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POTENTIAL PROBLEM AREAS: EXTENDED STORAGE OF LOW-LEVEL RADIOACTIVE WASTE*

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ABSTRACT

If a state or regional compact does not have adequate disposal capacity for low-level radioactive waste (LLRW), then extended storage of certain LLRW may be necessary. The Nuclear Regulatory Commission (NRC) has contracted with Brookhaven National Laboratory to address the technical issues of extended storage. The dual objectives of this study are (1) to provide practical technical assessments for NRC to consider in evaluating specific proposals for extended storage and (2) to help ensure adequate consideration by NRC, Agreement States, and licensees of potential problems that may arise from existing or proposed extended storage practices. Storage alternatives are considered in order to characterize the likely storage environments for these wastes. In particular, the range of storage alternatives considered and being implemented by the nuclear power plant utilities is described. The properties of the waste forms and waste containers are discussed. An overview is given of the performance of the waste package and its contents during storage (e.g., radiolytic gas generation, corrosion) and of the effects of extended storage on the performance of the waste package after storage (e.g., radiation-induced embrittlement of polyethylene, the weakening of steel containers by corrosion). Additional information and actions required to address these concerns, including possible mitigative measures, are discussed.

INTRODUCTION

The Low-Level Waste Policy Act (PL 96-573, December 22, 1980) established state responsibility to provide disposal capacity for low-level

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radioactive waste (LLRW), and it was envisioned that all states would be self-sufficient in this respect. In addition, the Act encourages the formation of interstate compacts which (subject to approval by Congress) may refuse LLRW from outside their respective compact areas after January 1, 1986. Amendments to the Act are now before Congress, but the availability of LLRW disposal capacity after January 1, 1986, remains uncertain. Should a state or state compact not have adequate disposal capacity, then extended storage of waste may be required until disposal means are available. The waste may be stored for a period of several months to several years at the site of waste generation (e.g., on site at a nuclear power plant), at the disposal facility, or at a state or regional facility dedicated to such extended storage.

LLRW storage needs that may result from the unavailability of disposal capacity constitute a relatively new radwaste management problem in the United States. Most nuclear power plants were not designed with on-site LLRW storage capacity of extended duration since, in accord with the customary procedure, it was assumed that the LLRW would be shipped to a disposal site whenever a truckload had accumulated. Similarly, most non-fuel-cycle LLRW generators have operated under the assumption that the waste would be shipped for disposal rather than stored. Extended storage of LLRW has not been necessary at the disposal site since disposal of the LLRW has usually occurred within a few days after receipt.

The U.S. Nuclear Regulatory Commission (NRC) provided guidance for LLRW storage practices at nuclear reactor sites in Generic Letter 81-83.[1] In this document the NRC has considered two phases or time scales for the storage of LLRW at a nuclear power plant:

1. interim contingency storage, for up to 5 years, and

2. long-term storage, for over 5 years.

Due to current uncertainties regarding the availability of LLRW disposal capacity, the NRC is aware that extended storage of LLRW may be pursued by nuclear power plant licensees and by other NRC licensees who generate LLRW. (In this paper, the term "extended storage" is generally considered to include both "interim contingency storage" and "long-term storage.")

Extended storage of LLRW is a relatively new undertaking in the U.S. In order to develop guidance for the extended storage of LLRW by NRC licensees and to help ensure the continued protection of public health and safety, the NRC has contracted with Brookhaven National Laboratory (BNL) to address the issue of extended storage of LLRW, focusing on the waste form and container but also considering storage alternatives in order to establish the likely range of storage environments that the wastes would encounter. The dual objectives of this study are (1) to provide practical technical assessments for NRC to consider in evaluating specific proposals for extended storage and (2) to help ensure adequate consideration by NRC, Agreement States, and licensees of potential problems that may arise from existing or proposed extended storage practices. In this paper, the major points of BNL's draft report[2] are summarized.

