AN INDEPENDENT EVALUATION OF THE PROPOSED EPA ENVIRONMENTAL STANDARD FOR HIGH LEVEL RADIOACTIVE WASTE DISPOSAL

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ABSTRACT

The Environmental Protection Agency has issued for public comment an environmental protection standard for high-level radioactive waste, which contains numerical limits for radionuclides reaching the "accessible environment" from a geologic repository over a period of 10,000 years. These release limits are derived from the basic criterion that the releases from a repository containing 100,000 metric tons of heavy metal (MTHM) shall result in no more than 1000 fatal cancers in the world-wide population over the 10,000 years. This paper examines the framework of logic and assumptions used by the EPA staff in establishing the standard and in deriving the numerical release limits. It is concluded that several of the assumptions and parameters used to derive the numerical release limits are subject to considerable technical controversy. The proposed standard may offer advantages to the Department of Energy over other possible forms of a standard for the demonstration of compliance, in that calculations of doses are not necessary. However, it is a matter of concern that assessments intended to evaluate isolation system designs (and their performance) against the proposed EPA standard may not provide a complete understanding of the overall system behavior.

BASIS FOR DEVELOPMENT OF THE EPA STANDARD

The basic criterion, or acceptable public health impact selected by EPA is 1000 estimated health effects over 10,000 years from a 100,000 MTHM repository.[1] Models were developed to estimate radioactivity release and transport through the geologic media to the surface (or accessible environment) from "reference repositories" located in bedded and domed salt, granite, basalt, and shale.[2] Environmental pathways, dose and health effects models were used to predict population dose and health effects from a number of radionuclides contained in high-level waste.[3] As a result of these analyses, EPA concluded that the several generic repository and site combinations examined could readily satisfy the basic risk criterion.[1]

In deriving the numerical release limits for the individual radionuclides, the EPA staff proceeded as follows. In essence, the environmental pathways and health effects model was used to "calculate back" from health effects to arrive at the number of curies of each radionuclide that would result in 1000 health effects over 10,000 years. In the detailed supporting analyses, population doses and health effects were calculated for a number of "modes," or potential ways in which radionuclides could be released from a repository to the "accessible environment." These include releases to a river, an ocean, land surface, and the atmosphere. Health effects per curie released were calculated for the "important" long-lived radionuclides in the waste inventory of the reference repository for the four release modes.[3] It was noted by the EPA staff that, for the cases examined, most of the calculated health effects (usually over 90%) were from the river release mode.[3] The following eight environmental transfer and "route-to-man" paths were included in the EPA model for the river release mode--drinking water ingestion, freshwater fish ingestion, ingestion of above surface crops, milk ingestion, beef ingestion, inhalation of resuspended material deposited by irrigation, external dose from contaminated ground surface (from irrigation), and air submersion dose from the resuspended contamination.

To obtain the curie release limits, only the results for the river release mode were used.[1] Table I shows the health effects per curie released to a river and the resultant release limits for the individual radionuclides identified in the proposed standard.

Some confusion may exist regarding the actual calculations used by EPA to obtain the release limits. It should be noted that the 10,000 year release limits were derived entirely from the results of the EPA environmental pathway models, and were arrived at independently of any calculations of release and transport from a repository to the accessible environment. This has been verified by calculations using equations from the EPA pathways report,[3] from which we were able to reproduce the results shown in Table I.[4] The calculated release limits are essentially independent of the time duration of the release; e.g., the release could occur all at once or at a constant rate over a long period of time.

The EPA pathway models[3] treat the transport of radionuclides through the several routes to man in some detail. The resultant dose to humans is calculated by the use of 50-year dose commitment factors for inhalation and ingestion, and by external dose factors for air submersion and exposure to contaminated ground. Doses to individuals are not calculated; environmental dose (dose equivalent) commitments, which are, in effect, population doses, are calculated for nine organs. The calculation of doses to individuals was avoided by going directly from amounts of radioactivity reaching humans to environmental dose commitment through a number of simplifying assumptions and manipulation of the model equations to eliminate population density as an explicit parameter.

