly in a quantitative performance standard is that both the probability of occurrence and the radiological consequences for some types of events (e.g., volcanic eruptions) are likely to be highly uncertain and contentious. I also believe that a standard should consider accidental events only if the radiological consequences of the released radioactivity are likely to be greater than other radiological or non-radiological consequences. For example, an analysis of a volcanic eruption through a repository has suggested that the radiological impacts from the waste will be less than the impacts from the natural radioactivity in the volcanic dust if the time delay between waste emplacement and the eruption is greater than about 2,000 years.[38] This analysis does not include the non-radiological impacts of the eruption, and these are probably the most important since the 1980 Mount St. Helens eruption was the example chosen. Therefore, since the intrinsic radiological hazard of high-level waste decreases significantly with time beyond 2,000 years,[5,39] the analysis indicates that volcanoes should be of concern for repository performance assessments for only a few thousand years at most. As another example, it seems clear that the non-radiological impacts associated with uncovering a repository via meteorite impact or glaciation would be so great as to render inconsequential by comparison any radiological impacts from the waste itself. This type of reasoning leads to the general conclusion that radiological impacts from waste disposal should not be evaluated in isolation from an evaluation of other radiological or non-radiological impacts.

Inadvertent human intrusion is a particularly important and controversial type of accidental event. In the EPA's analyses of repository performance, for example, most of the radiological impacts result from drilling-intrusion scenarios.[21] The proposed EPA standard assumes that active institutional controls can prevent inadvertent intrusion for 100 years after repository decommissioning and that passive institutional controls can substantially prevent intrusion for an unspecified period of time thereafter.[1] There is certainly a belief by some that a repository marker system combined with information transfer to future generations can reduce the probability of inadvertent intrusion to insignificant levels for thousands of years.[40-42]

It is difficult to envision an effective way of regulating human intrusion except by taking reasonable measures to reduce the possibility of an intrusive event. I do not believe, for example, that setting a dose limit for human intrusion would be particularly effective, because it is difficult to limit the dose to an individual if an intrusion occurs. Furthermore, the critical population group in this case consists of only a very few individuals, and it may not be cost effective to limit their potential exposures when the primary focus should be on protecting the general population.

It may be reasonable to include in the category of expected occurrences the drilling of wells into shallow aquifers away from the repository, even though the probability of such an event may be less than unity. But it does not seem reasonable to me to assume, as did the EPA,[21] that such drilling would occur with significant probability at any site. This assumption would effectively short-circuit the natural geologic barriers even for well chosen sites and negate much of the fundamental rationale for geologic waste disposal. Rather, in my opinion, the probabilility of well drilling into contaminated aquifers should be taken into account in performance assessments on a site-specific basis.

In Section 4.3, we discussed the idea that formulating an environmental standard basically involves deciding which issues are to be resolved in setting a standard and which are to be relegated to the licensing process. I believe that this line of reasoning is also valid in dealing with the question of normal and accidental events. It seems reasonable to me that accidents which can be distinguished clearly from normal occurrences can be excluded from a generally applicable environmental standard, because the risks from such accidents are highly site specific and because the evaluation of accident scenarios is quite judgmental and difficult to quantify. It is clearly proper, however, that accidents be considered in the licensing process. An example of a standard of this type of considered in Section 5.4. The alternative would be to write a different type of standard for accidental releases than for normal occurrences or to express the standard directly in terms of a limit on the risk to individuals.

4.7 Time Limit for Regulating Repository Performance

The radionuclide release limits in the proposed EPA standard[1] apply only to the first 10,000 years after disposal. The EPA argues that this time limit is sufficiently long to encourage the selection of sites where geochemical retardation of radionuclides in groundwater flow through the host rock will be an effective barrier, but sufficiently short that natural geologic processes are reasonably predictable.