EXTENDED STORAGE FACILITIES

Classification of Storage Facilities

The various types of LLRW storage facilities, whether existing, under construction, or proposed, have been categorized in a survey of utility plans and actions which was conducted by the Electric Power Research Institute (EPRI)[3] and also in a New York State study of LLRW management practices.[4] The EPRI survey was published in July 1984 and contained information valid as of 1983. The construction status of on-site storage facilities as given in that survey is presented in Table 1, from which it may be noted that the storage facilities are classified into three categories, viz., reinforced concrete structures, pre-fab structures (concrete or metal panels) and bunkers. In the New York State study, LLRW storage facilities are grouped into four categories, viz., shielded buildings, shielded storage modules, shielded casks, and unshielded facilities. Informal comments made by nuclear utility staff at two meetings -- Waste Management '85 in Tucson in March and the June '85 ANS meeting in Boston -- indicate that many utilities are building simple butler-building-type structures. Each storage facility is in some ways unique, and for the purposes of the present study, a spectrum of storage concepts based on both of the above-mentioned classification schemes will be considered.

TABLE 1. CONSTRUCTION STATUS OF ON-SITE STORAGE FACILITIES AT REACTOR SITES[a]

	Completed	Not Completed
Reinforced Concrete Structures	8	18
Pre-fab Structures (concrete or metal panels)	1	5
Bunkers	2	0

[a]Information from EPRI NP-3617, Reference 3.

The following spectrum of storage facility concepts ranges from shielded structures with temperature and humidity control through those with less environmental control to ones with minimal shielding as well as minimal environmental control:

- Large engineered structures. These are permanent buildings designed specifically for the extended storage of LLRW. They may be reinforced concrete structures or steel frame buildings with uninsulated metal siding and roofing. They are generally provided with separate shielded areas for the storage of dry active waste and solidified wastes. Typically, some control over the temperature and, sometimes, the humidity is provided, e.g., a heating system to prevent freezing during the winter. Overhead bridge cranes are used for remote handling of the waste packages.

- Shielded storage modules or bunkers. These are permanent concrete structures with removable covers. Waste containers are emplaced or retrieved from above with a gautry crane.

- Shielded storage casks. These are all-weather concrete containers, usually cylindrical, that can be located outdoors and that are designed to hold waste drums or liners.

- Unshielded pre-fab structures. These are unshielded buildings which provide some degree of weather protection but have no temperature control system. Simple steel frame buildings with uninsulated metal siding and perhaps an overhead crane or hoist would fall into this category. These structures are generally intended for the storage of low-specific-activity wastes. These facilities have generally been used for storage for decay rather than extended storage.

- Minimal unshielded facilities. These are simple fenced-in outdoor concrete pads or very simple storage sheds. Little or no environmental protection is provided by these facilities, which were generally intended as holding areas for waste packages awaiting pick-up by a waste broker and not as waste storage facilities.

Storage Environment Characteristics

The behavior of radioactive wastes, of the binder materials in which they are immobilized, and of the container materials will be affected by the environment within the storage facilities. The environmental variables considered are length of storage time, temperature, humidity, potential for wetting of the container, and radiation field. Unfortunately, explicit information about these variables is generally not presented in descriptions of LLRW storage facilities.

The potential storage time is a variable significantly impacted by factors other than technical considerations. The storage space available and the rate of waste production are, of course, important, but social, political, and economic factors that affect the availability of disposal sites for LLRW are likely to be the major considerations in determining the length of time for which storage of LLRW may be needed.

The temperature of the storage environment will vary only slightly in the more elaborate large engineered structures for containerized radwaste, which include HVAC systems in their design. A minimum temperature of 50°F (10°C) is explicitly mentioned by one utility for its LLRW storage facility.(5) Values for the relative humidity were not given, but the environment provided by this facility for the stored drums was considered noncorrosive. The critical value at which atmospheric corrosion becomes significant for steel ranges from about 50% to 70%. In the less elaborate large engineered structures, which have only heating and ventilation system, temperatures will be kept above freezing during the winter but may easily exceed 100°F during the summer. For example, temperatures for the indoor storage of resin waste in spent resin holding tanks at two nuclear power plants have been reported to range from 40°F to 90°F (4°C to 32°C) and 70°F to 100°F (21°C to 38°C).(6) At the other extreme, the wastes in

a simple fenced-in concrete storage pad will be exposed to the outdoor temperature and the outdoor humidity, which over the course of a year in some locations may range from below -40°F (-40°C) to above 104°F (+40°C) and from 0% to 100%, respectively. For such outdoor storage there is, of course, a significant potential for wetting of the container by rain or, in locations near bodies of salt water, by salt spray, which is very corrosive towards carbon steel.