Table I. Health Effects per Curie Released to a River and the 10,000 year Release Limits

Nuclide	Health Effects per Ci Released to a River a/	Release Limit for 1000 Health Effects b/
Am-241	7.19×10^{-1}	10
Am-243	2.68	4
C-14	4.58×10^{-2}	200
Cs-135	3.81×10^{-3}	2000
Cs-137	1.98×10^{-2}	500
Np-237	5.95×10^{-1}	20
Pu-238	2.29×10^{-2}	400
Pu-239	6.92×10^{-2}	100
Pu-240	6.53×10^{-2}	100
Pu-242	6.76×10^{-2}	100
Ra-226	3.16	3
Sr-90	1.21×10^{-1}	80
Tc-99	2.85×10^{-4}	10000
Sn-126	1.20×10^{-1}	80

a/ From ref. 3, Table D-2.
b/ From ref. 1, Table II, expressed as curies per 1000 MTHM; based on 1000 health effects from a 10^5 MTHM repository. Numbers shown are for each nuclide considered separately. For mixtures of nuclides, the sum of the ratios of calculated 10,000 year releases to the limit for each shall not exceed 1.

The need to estimate population distributions over space and time was circumvented by calculating the fractions of released radionuclides that ultimately cause exposure to humans, and by assuming a constant world-wide population of 10 billion over the 10,000 years. Environmental transfer parameters (e.g., for uptake by plants and animals and subsequent transfer to humans) are assumed to be independent of location and time. These parameters, including dietary habits, are assumed to be the same for all population groups that may be affected over the 10,000 year post-closure period.

The environmental dose commitments for each organ (independent of the number of individuals involved) are converted directly to health effects using numerical coefficients derived from the so-called "linear, non-threshold hypothesis." This hypothesis asserts that the additional numbers of fatal cancers appearing in a population exposed to ionizing radiation is directly proportional to the total dose received, with no dose threshold. EPA assumes that a constant of proportionality between population dose and the numbers of health effects holds, "even at very low individual doses."[1]

CONCEPTUAL FRAMEWORK FOR A HIGH-LEVEL WASTE PROTECTION STANDARD

Figure 1 shows, in schematic form, two parallel and complementary analytical exercises for the derivation of a performance standard and the subsequent verification of the proposed isolation system performance. EPA started with 1000 health effects as the basic overall performance criterion, and from it, derived the numerical release limits--the actual standard to be met by a licensed geologic disposal system. It can be seen, however, that several alternative approaches were possible. Having chosen the basic risk criterion, EPA could have issued the risk criterion itself as the numerical standard, or issued a numerical dose limit derived from the risk criterion. Or radiation dose could have been selected as the fundamental criterion, with numerical dose limits or release limits as the derived standard.

Within the framework illustrated in Fig. 1, once the fundamental criterion is selected (largely a matter of philosophy), the remainder of the exercise is essentially one of analysis. Satisfaction of the standard can only be verified through calculations (using models and assumptions) which predict the performance of the isolation system. Depending upon the choices for the fundamental criterion and implemented standard, the beginning and end points of the complementary processes shown in the two columns of the figure shift accordingly. Assume, for purposes of illustration, that EPA had proposed a standard in the form of a dose; then the prediction of doses from radionuclides released to the environment would be required to verify the performance of the waste isolation system. Regardless of which form of standard is used, the total number of analytical steps (each with its attendant uncertainties) remains the same; the responsibility merely shifts between regulator and repository developer.

Derivation of the Standard	System Performance Evaluation
Establish Overall Performance Criterion or Safety Goal (EPA-1000 health effects)	(models and assumptions)
	Calculate Releases
(models and assumptions)	
	(models and assumptions)
Calculate Dose	
	Calculate Dose
(models and assumptions)	
	(models and assumptions)
Establish Release Limits	
	Calculate Health Effects

Fig. 1. Conceptual Framework of High-Level Waste Standard Development

CRITIQUE OF THE EPA STANDARD

What follows is a critical discussion of several aspects of the proposed EPA standard and some of the implications thereof. Consideration is given to the effects of the various assumptions used in deriving the numerical release limits and to the identification of problems potentially posed by the implementation of the standard. Emphasis is on the technical and practical aspects--the implications for site selection and overall system performance assessment, as opposed to philosophical, political or legal considerations. This discussion represents a partial summary of unpublished analysis performed jointly by the authors and of work performed on isolation system performance assessment in which the first author participated at the University of California. Space does not permit a detailed discussion of all this work here.