Regardless of the reasoning used to justify a time limit for a high-level waste standard, it seems to me that choosing a value is somewhat arbitrary. For example, some geologists have suggested that significant effects on repository performance due to natural geologic processes are not likely to occur for at least 100,000 years,[43] rather than the shorter time period chosen by the EPA.[1]

Two other possible bases for setting a time limit for a standard are (1) a comparison of the intrinsic ingestion hazard of high-level waste with that of an equivalent amount of unmined uranium ore and (2) a discounting of future detriment with time. The first is an attractive possibility if one believes that buried waste is less likely to be transferred to the biosphere than unmined ore at any time after disposal. However, the waste/ore-body comparison also yields a somewhat arbitrary time limit because of uncertainties in the data used to convert intake of a unit quantity of a radionuclide to dose and health risk, especially for the important artificial actinide elements. For example, early comparisons of high-level waste and uranium ore clearly suggested that the intrinsic ingestion hazard of the waste is less than that of uranium ore after only a few thousand years or less.[32,39,44] However, more recent dosimetric data give a less pronounced decrease in the intrinsic ingestion hazard of the waste with time; thus, the hazard is reduced to that of uranium ore only after 10^4-10^5 years, depending on the type of waste assumed.[39] The comparison of the intrinsic hazard of high-level waste and uranium ore could change still further if recommended changes in gastrointestinal absorption for environmental plutonium and neptunium[45,46] were adopted.

The use of discounting of future detriment[47] with time to set an effective time limit is usually accomplished by means of a constant discount rate. This approach can be very effective in limiting the future time period of concern. For example, a discount rate of only 0.1% per year leads to a vanishingly small detriment after about 10,000 years. In using discounting of future detriment to set a time limit, it must be recognized that the choice of a discount rate is largely arbitrary. (The use of an explicit time limit as in the proposed EPA standard[1] is a particular form of discounting in which the discount rate is a sharply discontinuous function of time.) Furthermore, I am not aware of any logical support for this approach that our present society likely would accept.

Some type of time limit clearly is desirable if a standard is based on limiting population detriment or if population detriment is used in applying the ALARA principle, unless a de minimis dose or risk for the average individual is used to truncate the calculation in time. Otherwise, one is forced to assess the population detriment until every last radionuclide in the waste has decayed, and, in my opinion, this is a largely meaningless exercise. I believe that a time limit for assessing future detriment can be defended if it is reasonable to expect that the detriment neglected would be less than the detriment during the time period of concern or if the detriment neglected would still be considered insignificant.

The need to choose a time limit which is somewhat arbitrary can be avoided by formulating the performance standard in certain ways. For example, a standard based on limiting the detriment to maximally exposed individuals or on comparing the radiological consequences of high-level waste disposal with those of unmined uranium ore need not involve a time limit. In either case, one estimates the maximum consequences from waste disposal regardless of when they are expected to occur and compares them with the standard. In essence, however, this approach would also establish a time limit implicitly, because the intrinsic ingestion hazard of the waste decreases monotonically with time, but the advantage is that the time limit would be related to some reasonable perception of risk rather than imposed arbitrarily.

In general, I believe that the issue of a time limit should be resolved in such a way as to minimize the apparent degree of arbitrariness or the degree to which the detriment neglected might be perceived as more significant than the detriment taken into account. Otherwise, there may be considerable contention over the time limit and the arguments won't, in my opinion, have very much relevance to the safety of waste disposal.

4.8 Specification of Conditions for Performance Assessments

It is likely that a high-level waste standard will need to specify, either directly or indirectly, certain conditions to be assumed in evaluating repository performance. Perhaps the most important of these involves prescribing the boundary of the accessible environment (see Section 3.6). I would reiterate my belief that this issue is too site specific and too important to the evaluation of risks from geologic waste disposal to lend itself to a meaningful generic prescription, as has been done in the proposed EPA standard.[1] Rather, it would seem more sensible for the standard to set guidelines for defining the accessible environment but to leave the details of its specification to the licensing process. The definition should bear some relationship to the likelihood of human exposures at actual sites.

For some formulations of a standard, one may want to specify certain other conditions to be assumed in evaluating human exposures, such as dietary habits or the number and physical locations of exposed individuals. Even though these are also site-specific considerations to some extent, I believe it could be reasonable to specify these conditions generically in a standard. As discussed in Section 4.3, I do not believe that variations in human exposure patterns with location of a repository are likely to be significant compared with the variations between sites of repository performance itself.