For α and β radiation it may be assumed to a very good approximation that radiation emitted within the waste package is absorbed within the package. The γ-radiation field within a particular waste package will depend on the radiation emitted within the package itself and also on the γ radiation emitted by nearby packages. The γ radiation emitted within a particular package is generally not completely absorbed within the package itself. For example, at points of contact between two containers loaded with γ emitters, the dose to the container material to a very good approximation will be the sum of the doses to those points for each of the two containers in isolation, i.e., when considering the dose to waste packages stored in proximity to one another, the γ-radiation field intensities of the individual packages should be superimposed. The dose to the contents of a waste package from the adjacent waste packges in a closely packed stacked array of such packages may be conservatively estimated by replacing the individual waste packages by an infinite medium. For example, the γ-ray dose to the contents of a stacked 55-gallon drum may be conservatively estimated by tripling the γ-ray dose to a 55-gallon drum in isolation. (It is assumed in making this estimate that all the drums in the stacked array contain the same concentrations of γ emitters.)[2]

It should be noted that in certain respects, the storage environment can be more severe than the disposal environment. According to guidance provided by the NRC to waste generators, under the expected disposal conditions, Class B and C waste forms should maintain gross physical properties and identity over a 300-year period and high integrity containers should be designed to maintain their structural integrity over such a period. Yet, because of the greater severity of certain storage environment, waste packages which would be expected to meet the 300-year disposal lifetime criteria may suffer severe performance degradation over a much shorter extended storage period. Among the ways in which a storage environment can be more severe than a disposal environment are temperature fluctuations (in unheated facilities in areas with cold winters) and corrosive atmospheres (e.g., industrial and marine atmospheres, as well as acid deposition). Also, no subsequent handling of the waste package after disposal is anticipated. Stored waste packages, on the other hand, need to maintain sufficient integrity to prevent dispersal of the waste during storage, transport, and handling up to and including emplacement for disposal. Loss of waste package integrity prior to disposal will require repackaging of the waste.

THE LOW-LEVEL RADWASTE PACKAGE

Properties of Waste Package Components

In this section, an overview is given of the properties and behavior of low-level radioactive waste (LLRW) streams, solidification agents, and

container materials. The emphasis is on those characteristics of these materials that may be important for predicting the behavior of the waste forms and containers during extended storage and for assessing the effect of extended storage on waste form stability and container integrity during transport and after disposal. In addition to ordinary chemical processes which may degrade the performance of the binder or container materials (e.g., atmospheric corrosion of carbon steel containers), the effects of the radiation field on the properties and behavior of the waste package materials are also considered.

In 10 CFR Part 61 Subpart D, LLRW is classified based on the concentration of radionuclides. Class A waste must meet certain minimum requirements for near-surface disposal and Class B and Class C wastes, with progressively higher concentrations of certain radionuclides, must meet more rigorous requirements for disposal. Class A wastes are mostly trash, paper, plastic, low-specific activity resins, and various institutional wastes; Class B wastes tend to be evaporator concentrates, resins, and spent filters; Class C wastes include certain wastes generated by industry, e.g., rejected or spent radiation sources, as well as discarded activated parts and equipment from commercial nuclear power plants.[7,8]

It must be emphasized that non-radiolytic effects are likely to be the primary concern for the majority of LLRW packages. Based on the concentrations of radionuclides, most LLRW packages are found to contain Class A waste. For example, according to a recent study by New York State,[7] the LLRW volumes generated by the commercial sector (i.e., commercial nuclear power plants, academic and medical institutions, and industries) may be categorized as follows: 60% Class A, 30% Class B, and 10% Class C. Even higher percentages of Class A waste have been estimated as a result of a survey carried out by BNL for the NRC.[8] The 16 nuclear power plants responding to the survey all reported that over 80% of their LLRW volume shipped off-site in 1984 was Class A. In this regard, it should be emphasized that the information in this paper is based on the results of tests and experiments that in many cases, particularly for phenomena involving radiation, were carried out under worst-case (or even beyond realistic worst-case) conditions in order to accelerate testing or for the sake of conservatism.