Limited Performance Assessment Needed to Show Compliance

The proposed standard contains no requirement for estimating doses to individuals or to population groups. It does not require prediction of radioactivity releases and radiation doses for time periods greater than 10,000 years. Thus, the difficult problem of predicting releases over the millions of years for which significant radionuclide inventories will exist is avoided. The proposed standard may appear to offer advantages to the repository designer. It seems to fulfill the objectives of a performance criterion based on population dose, but it requires no calculations of numbers, locations, or living habits of affected future populations.

Not only would the standard, as proposed, simplify the calculations to demonstrate compliance, it would seem to have relatively little impact on repository site selection. For any location, the same fraction of released radionuclides would be assumed to be reaching humans as for any other location. Very little hydrologic information concerning a proposed site beyond groundwater flow characteristics would be required, as there would be no need to calculate concentrations of radionuclides in surface water and environmental media, since individual doses are not required. In the derivation of the release limits, it makes no difference whether the released activity is distributed over a large number of people, or whether it is distributed to a small number; in either case the population dose is expected to be the same. Under this reasoning, sites with large populations nearby would be as acceptable as ones with low present and predicted future populations.

In the draft EPA standard, the "accessible environment" is defined as "surface waters, land surfaces, the atmosphere, the oceans, ..., and all groundwater formations that are more than ten kilometers from the original location of [the emplaced wastes]."[1] It is assumed that this definition is to be used in calculating releases for the assessment of proposed repository-site combinations and comparison against the EPA standard. Although the release limits were derived from the assumed use of river water, they are evidently intended to apply to any use of contaminated water at the ten kilometer location. There would apparently be no incentive, in demonstrating compliance with the proposed standard, to consider releases to the actual environs of a proposed site, or to seek sites with greater distance to locations of possible water use by humans.

Individual Doses Implied by the Standard

Individual doses are not calculated in the derivation of the EPA release limits. However, it is worth examining doses to individuals that could be received within the release limits, as these are the most meaningful measures of risk to individuals.

Using equations in the EPA environmental pathway models report,[3] it is possible to calculate doses to individuals. Although it is necessary to provide values for some parameters not supplied in the report, most of the parameters and necessary assumptions are drawn from the report. The individual doses resulting from the release to a river were calculated for several of the radionuclides listed in Table II of the proposed standard.[4] It was assumed that each radionuclide was released at a constant rate at the limit of the EPA standard for a period of 8,000 years. This allows 1000 years for onset of release from a repository and 1000 years for the radionuclides to move in groundwater from the repository to a river. A river flow rate of 10^{13} liters per year, about one-tenth of the average flow rate of the Columbia River near the Hanford Reservation,[4] was assumed. Examples of calculated annual individual doses (whole-body) for several radionuclides are 7×10^{-4} rem for Cs-135, 6×10^{-5} rem for Tc-99, and 9×10^{-6} rem for Sn-126. These are 50-year committed dose equivalents from ingestion of contaminated drinking water, freshwater fish, food crops, beef, and milk. Inhalation and external exposure were neglected, as their relative contributions are only a few percent or less, in these examples.

Still lower individual doses can be inferred from the EPA release limits. Since the individual dose as calculated by the EPA model equations is inversely proportional to the river flow rate, a river flow rate equal to that of the Columbia River would result in calculated doses one-tenth of those presented above. Furthermore, recognizing that food grown from the contaminated water can be shipped worldwide, the EPA model allows for the possible worldwide distribution of a fraction of the released radionuclides in agricultural products grown with contaminated river water. Using EPA data, it is estimated that if Tc-99 were discharged uniformly at the proposed release limit (10,000 Ci) over a period of 8,000 years and food products grown on the contaminated soil were distributed worldwide, the average annual dose to individuals in the world population assumed by EPA (10 billion) would be as low as 6×10^{-7} rem.[4]