5. PROPOSED HIGH-LEVEL WASTE STANDARDS

5.1 Introduction

This section presents a review of some published proposals for a high-level waste environmental standard. The proposals include those of Maxie et al.,[29] Ross,[19] the Swiss Federal Office of Energy,[48] and Hill.[49] The discussion particularly emphasizes the various approaches of the proposed standards for resolving the issues raised in Sections 2 and 4 of this report.

5.2 General Criteria Proposed by Maxie

The paper by Maxie et al.[29] provides a general overview of suggested criteria for high-level waste disposal. Of particular interest to this report is one of the three proposed approaches for determining the acceptable level of risk. This approach is termed the "three-stage ore-body comparison" and is somewhat similar to the ore-body comparison discussed in Section 4.2.3. The difference is that instead of comparing directly the risks from high-level waste disposal with those from an equivalent amount of unmined uranium ore, a comparison that requires complex and highly uncertain models for both parts, a comparison is made for each of three separate aspects: (1) stability of the waste form/ore body weighted by the relative toxicities of the two, (2) integrity of the host medium, and (3) isolation from the biosphere. If the proposed repository were judged to be better than a reference uranium ore body in each of these three aspects, then the repository would be judged acceptable without requiring a more comprehensive analysis.

In my opinion, the line of reasoning embodied in the three-stage ore-body comparison is useful in three respects. First, the multiple-barrier or defense-in-depth approach which is familiar from repository design considerations is applied to standards setting itself, and this would provide increased confidence that the overall safety goal will be met. Second, a finding of safety can be reached without concern for what the actual risks may be. Third, the basis for acceptable risk is a reference uranium ore body, and I believe that this is a particularly strong line of reasoning. It is unfortunate, however, that the reference ore body to be used for comparative purposes was not defined in the paper.

The other general criterion proposed by Maxie et al.[29] which is of interest here is that the ALARA principle must be applied to waste disposal with no discounting of future risk. I have previously indicated in Section 3.4 my reservations over the application of ALARA to high-level waste disposal, except in the site-selection process. It should also be noted that the use of an ore-body comparison as the basis for a standard allows both the standard and ALARA to be applied without explicitly specifying a time limit.

5.3 Criteria Proposed by Ross

A detailed set of disposal criteria for high-level waste has been presented by Ross.[19] The important features of the proposed criteria are listed below.

1. There should be no releases of radioactivity to the accessible environment for 500 years.

2. In the absence of human intervention and the construction of water wells, the fifty-year accumulated effective dose equivalent to the maximally exposed individual at any time within 100,000 years shall (a) be expected to be less than 50 mrem, (b) be quite unlikely to be more than 1 rem, and (c) not exceed 100 rem in any credible circumstances.

3. In the absence of human intervention, the waste shall be quite unlikely to contaminate water which could be withdrawn through a well from any aquifer in the accessible environment beyond the

level acceptable for drinking water in the NRC rulemaking 10 CRF 20 (Ref. 17) at any time within 100,000 years.

4. The wastes shall be located in a place relatively unlikely to attract human intervention, and the location shall be marked and documented as well as reasonably achievable.

5. Population exposures should be reduced whenever it is reasonable to do so, taking into account social and economic factors. However, a rigorous cost-benefit analysis is not the basis for this criterion. In estimating population detriment, the following considerations apply: (a) the time over which population exposures are evaluated should not be unbounded but should be limited by taking into account the potential hazards of the unmined uranium ore; and (b) population dose should not be used without consideration of dose rates, and average individual doses greater than 0.1 mrem/y should be given the greatest consideration.

On the whole, I believe that these criteria represent a reasonable and thoughtful proposal. Specific comments and opinions on some of these provisions are presented below.