The following discussion of waste package component characteristics deals only with fuel-cycle wastes. Because of the varied nature of non-fuel-cycle wastes, generic waste descriptions are not possible. Concerns such as radiolytic gas generation, production of corrosive liquids, and biodegradation will be relevant to particular non-fuel-cycle wastes, but except in special cases, e.g., LLRW generated by Union Carbide Corporation, New England Nuclear Corporation, and the 3M Corporation as described in recent reports by BNL for the NRC,[9,10,11] no general accounts of properties and behavior are available. Even for these special cases, the descriptions refer to wastes generated prior to the effective date of 10 CFR Part 61. If a non-fuel-cycle waste is Class A, it is likely to be stored in dewatered form in its shipping container; if a non-fuel-cycle waste is Class B or Class C, then stabilization, either by incorporation into a binder material or by use of a high integrity container (HIC) is required. In either case, much of the discussion below will be applicable. Based on the results of a recent survey of LLRW generators,[8] only a small

proportion (<5%) of the non-fuel-cycle LLRW volume is likely to be greater than Class A.

Container Materials: Carbon Steel

- *The following generic types of corrosion are considered to be of* concern in the degradation of steel LLRW containers during storage: uniform attack, localized attack (pitting and crevice corrosion), galvanic attack, dealloying attack, and cracking phenomena (stress corrosion cracking).

- Corrosion by the atmosphere, generally in the form of uniform corrosion, results from the interaction of carbon steel container material with the atmosphere and depends on the temperature, the relative humidity, and the contaminants in the atmosphere. This is the familiar but somewhat difficult-to-quantify type of corrosion which is commonly known as "rust". Rates of 0.1 to 0.5 mils per year (mpy) are reported for the atmospheric corrosion of steels in an industrial atmosphere; these values are ten-year averages with about half of the corrosion occurring during the first year.[12] Rates of 30 to 55 mils over a 20-year period have been estimated from tests of carbon steel in a marine atmospheric environment, which is one of the most severely corrosive atmospheric environments because of the presence of salt water spray.[13]

- Corrosion of carbon steel containers may occur as a result of chemical reactions with aggressive components of the waste.

  - Corrosion rates of 0.4 to 4 mpy have been reported for mild steel immersed in various simulated unsolidified LLRW as a result of some preliminary work at BNL.[14,15] (This is of relevance for carbon steel containers with Class A waste, which does not have to be solidified but only dewatered).

  - Corrosion of carbon steel embedded in solidified wastes has also been observed. It is minimal for steel embedded in cement.[14] Corrosion of metals in bitumen has been attributed to biodegradation.[16] A corrosion rate of about 0.01 mil/day (4 mpy) is reported for mild steel embedded in waste forms consisting of a chelating decontamination reagent solidified in vinyl ester-styrene.[17]

Container Materials: Polyethylene[18,19]

- High density polyethylene (HDPE) is resistant to attack by a large number of chemical reagents (at least in the absence of a radiation field).

- Irradiation of polyethylene under anoxic conditions promotes cross-linking rather than degradation. Irradiation in air produces, in addition, radiolytic oxidation at the surface. This oxidized zone is believed to gradually penetrate into the bulk of the polyethylene material as the irradiation proceeds, eventually resulting in oxidative degradation of the material. In addition to the total

dose, the dose rate is once again important in these radiolytic processes. Furthermore, the rate-limiting steps of irradiation-induced cross-linking and of radiolytic oxidation are thought to be activated processes, so that the rate will be temperature dependent. It is not clear however, whether radiolytic oxidation of HDPE is an important degradation mode for containers stored at ordinary temperatures.

Binder Materials: Bitumens

- Radiolytic generation of gas has been observed in bitumens. The major component of the gas is hydrogen, which may pose a flammability or explosion hazard under certain storage conditions. The G-values for gas generation depend on dose rate and the presence of oxygen, whether in the gas phase or incorporated into the solid matrix of oxidized bitumens.[18]

- Biodegradation of bitumens has been observed. There is some evidence that corrosive substances may be produced as a result of biodegradation of bitumens.[16]

Binder Materials: Cement

- Radiolytic generation of gas, predominantly hydrogen, has been observed in waste forms consisting of low-level waste solidified in cement and has been attributed to radiolysis of water in the cement.[20]

- Freeze-thaw cycling can damage cements which contain sufficient amounts of freezable water, particularly if mitigative measures have not been taken (e.g., air entrainment).[21]

- Certain of the products of waste radiolysis, such as low-molecular weight organic acids, have been found to attack cement.[21]

Binder Materials: Thermosetting Organic Polymers

- Radiolytic gas generation has been observed from at least one thermosetting organic polymer, vinyl ester-styrene, but the details are proprietary. There does not appear to be any information on the radiolytic generation of corrosives from this category of binder materials.

