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DEVELOPMENT AND APPLICATION OF A CONCEPTUAL APPROACH FOR DEFINING HIGH-LEVEL WASTE*

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ABSTRACT

This paper presents a conceptual approach to defining high-level radioactive waste (HLW) and a preliminary quantitative definition obtained from an example implementation of the conceptual approach. On the basis of the description of HLW in the Nuclear Waste Policy Act of 1982, we have developed a conceptual model in which HLW has two attributes: HLW is (1) highly radioactive and (2) requires permanent isolation via deep geologic disposal. This conceptual model results in a two-dimensional waste categorization system in which one axis, related to "requires permanent isolation," is associated with long-term risks from waste disposal and the other axis, related to "highly radioactive," is associated with short-term risks from waste management and operations; this system also leads to the specification of categories of wastes that are not HLW. Implementation of the conceptual model for

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defining HLW was based primarily on health and safety considerations. Wastes requiring permanent isolation via deep geologic disposal were defined by estimating the maximum concentrations of radionuclides that would be acceptable for disposal using the next-best technology, i.e., greater confinement disposal (GCD) via intermediate-depth burial or engineered surface structures. Wastes that are highly radioactive were defined by adopting heat generation rate (i.e., power density) as the appropriate measure and examining levels of decay heat that necessitate special methods to control risks from operations in a variety of nuclear fuel-cycle situations. We determined that wastes having a power density greater than 200 W/m^3 should be considered highly radioactive. Thus, in the example implementation, the combination of maximum concentrations of long-lived radionuclides that are acceptable for GCD and a power density of 200 W/m^3 provides boundaries for defining wastes that are HLW. On the basis of this analysis, the conceptual model was judged to have merits and further studies are being undertaken to develop a more refined proposal for a HLW definition.

INTRODUCTION

The Nuclear Waste Policy Act (NWPA) of 1982 (Public Law 97-425) provides a legal description of high-level radioactive waste (HLW), in which the term "high-level radioactive waste" means -

[1] the highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations; and

[2] other highly radioactive material that the Commission, consistent with existing law, determines by rule requires permanent isolation.

The term "Commission" in the second statement means the U.S. Nuclear Regulatory Commission (NRC).

The first description of HLW in the NWPA reflects the historical view that HLW often has been defined according to its source of generation, i.e., as spent nuclear fuel or materials derived from the reprocessing of spent nuclear fuel (e.g., see ref. 1 and references therein), although the NWPA description is modified by the phrases "highly radioactive" and "sufficient concentrations." The NWPA emphasizes that HLW will require permanent isolation, most likely by means of disposal in a deep geologic repository. The second description of HLW recognizes that wastes from other sources may present hazards equivalent to those from spent fuel or reprocessing wastes and, thus, may require permanent isolation in a similar manner. The NRC then has the responsibility for developing a quantitative definition of HLW for the purpose of identifying any other highly radioactive materials requiring permanent isolation.

The NRC recently has issued a report addressing a possible quantitative implementation of the NWPA description of HLW as highly radioactive material that requires permanent isolation.[2] The NRC examined concentrations of different radionuclides in representative waste streams and forms traditionally considered to be HLW, and assumed that any waste materials containing these radionuclides in similar or higher concentrations then could be classified as HLW. From this analysis, the NRC suggested that highly radioactive material requiring permanent isolation might be defined as any waste materials in which the radionuclide concentrations exceed 30 times the concentration limits for Class-C low-level waste (LLW) as defined in 10 CFR Part 61.[3] Thus, for example, the NRC suggested that concentrations of radionuclides greater than the following would require permanent isolation: 210,000 Ci/m^3 of ^{90}Sr, 138,000 Ci/m^3 of ^{137}Cs, 3,000 nCi/g of alpha-emitting transuranic (TRU) radionuclides with half-lives greater than 5 years, and 105,000 nCi/g of ^{241}Pu. For waste streams containing mixtures of radionuclides, the sum-of-fractions rule would apply; i.e., the wastes would require permanent isolation if the ratio of the concentration of each radionuclide to 30 times its Class-C limit summed over all radionuclides exceeds unity.

From a review of the NRC's suggestion for defining HLW, we concluded that the proposal was flawed in several important respects. First, the definition was not based on health and safety considerations; i.e., the analysis did not consider whether any wastes with radionuclide concentrations greater than 30 times the Class-C limits for LLW would require permanent isolation in a deep geologic repository in order to achieve an acceptable level of protection of public health and safety. Second, the proposal appeared to be inconsistent with the NWPA definition of HLW, which refers to "highly radioactive materials," and with the substance of previous legal definitions.[1] Third, the proposal does not appear to allow for waste fractionation in determining wastes requiring permanent isolation. Finally, since the proposal does not consider the concept of "highly radioactive," the suggested definition could result in a substantial amount of TRU waste being reclassified as

HLW. Thus, the proposal could have a severe impact on current plans of the U.S. Department of Energy for disposal of defense TRU waste at the Waste Isolation Pilot Plant (WIPP) in New Mexico and on the disposition of commercial TRU wastes.