In limiting the detriment to maximally exposed individuals in the second and third criteria, the proposal follows the general recommendations of the ICRP.[16] The primary reasons given for this choice are, first, enhanced societal acceptability by assuring that no individual is placed at severe risk and, second, the belief that it is easier to demonstrate compliance with an individual dose standard than with a standard for population detriment because of the difficulties in predicting future population densities and water usage rates. (The recent National Academy of Sciences study on waste disposal[50] also rejected a standard based on population dose for essentially the same reasons.) With regard to the second argument presented by Ross, it should be clear from the discussion in Section 4.5 that I do not agree. In my opinion, predictions of total activity released, which are needed for estimating population detriment, are likely to be significantly more credible than the predictions of release rates and environmental concentrations which are needed for estimating individual detriment. It is possible that the proponents of a standard based on limiting individual detriment do not appreciate that, for the long-lived radionuclides which are likely to be released to the biosphere, the short-term, first-pass exposures in the vicinity of the release location may be less important than the long-term exposures over a wide geographical area.

The manner in which the individual dose limits are expressed in the second criterion has three strengths. First, the use of three different dose levels requiring different levels of assurance is reasonable in light of the very large range of predicted radiological consequences from waste disposal and the importance of releases with low probability but severe consequence for the expectation value of risk. This three-tiered dose limitation system clearly allows for the inclusion of accidental as well as normal occurrences. The alternative of using a single dose standard could lead to a repository which is designed against smaller but much more likely releases of radioactivity. Second, the levels of assurance that apply to the different dose limits are described qualitatively, not as numerical probabilities. (Oston et al.[51] have suggested that "expected" can be interpreted as a probability between 0.5 and 1, "quite unlikely" as less than 0.01, and "incredible" as less than 10^{-4}, but these probabilities are intended to serve only as guidelines.) The reason given for not imposing numerical requirements on probabilities is that both the probabilities and the consequences of various release scenarios cannot be assessed in a fully quantitative fashion. The use of qualitative statements about probabilities explicitly recognizes the subjective and judgmental nature of decisions about the safety of waste repositories; i.e., the bases for decisions will be similar to those used in trials and lawsuits where qualitative levels of assurance are quite familiar. (I strongly agree with formulating a standard so that the judgmental aspects of decision making are emphasized, and I believe that this is an essential attribute of an effective high-level waste standard.) Finally, the dose limits in the second criterion are conservative. The 50-mrem lifetime dose limit for expected occurrences is a small fraction of variations in natural background; the 1-rem lifetime limit for quite unlikely events corresponds approximately to the standard deviation in natural background; and the 100-rem lifetime limit for any credible events corresponds approximately to current occupational dose limits and eliminates nonstochastic radiation effects. The three dose limits correspond to a lifetime risk to maximally exposed individuals of only about 10^{-6}, which is about two orders of magnitude less than the acceptable risk implied by the EPA's uranium fuel-cycle standard.[4]

The separate (and higher) dose limit for exposures via well drilling in the third criterion is justified on the basis that (1) well-water doses would very often control determination of whether a single dose limit would be met and this would effectively short-circuit further dilution effects prior to discharge of the waste to surface waters, (2) water from aquifers does not enter the food chain without human action and wells are unlikely to be drilled near a repository if knowledge of the repository location is maintained, and (3) a standard for aquifer contamination only would introduce a bias in favor of fast-flowing or saline aquifers and would likely increase discharges of radioactivity to surface waters. I would also note an additional justification that well drilling probably would affect only a few individuals. This separation of well-drilling scenarios from other types of releases which do not involve human intervention strikes me as quite reasonable.

In the fifth criterion, the "reasonable" rule for reducing population exposures is intended to be considerably less stringent than the normal ALARA requirement of "as low as reasonably achievable," in order to achieve a more even-handed balancing between radiation protection and other societal goals. The primary aim of this criterion is to ensure that population dose is considered in choosing the disposal system. The criterion also recognizes that quantitative predictions of population dose cannot be made with high confidence, so that a rigid cost-benefit analysis is not reasonable. In evaluating population dose, the admonition to consider the hazards from unmined uranium ore and individual dose rates which are above an essentially de minimis level effectively imposes a finite time period for concern and largely eliminates the problem of accruing trivial individual doses over very large populations in estimating population detriment.