On the other hand, because of the strong dependence of individual dose on the concentration of radioactivity in water, it is easy to construct scenarios wherein very large doses to individuals and perhaps small population groups are received. The EPA definition of "accessible environment" includes underground water formations which could be used as water supplies for human consumption and for agricultural purposes. Consider the case in which a well intercepts a contaminated aquifer and an individual obtains all his liquids from the well, and obtains all his food and animal products from land irrigated by the well water. In a supporting analysis performed for the EPA standard, the base case well scenario assumed an aquifer flow rate of 5×10^{7} liters per year.[5] Assuming that the allowable limits are released to an aquifer at a constant rate over 8,000 years, and that the aquifer is completely mixed where the well intercepts the aquifer, individual whole-body dose commitments in the range of several hundred rem per year are estimated using the EPA pathway models equations.[3] For example, the dose calculated for Cs-135 is 135 rem, and for Pu-238, 230 rem. Using underground water flow rates in the vicinity of a site under consideration by the National Terminal Waste Storage Program, separate calculations yield individual doses between 10^3 and 10^4 rem per year.[6] These doses are in a range in which acute, or short-term radiation effects may be of greater concern than the "stochastic effects" assumed in the formulation of the EPA standard.

The Assumption of a Linear Non-Threshold Relationship Between Dose and Effect

EPA used in its calculations constant coefficients relating organ dose to fatal health effects, assuming a zero threshold for the range of validity of the coefficients. In its discussion of the proposed standard, EPA states that it believes that such an approach is a prudent one to use in "developing radiation protection requirements."[1] The validity of the linear, non-threshold hypothesis as applied by EPA is questionable in view of the extremely large range of individual dose rates calculable within the framework of the EPA derivation.

The discussion in the supplementary information accompanying the proposed standard[1] implies that this approach is based on studies prepared by the National Academy of Sciences (NAS). EPA has sponsored several studies by the NAS on the scientific and policy aspects of dose-effect relationships. In the first study published in 1972,[7] the NAS Committee on the Biological Effects of Ionizing Radiation (BEIR) recommended a linear relationship between dose and effect extrapolated to low doses. The Committee made numerical risk estimates for the continuous lifetime exposure of 100 millirem per year to a population. The Committee did not, so far as can be discerned, offer any guidance regarding the validity of applying the constant risk coefficients below this level.

In 1980, the NAS BEIR Committee issued a report in which the relationship between dose and effect in populations exposed to low levels of radiation was reevaluated.[8] This included a review of the estimating process used in the 1972 report. It was concluded (in the 1980 report) that it was "arbitrary and of uncertain validity, especially because values for the low-dose region were estimated by linear extrapolation from data in the high dose region (100 rads or more) to which most human data pertained."[8] Recognizing that risk estimates are necessary for making policy decisions and exercising regulatory authority, the 1980 report concluded that the best method of dealing with the many uncertainties was to present an envelope of risk estimates. The following three scenarios were chosen for developing numerical risk estimates:

1. A single exposure of a representative population to 10 rads.

2. A continuous, lifetime exposure of a representative population to 1 rad per year.

3. An exposure of 1 rad per year over several age intervals, exemplifying conditions of occupational exposure.

Regarding numerical estimates for doses below these levels, the Committee felt that uncertainties were too great to justify calculation.[8] The Committee further stated that "...it is by no means clear whether dose rates of gamma or X radiation of about 100 millirads per year are in any way detrimental to exposed people...."[8] Yet, in developing its proposed standard, EPA applies the assumption of a constant of proportionality to implied individual doses which are as much as three to six orders of magnitude below the range for which the recent BEIR Committee considers the approach to be valid.

On the other hand, individual doses can be calculated that are near the upper limit or above the range of applicability of constant risk coefficients. Because of the very large uncertainties produced by this approach to their calculations, the degree of protection to future populations provided by the standard is unknown.

Effects of the 10,000 Year Time Limit

The 10,000 year time limit plays essentially no role in the calculation of the curie release limits by EPA. The selection of the time period evidently resulted from the EPA staff analyses of repository-isolation system performance reported in the draft report by C. B. Smith et al.[2] Though a review of the EPA performance analysis is beyond the scope of this paper, a few comments on the 10,000 year time period are warranted because of the distorting effect this has on the understanding of long-term isolation system behavior.