Because of the apparent deficiencies in the NRC's suggested definition of HLW, we concluded that a concrete alternative was needed for input to the NRC's rulemaking process. This paper presents a conceptual approach that we have developed for defining HLW and a preliminary quantitative definition obtained from an example implementation of the conceptual approach.

CONCEPTUAL APPROACH TO DEFINING HLW

The conceptual approacn to defining HLW presented in this paper was developed under the following constraints:

- the approach should be consistent with the NWPA;
- the approach should be consistent with existing waste categories and the methodologies used in developing them (e.g., the definition of LLW in 10 CFR Part 61 and the associated methodology[3-5]) insofar as practical;
- the approach should be based primarily on health and safety considerations;
- the approach should be consistent with historical definitions of HLW insofar as practical; and
- the approach should be logical and defensible.

The basis for our conceptual approach to defining HLW is the statement in the NWPA that HLW is "...highly radioactive material that...requires permanent isolation." We have interpreted this statement as implying that HLW has two attributes: namely, HLW is

[1] highly radioactive and

[2] requires permanent isolation.

This conceptual approach results in a two-dimensional waste categorization system in which one axis is related to whether or not the wastes require permanent isolation and is associated with long-term risks from waste disposal and the other axis is related to whether or not the wastes are highly radioactive and is associated with short-term risks from waste management and operations.

On the axis of the waste categorization system associated with long-term risks from waste disposal, the conceptual approach to defining wastes requiring permanent isolation involves establishing maximum concentrations of radionuclides that would be acceptable for disposal using the next-best disposal technology; namely, greater confinement disposal (GCD) (e.g., via intermediate-depth burial or engineered surface structures). The conceptual approach to defining wastes that are highly radioactive is based on the principle that radionuclide concentrations above some point will necessitate the use of special engineering or operational methods to provide safe handling or containment of the materials in waste management and operations. The point at which radionuclide concentrations are sufficiently high that special methods are required is determined by examining a variety of situations in existing and proposed waste management systems.

Conceptually, then, HLW is defined as wastes that both require permanent isolation (for limitation of long-term risks to the general public from disposal of long-lived radionuclides) and are highly radioactive (require special handling to limit short-term risks in waste management). Wastes that do not simultaneously exceed both limits would not be HLW. Such a two-dimensional waste categorization system also specifies categories for wastes that are not HLW. For example, TRU wastes would fall into the category of wastes that require permanent isolation but are not highly radioactive, and LLW would fall into the category of wastes that neither require permanent isolation nor are highly radioactive.

EXAMPLE IMPLEMENTATION OF CONCEPTUAL APPROACH

Specific analyses constituting a preliminary example implementation of the conceptual approach for defining HLW were undertaken to demonstrate that the approach could, in practice, be quantified and that a reasonable and useful HLW definition likely would result.

Wastes Requiring Permanent Isolation

The boundary between those wastes that require permanent isolation and those that do not was determined by estimating the maximum concentrations of different radionuclides that would be acceptable for GCD using either intermediate-depth burial or engineered surface structures. The term "acceptable" means that the resulting radiation dose to inadvertent intruders at the waste disposal site after loss of active institutional controls would not exceed the limit embodied in the

NRC's low-level waste standard (10 CFR Part 61).[3] Except for such radionuclides as ^{241}Pu that decay to radiologically significant long-lived daughter products, only radionuclides with half-lives greater than 15 years need to be considered for permanent isolation, because it can be shown easily that shorter-lived radionuclides in any concentrations are acceptable for disposal as LLW according to the criteria in 10 CFR Part 61.[3]

The analyses of maximum concentrations of long-lived radionuclides that would be acceptable for disposal by the two GCD options considered were based on an extension of the methodology developed by the NRC in establishing concentration limits for LLW in 10 CFR Part 61.[4,5] The results of the NRC methodology are expressed in terms of pathway dose conversion factors (PDCFs), which, for an assumed exposure scenario and exposure pathways, give annual doses per unit concentrations of radionuclides in environmental media.

The assumptions used in modifying the results of the NRC methodology to obtain maximum radionuclide concentrations that would be acceptable for disposal via intermediate-depth burial are described below.

- Burial of the wastes would be at depths sufficiently great to eliminate all direct intrusion scenarios involving animal, plant, and human activities.