The proposed criteria specify a time limit of 100,000 years for assessing compliance with the individual dose limits. This value is a compromise based on the following considerations: (1) it is questionable that many geologic processes can be predicted reliably beyond several tens of thousands of years; (2) after a few million years, the waste consists of little more than naturally occurring ^{238}U and its daughter products and, before mining, these natural substances were closer to the earth's surface than a waste repository; and (3) the intrinsic ingestion hazard of the waste is about the same as that of unmined uranium ore at approximately 100,000 years and declines only slowly thereafter. Although peak releases may occur after 100,000 years, they would be limited indirectly by imposing standards prior to that time. Furthermore, the admonition to reduce population exposures extends beyond 100,000 years. These arguments seem reasonable to me, but I would remark again that an explicit time limit is not necessary when a standard is based on limiting individual detriment, and that the time limit is still somewhat arbitrary.

In performing assessments to demonstrate compliance with the limits on individual dose, the proposed standard recommends that parts of the calculation involving environmental transport and human exposures be standardized to a so-called "reference environment." I have previously commented in Section 4.8 that this is reasonable because of the relative insignificance of the potential variability in these parts of an overall performance assessment.

5.4 Criteria Proposed by the Swiss Federal Office of Energy

Niederer[48] has presented the protection goals for radioactive waste disposal which have been developed by the Swiss Federal Office of Energy. There are only two protection goals which are regarded as absolute requirements. Criteria to accompany the protection goals, which are regarded as less binding rules of judgment to be used for planning and evaluation, have not yet been developed.

The first protection goal is that radionuclide releases from a sealed repository to the biosphere from "reasonably expectable processes and events" should at no time result in individual doses exceeding 10 mrem/y. This goal is augmented by four additional safety features: (1) the dose limit must be small compared with doses from natural background radiation and with variations in doses due to differences in individual living habits; (2) the dose limit applies to the most unfavorable of the expected events, so that the doses normally will be well below this limit; (3) the dose calculations for evaluating compliance must be based on conservative assumptions which take into account uncertainties in long-term repository performance; and (4) the risk from a repository must be reduced as far as reasonably achievable within the state of science and technology.

The second protection goal has two requirements. The first is that a repository must be designed so that at any time it can be sealed within a few years. The second is that after sealing of a repository it must be possible to forgo all safety and surveillance arrangements. The latter requirement does not rule out retrieval of the buried wastes, but it expresses the belief that retrievability should never be considered as the safety measure of last resort in case anything goes wrong with a sealed repository. Rather, the waste should not be sealed in a repository unless safety can be reasonably assured in advance.

Perhaps the most interesting aspect of the Swiss protection goals is the classification of processes and events into those which are reasonably expectable and those which are regarded as exceptional. Events which are exceptional need not meet the dose limit in the first protection goal, but they are subject to the requirement that the risk be reduced as far as reasonably achievable. The paradigm of a reasonably expectable event is the so-called normal case, which is the release scenario involving water intrusion, leaching of the waste, and radionuclide transport to the biosphere via groundwater flow. This scenario also includes the continuous changes in parameters which are expected to take place as a result, for example, of thermal effects from the waste and of natural geologic processes. Any other event may then be considered as a perturbation on the normal case.

The need to classify events as reasonably expectable or exceptional manifests itself with incidents which could lead to doses above the 10-mrem/y limit, but the protection goals do not given a rigorous definition of the two types of events. As an example, however, Niederer[48] states that an event could be classified as exceptional either if it has a low probability of occurrence or if the primary effects of the event are greater than the radiological consequences of the waste released by the event. The protection goals recognize that inadvertent human intrusion is an event which is particularly difficult to classify as reasonably expectable or exceptional.

The protection goals explicitly acknowledge that the classification of events is open to judgment, and the site itself is recognized as an important factor in making this judgment. Thus, decisions on the classification of events are basically relegated to the licensing process, where all events must be considered as part of the safety analysis. In my opinion, this type of subjectivity is very desirable in a standard, because it gives the licensing authorities an essential degree of flexibility in reaching decisions and it allows for differences in interpretations as the state of science and technology advances.