This discussion is based on the premise that the most likely release mode from a high-level waste repository is by slow dissolution-leaching from waste packages and transport by groundwater to the surface. The adoption by EPA of the 10,000 year cutoff is based in part on the premise that if a disposal system is predicted to satisfy the curie release limits for 10,000 years, it will continue to provide adequate protection beyond 10,000 years.[1] Various analyses of long-term performance, for example as reported by Cloninger and Cole,[9] and by Pigford et al.,[6] indicate that larger quantities of most of the radionuclides will reach surface waters or "accessible" aquifer locations after 10,000 years than before 10,000 years. Radionuclides do emerge from the repository sooner in the EPA calculations than some of the other analyses, apparently as a result of the low values of retardation constants assumed by EPA for the purpose of making conservative estimates of release.[4]

Another important result is obscured by the 10,000 year cutoff. The mix of radionuclides emerging from a repository is much different in times greater than 10,000 years (e.g., 10^5 to 10^6 years) than that which is predicted to appear prior to 10,000 years.[6]

These distortions caused by the 10,000 year cutoff tend to obscure understanding of the sensitivity of time-dependent radionuclide release quantities to important repository and site characteristics. These characteristics, described by appropriate parameter values used in performance predictions, include: the leach rate of the waste material, the solubility of the leached radionuclides in groundwater, the retardation of dissolved radionuclides during water transport through the geologic media, and the travel time of water from a repository location to locations in which the water is used by humans.

Sensitivity of the Release Limit Quantities to Parameter Values in the Pathway Models

In addition to the many assumptions incorporated in the environmental pathway models which were used to derive the proposed release limits, a very large number of parameter values are required.[3] These include environmental transfer coefficients and dose conversion factors, which are themselves calculated using other models and assumptions, and incorporated in the data libraries of the EPA computer codes.[3]

For example, the EPA model uses 50-year ingestion and inhalation dose conversion factors to calculate organ dose commitments, which are largely based on 1978 results from the Oak Ridge National Laboratory (ORNL) INREM-II internal dosimetry models.[10] These models have since been updated,[11] and in 1979 and subsequently, new internal dose factors were released by the International Commission on Radiological Protection (ICRP) in support of the 1979 recommendations for limitations on intake of radionuclides by radiation workers in ICRP Publication 30.[12] In order to examine the effect of the use of the newer recommended dose conversion factors on the EPA release limits, ICRP 30 ingestion dose conversion factors were substituted into the EPA model equations for several of the radionuclides in Table I. Nuclides were selected for which the health effects, as calculated by EPA, are dominated by the ingestion dose.[3]

The calculation resulted in the following changes in the 10,000 year release limits: Cs-135 would increase from the present value of 2,000 to about 20,000 curies; Ra-226 would increase from 3 to about 20 curies; and Np-237 would decrease from the current value of 20 to slightly less than one curie. It is reasonable to expect that as a better understanding of the many processes which influence environmental transport and uptake of radionuclides is gained, improvements in the calculational models and changes in the many parameters used in the calculation would be warranted. Thus, a periodic reevaluation of the derived release limits would be required in order to maintain their validity in terms of the basic protection criterion.

Summary and Conclusions

Based upon the evaluation summarized in this paper, it is concluded that the EPA high-level waste standard, in its present proposed form, has several serious technical shortcomings. These include:

1. Protection is not necessarily assured for individuals and small groups of individuals.

2. Only a limited performance assessment would be required to demonstrate compliance. Compliance can be demonstrated independently of population distributions and other important site characteristics.

3. Use of the linear hypothesis for the relationship between dose and effect in a range of annual individual doses between 10^{-6} rem and 10^{4} rem is highly questionable.

4. Limiting the assessment of releases to 10,000 years, while simplifying calculations for compliance, obscures important effects which are predicted from calculations of performance over longer time periods. Thus, the level of protection intended by the basic 1000 health effects criterion over 10,000 years is not necessarily provided for time periods beyond 10,000 years.

5. The derived release limits are highly dependent on numerous simplifying assumptions and parameter values. This dependency weakens the regulatory basis for the standard, and exposes the standard to continuous review and revision.

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