- An intruder accesses the wastes by drilling a deep well which passes through and draws water from the waste.

- Intrusion exposures occur at 100 years after waste disposal.

- The PDCFs calculated by the NRC for the leaching and migration scenario to an on-site well[4,5] do not apply directly to the assumption of well drilling directly into the wastes. Thus, the PDCFs calculated by the NRC were adjusted for application to direct drilling into the wastes using modifying factors obtained from a previous waste-classification analysis by the NRC which considered an intruder-reclaimer scenario.[6]

- The resulting concentration limits were adjusted upward by a factor of 10 to be consistent with the derivation of concentration limits for Class-C LLW in 10 CFR Part 61.[3-5] This adjustment factor accounts for the expected ratio of maximum and average concentrations of radionuclides in the wastes.

The calculations for disposal in an engineered surface structure involved a straightforward extension of the NRC methodology for disposal of LLW.[4,5] The assumptions are described below.

- An intruder-agriculture scenario would be precluded by the design and engineering of the facility.

- Exposures would occur according to an intruder-construction scenario for a duration of 500 hours in one year.

- Intrusion exposures occur at 500 years after waste disposal.

- The ratio of maximum to average concentrations of radionuclides in the wastes is a factor of 10, as in the analysis for intermediate-depth burial.

Estimates of the maximum concentrations of radionuclides that would be acceptable for GCD generally differ for intermediate-depth burial and an engineered surface structure. The concentration limit used to define the boundary for wastes that require permanent isolation then was taken to be the larger (i.e., the least restrictive) of the two concentration limits so obtained.

The results of the analysis of maximum concentrations of selected radionuclides that would be acceptable for GCD are given in Table I. Again, any radionuclide concentrations greater than these values would require permanent isolation (but would not necessarily be HLW). For wastes containing mixtures of radionuclides, the sum-of-fractions rule would apply to determining whether or not permanent isolation is required. The ratio of the concentration requiring permanent isolation to the corresponding concentration limit for Class-C LLW[3] ranges from 1-2 for ^{94}Nb and ^{137}Cs to 5,000 for ^{14}C. The average ratio for TRU radionuclides, for which the Class-C limit is 100 nCi/g (about 0.16 Ci/m^3) except 3,500 nCi/g (5.6 Ci/m^3) for ^{241}Pu, is about 60.

Wastes That Are Highly Radioactive

In order to define the boundary between thoses wastes that are highly radioactive and those that are not, we adopted heat generation rate (i.e., power density) as the appropriate unit of measure for relating levels of radioactivity to short-term risks from waste management and operations. The rationale for defining highly radioactive wastes in terms of the heat generation rate is as follows.

- The potential for radioactive material to disperse itself depends on the heat generation rate in the waste.

- The power density of the waste is important in virtually all waste management operations.

- Heat may be a more encompassing feature of highly radioactive material than either concentration of activity or radiation dose; i.e., all radionuclides generating high radiation levels also generate significant heat, but not all wastes generating high heat levels also generate high radiation levels.

- Calculation of heat generation rates is more straightforward and requires fewer important assumptions than calculation of external radiation dose in the vicinity of waste packages.

In order to quantify the boundary defining highly radioactive waste, a variety of existing and conceptual radioactive waste handling, transport, and storage systems were identified, and each system was examined to estimate the point at which the power density would limit system design or the method of operation. The different situations examined include (1) limiting the temperature rise in a stack of waste packages to levels that would prevent boiling of water, (2) the heat generation rate that would require active cooling measures in a liquid waste tank, (3) heat generation rates in transport containers for TRU wastes, and (4) acceptance criteria for contact-handled and remote-handled defense TRU wastes at the WIPP. The minimum power density that would affect system design or method of operation for these situations was estimated to be in the range 10-300 W/m3. It is also noteworthy that the maximum concentrations of ^{90}Sr and ^{137}Cs in Class-C LLW[3] fall in the middle of this range of heat generation rates.

From the analysis described above, we concluded that the boundary defining highly radioactive wastes can be approximated by a power density for the average waste package of 50 W/m^3. Since the contents of individual waste packages may be quite inhomogeneous and a distribution of power densities is expected in a population of packages, we assumed that it would be appropriate to increase the boundary value by a factor of 4 for individual waste packages in order to achieve the desired average value. Thus, the boundary quantifying highly radioactive waste was taken to be a power density of 200 W/m^3, and this value applies to waste packages that are small enough to achieve benefits from intermingling of packages having varying power densities.

Summary of Example Implementation

The combination of the two boundaries related to concentration limits of long-lived radionuclides that require permanent isolation and limits on power density that define highly radioactive wastes results in HLW being defined as waste that simultaneously has (1) radionuclide concentrations greater than the limits in Table I, calculated according to the sum-of-fractions rule, and (2) a power density greater than 200 W/m^3.