Two other points concerning the Swiss protection goals are noteworthy. First, as we have discussed in Section 4.7, a standard based on limiting the detriment to individuals need not impose a time limit for determining compliance with the standard. Second, the dose limit of 10 mrem/y is based in part on the current Swiss standard for nuclear power plants of 20 mrem/y and certain arguments which support a lower limit for waste disposal. The discussion by Niederer[48] gives the impression that lowering the dose limit by a factor of two is expected to establish a lower level of risk from waste disposal than from nuclear power plants. I have previously argued in Section 4.3 that this type of reasoning is not valid. I do not believe that there is one iota of difference between a 10-mrem/y and a 20-mrem/y dose limit with regard to the actual risks that will result from a repository that is judged to be in compliance with the standard, because of the large uncertainties in evaluating repository performance and the highly subjective nature of such evaluations.

5.5 Criteria Proposed by Hill

Hill[49] has proposed radiological criteria for high-level waste disposal which are presumably being considered by the U.K. National Radiological Protection Board. The proposal is based on the following principles.

1. Radiological protection criteria for waste disposal should be based on risk, i.e., consideration of probabilities of events as well as consequences.

2. Maximum risks to individuals should not at any time exceed a specified level.

3. The total risk to populations should be ALARA, economic and social factors being taken into account.

The choice of formulating a standard in terms of a limit on risk, rather than a limit on dose as recommended by the ICRP,[16] is based on the reasoning that a dose standard is impractical when one must consider low-probability, high-consequence events which could lead to doses above any selected limit. In such a standard, normal and accidental events need not be segregated but can be considered together. As discussed in Section 5.3, Ross[19] addressed this problem by formulating a three-tiered dose-limitation standard based on subjective judgments of the probability of occurrence of different dose levels. Hill's approach also seems reasonable, except the problems remain that (1) probabilities of events must be evaluated quantitatively in order to judge compliance with a quantitative risk limit, (2) there is no lower cutoff in probability for ignoring highly improbable events, and (3) there is no provision for taking into account consequences of low-probability events other than release of the waste.

Hill[49] recommends a risk limit for maximally exposed individuals of 10^{-5} per year. This limit is chosen because it is believed to be a risk that would be accepted by most members of the public, and because it is reasonably consistent with the ICRP dose limit for members of the public of 500 mrem/y for exposure situations which are virtually certain to occur.[16] For application in the U.S., however, I believe that a practical upper limit for acceptable risk from waste disposal would be dictated by current dose limits in the EPA's uranium fuel-cycle[4] or drinking water[25] standards, which are considerably less than the ICRP recommendation. Thus, a risk limit greater than about 10^{-6} per year would be difficult to justify even if one does not believe that additional degrees of conservatism should be included in a high-level waste standard. An additional problem with Hill's risk limit is that the public will not necessarily accept the same level of risk from waste disposal as from other, more familiar activities.

With regard to the question of establishing conservative standards and requiring conservative performance assessments, it is Hill's belief that a standard should not be set conservatively if uncertainties in parameter values are explicitly taken into account in the calculations used to demonstrate compliance. To make allowance for uncertainties in performance assessments in setting a dose or risk limit as well is believed to be unreasonable, since it would be "double counting" and would lead to a limit which is too restrictive. Hill's arguments notwithstanding, I still believe that incorporating a degree of conservatism in the standard itself is reasonable. As we have discussed in Section 4.4, the issue here is how much of the desired conservatism should be in the standard and how much in the demonstrations of compliance. I believe that a standard is the better place to take into account that the models used in performance assessments could, in a general way, leave important processes and parameters out of account and, thus, underestimate actual risks even if models which are believed to be conservative are used. It also has not been demonstrated that conservative standards coupled with a requirement of conservative demonstrations of compliance will result in an inability to license repositories. To my way of thinking, the issues involved in determining if waste disposal is safe enough will boil down to those of subjective judgment regardless of how conservatively standards are expressed or repository performance is evaluated.

5.6 Summary of Proposed Standards

It is evident from the discussions of the proposed EPA standard[1] in Section 3.6 and elsewhere and from the descriptions of other proposed standards in Sections 5.2-5.5 that several different approaches have been taken in attempting to resolve the various technical issues of importance to the development of standards for high-level waste disposal. For example, the various proposals differ significantly in their approaches to the following:

[1] determining a basis for specifying the acceptable level of risk (e.g., best available technology, risks from unmined uranium ore, natural background radiation, and standards for other radiation-related activities);

[2] the specific performance objectives which express the level of acceptable risk (e.g., cumulative release limits of radionuclides to the accessible environment, direct comparisons of high-level waste with unmined uranium ore, annual or lifetime dose to maximally exposed individuals, and annual incremental risk to maximally exposed individuals);

[3] the degree of conservatism embodied in the standard (e.g., the proposal of Hill[49] represents a lifetime risk to a maximally exposed individual which is about four orders of magnitude greater than the risk to an average individual in the U.S. embodied in the proposed EPA standard[1]);

[4] limiting individual or population detriment;

[5] the inclusion of accidental (unexpected) as well as normal (expected) occurrences;

[6] the degree of assurance which is required for demonstrations of compliance and the manner in which uncertainties are to be taken into account;

[7] incorporation of a time limit for application of the standard (e.g., 10,000 years, 100,000 years, an implicit time limit determined by the basis for acceptable risk, or no time limit);

[8] the manner in which the ALARA principle is to be applied; and

[9] the extent to which certain conditions to be assumed in assessing compliance are specified.

To my way of thinking, the variety of thoughtful approaches to standard setting discussed in this report clearly indicates the subjective nature of the exercise and the likelihood that there are no clearly preferable choices on technical grounds alone for resolving the various technical issues which must be considered in developing a standard.

6. CONCLUDING REMARKS

This report concludes with a few summary remarks which represent the personal opinions of the author.

The purpose of a high-level waste standard is to establish an acceptable level of risk and to provide a framework for ensuring that waste disposal will indeed be safe. In a sense, this purpose has two different aspects. The first is to ensure that sound technical arguments will be used in deciding whether waste disposal is safe, and the second is to convince the public that this is indeed the case. I would caution that these two objectives may not be entirely compatible. For example, I believe on technical grounds alone that the formulation of a system performance standard in terms of detailed quantitative requirements doesn't necessarily ensure safe disposal. My reasoning is that there are important aspects of long-term repository performance that are poorly understood and difficult to quantify. On the other hand, a numerical standard may be necessary for convincing the public that a proper decision has been made.

If a high-level waste standard is formulated in terms of detailed, quantitative requirements, then there will be strong incentives for developing complex mathematical models of repository performance in order to demonstrate compliance with the standard. I believe there is a danger that the use of these models for this purpose will give the misleading impression that performance assessment is an objective and quantitative science, and that there can be complete confidence in the model predictions for licensing purposes. The danger is that any decisions that appear to be based primarily on these calculations may not be able to withstand the vigorous challenges to the validity of the models which will inevitably occur in licensing, and the public may lose confidence in the entire decision-making process. I would prefer that mathematical models be used only if they are accompanied by candid admissions of the assumptions involved and the possible limitations on the validity of the results. I also believe that such models should be used only as one of several alternative lines of reasoning in reaching decisions on the safety of waste disposal.

The following comments pertain to some of the technical issues which must be considered in developing a high-level waste standard.

1. The acceptable level of risk (whether it be a numerical requirement or something more qualitative and subjective) should be set conservatively compared with current standards for other nuclear activities. The standard should also be related to other risks which are unavoidable, such as those from natural background radiation and unmined uranium ore.

2. The manner in which an acceptable level of risk is expressed could be important. For example, I would not base a standard on an acceptable number of health effects. Rather, I would express the same level of risk in terms of incremental risk to an average individual. While the risk in either case would be the same, public perception of that risk could be quite different. In this example, a limit on health effects might be interpreted as a license to kill a certain number of people, and a standard may be attacked on those grounds even when the incremental risk associated with that number of fatalities is very low.

3. A standard should allow for demonstrations of compliance which can provide "reasonable assurance," to use the NRC's language,[2] that the requirements are met, taking into account uncertainties in the models used to assess repository performance. Such a qualitative requirement acknowledges the importance of subjective judgments in decision making.