As noted previously, the conceptual approach for defining HLW also results in definitions for other waste types. The definitions of all waste types are depicted schematically in Fig. 1. The five waste categories shown in the figure can be described as follows:

[1] HLW – material having a power density greater than 200 W/m^3 and for which the sum-of-fractions rule based on the concentration limits in Table I is greater than unity (i.e., waste that is highly radioactive and requires permanent isolation);

[2] TRU waste – material having a power density less than 200 W/m^3 and for which the sum-of-fractions rule based on the concentration limits in Table I is less than unity (i.e., waste that is not highly radioactive but requires permanent isolation);

[3] high-activity waste (HAW) – material having a power density greater than 200 W/m^3 and for which the sum-of-fractions rule based on the concentration limits in Table I is less than unity (i.e., waste that is highly radioactive but does not require permanent isclation);

[4] LLW – material having a power density less than 200 W/m^3 and concentrations of radionuclides less than the Class-C limits in 10 CFR Part 61;[3] and

[5] intermediate-level waste (ILW) – material having a power density less than 200 W/m^3 and for which the sum-of-fractions rule based on the concentration limits in Table I is less than unity but the concentrations of radionuclides are greater than the Class-C limits in 10 CFR Part 61.[3]

Both LLW and ILW are wastes that are neither highly radioactive nor require permanent isolation.

FURTHER EVALUATIONS OF THE APPROACH

It is clear that additional studies are required to delineate more carefully the proposed boundaries between the various waste categories, and to make the resulting waste categories more consistent with existing law. We are currently undertaking the following studies:

- a reexamination of the quantitative definition of wastes requiring permanent isolation including evaluation of (1) the most appropriate GCD technology for use in the analysis, (2) the most appropriate exposure scenarios and pathways to be assumed for an inadvertent intruder, (3) the assumptions in the methodology for LLW disposal in 10 CFR Part 61 and the most appropriate modifications of this methodology for GCD, and (4) concentration limits for potentially important radionuclides not included in Table I (e.g., ^{226}Ra, $^{229,230}Th$, and $^{233,234,236}U$);

- a reexamination of the approach taken in defining wastes that are highly radioactive including (1) consideration of radiation dose or an appropriate combination of power density and radiation dose as the unit of measure for defining such waste and (2) a more detailed analysis of the measure that seems most appropriate;

- development and implementation of an approach for defining surface-contaminated wastes that require permanent isolation; and

- examination of ways of reducing the number of waste categories in the example implementation of the conceptual approach in Fig. 1 and making the categories more consistent with the definitions of HLW, LLW, and TRU wastes in existing laws, including the recently passed Low-Level Waste Policy Act.

SUMMARY AND CONCLUSIONS

We emphasize that the most important aspect of this paper is the development of the conceptual approach that HLW can be defined as wastes that are highly radioactive and require permanent isolation. From our analysis, we conclude that the conceptual approach is sound and can produce a workable waste categorization scheme that is (1) consistent with existing law, (2) based on considerations of health and safety, (3) compatible with existing waste categories and the methodologies used to develop them, and (4) logical and defensible without having adverse effects on current waste management activities and plans.

An example implementation of the conceptual approach was presented in which wastes requiring permanent isolation were defined as those with radionuclide concentrations too large to be acceptable for greater confinement disposal via intermediate-depth burial or engineered surface structures, and wastes that are highly radioactive were defined as those with a power density greater than 200 W/m^3. The implementation presented here is intended primarily to demonstrate that the conceptual approach is indeed workable, but is not intended to be taken as a final result. Further work to develop a more refined definition of HLW is currently being undertaken.

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TABLE I.

Radionuclide Concentrations Requiring Permanent Isolation

Radionuclide	Boundary concentration (Ci/m^3)
^{14}C	4 E+4
^{59}Ni	2 E+2
^{63}Ni	7 E+3
^{94}Nb	2 E-1
^{90}Sr	4 E+5
^{99}Tc	7 E+3
^{129}I	2 E0
^{137}Cs	9 E+3
^{235}U	1 E-2
^{237}Np	4 E-1
^{238}Pu	7 E0
$^{239/240}Pu$	9 E0
^{241}Pu	5 E+2
^{242}Pu	1 E0
^{241}Am	2 E+1
^{243}Am	1 E+1
^{244}Cm	2 E+1

Note: The limits for ^{135}Cs and ^{238}U are greater than their maximum theoretical specific activities.

FIGURE CAPTION

Fig. 1 – Pictorial depiction of waste categories resulting from example implementation of proposed conceptual approach for defining HLW.

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