4. Basing a standard for normal operations of a waste repository on protection of the population is probably preferable to limiting the detriment to maximally exposed individuals, primarily because of the greater difficulties associated with demonstrations of compliance for a standard based on individual detriment. For some special circumstances, however, such as the drilling of wells into contaminated aquifers, a standard which limits individual detriment may be more appropriate.

5. If a standard is based on acceptable risk, then it seems reasonable that the standard must consider accidental as well as normal occurrences, including inadvertent human intrusion. But I don't have a strong feeling for how this can best be done, except for my belief that imposing numerical requirements on both probabilities and consequences, as in the proposed EPA standard,[1] could result in a standard which is difficult to implement and, thus, is ineffective. I rather like the approach of the Swiss protection goals,[48] which recognize that the risks from accidental events are highly site specific and require only that these risks be considered in licensing and judged acceptable. Perhaps a multi-tiered dose limitation standard,[19] in which different dose limits are associated with different subjective and nonquantitative probabilities of occurrence, would be effective. A third reasonable alternative may be to express the performance requirements directly in terms of acceptable risk,[49] provided that low-probability, high-consequence events are accorded special treatment. I also believe that standards for low-probability, disruptive events should take into account both the radiological and the nonradiological impacts which are not associated with the waste itself.

6. A standard should be written so that it avoids consideration of trivial effects, e.g., the estimation of population dose by accruing very small individual doses over very large populations.

7. Strict application of the ALARA principle and cost-benefit analysis does not appear to be appropriate for high-level waste disposal. One can encourage reduction in risk without the use of such a formal but highly dubious exercise. However, some type of ALARA requirement may be appropriate for site selection.

8. An explicit specification of a time limit for a high-level waste standard should be related to some acceptable level of risk, such as the risk from unmined uranium ore. The time limit in the proposed EPA standard[1] appears to be rather arbitrary because it

isn't related clearly to the potential risk from waste disposal. Some methods of formulating a standard involve implicit time limits, but the advantage is that the limit is not imposed arbitrarily.

9. The definition of the boundary of the accessible environment should represent a reasonable boundary for likely human exposures. Thus, this boundary is probably site specific and should not be arbitrarily defined in a generic standard.

I have emphasized throughout this report that one of the consequences of any particular standard for high-level waste disposal is that it determines which performance-assessment issues will be debated in standard setting and which issues will be relegated to the licensing process. I would reiterate my belief that licensing should focus on the performance of the engineered and the natural geologic barriers and that a standard should resolve issues over the radiological consequences per unit release of activity to the biosphere.

I believe that the most effective way to obtain a reasonable finding that waste disposal is safe is to require a system of multiple engineered and natural geologic barriers. It may not be necessary to require that either the engineered or the natural barriers by themselves provide the requisite waste isolation, but each barrier should be required to contribute significantly to overall system performance. In this way, performance assessments can focus on those components of the total repository system which are important for waste isolation and for which there is a reasonable chance of judging, at least qualitatively, that the components will perform as required. This approach would allow a finding of confidence in the safety of waste disposal without concern with what the overall risk might actually be.

Because I believe that judgments on repository performance will involve a high degree of subjectivity, I do not believe that the imposition of detailed and rigid numerical performance requirements necessarily will make waste disposal safe. Rather, I believe that overall system performance objectives should be flexible in the sense that they allow and encourage the exercise of subjective scientific judgments involving the widest variety of models, lines of reasoning, and expert opinion. Furthermore, I believe that such an approach will allow reasonable and defensible judgments to be made.

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This report discusses the different technical issues that must be considered in developing an environmental standard for geologic disposal of high-level radioactive wastes. These issues include (1) defining acceptable risk, (2) specifying acceptable risk in the standard, (3) formulating the standard so that reasonable demonstrations of compliance can be obtained, (4) applying the standard to protection of individuals or the population, (5) applying the standard to expected occurrences only or to unexpected processes as well, (6) determining a time limit for the standard, and (7) specifying conditions to be assumed for demonstrating compliance. It is concluded that many issues are not resolvable on technical grounds alone, but that an effective standard will allow flexibility and the exercise of subjective scientific judgments in reaching licensing decisions.

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