- During short-term, small-scale testing, a small amount (<0.4 volume percent) of a free liquid (pH=5) as been observed on the surface of waste forms consisting of simulated LWR waste streams solidified in vinyl ester-styrene. Thermal cycling of these waste forms increases the amount of this free liquid (up to 1.3 volume percent).[22] Similar data on full-scale waste forms do not seem to be available.

Ion-Exchange Resins

- Radionuclide loadings on spent ion-exchange resins vary, typical loadings at different reactors ranging from 0.1 to 30 Ci/ft^3 and maximum loadings from 0.3 to 60 Ci/ft^3. Dose rates to the resin for a loading of 10 Ci/ft^3 are estimated to range from 10^2 to 10^3 rad/h. Based on the guidance given to LLRW generators in the NRC Technical Position (TP) on Waste Form, the accumulated dose to the resins should not exceed 10^8 rad.[23]

- A variety of radiation effects have been identified which may be of significance for the storage of spent ion-exchange resins, especially if the 10^8 rad accumulated dose limit recommended in the TP is exceeded. It should be noted that the following radiation processes may be affected both quantitatively and qualitatively by the partial pressure of oxygen and by the dose rate.

  - Irradiation of ion-exchange resins may produce and/or release chemically active substances that can adversely affect the binder and container materials.[15]

  - Radiolytic generation of gases from ion-exchange resins has been observed in the laboratory and from the Epicor-II pre-filters used in the cleanup of contaminated water at Three Mile Island Unit 2 (TMI-2).[25] The predominant gas was found to be hydrogen, which may pose a flammability or explosion hazard under certain storage conditions. In addition, the generation of other gases, such as carbon dioxide, methane, and trimethylamine, as well as the uptake of oxygen have been reported as resulting from the irradiation of ion-exchange resins.[25]

- Biodegradation has been identified as a possible cause of agglomeration of and gas buildup in unsolidified ion-exchange resins during storage.[26]

Other LWR Wastes

- The radiolytic generation of gases (predominantly hydrogen) and of corrosive substances has been observed in cellulosic materials.[11]

- Because much of this waste consists of organic materials (e.g., cellulose) biodegradation is likely if the wastes have not been self-sterilized or treated with a biocide. However, specific information on the nature of the biodegradative products (e.g., gases, corrosive materials) and their effects, if any, on binder and container materials does not seem to be available.

Waste Package Performance During and After Extended Storage

Only a few data on the performance of low-level waste packages during storage and handling are available (e.g., radiolytic gas generation data from the Epicor-II pre-filter resins at TMI-2) and thus their performance for the most part must be inferred from the characteristics of the storage

environments and the properties of the waste package components discussed above.

One of the most important performance parameters for steel containers, especially carbon steel drums and liners, is the rate of corrosion of the container material. Corrosion of carbon steel containers has not been considered a problem since such containers, which have generally been given no credit for containment after emplacement in the disposal trench, have traditionally been used for the short-term storage and shipment or dry or dewatered Class A waste and of solidified Class B and Class C waste. However, if an extended storage period between the packaging and disposal operations should become necessary, then container corrosion will need to be addressed because of its possible effect on the performance of the waste package during storage and during handling after storage.

Internal corrosion of shipping containers, whether radiolytic or nonradiolytic in origin, may lead to failure of the container during storage, either by localized pitting attack, resulting in penetration of the container wall, or by any of several corrosive attack mechanisms, resulting in loss of structural strength and possibly in eventual collapse of stacked containers. Atmospheric corrosion of shipping containers may also result in failure of the containers during storage. Furthermore, as a result of the action of internal or external corrosion (or both), the containers may not meet the Department of Transportation (DOT) requirements for radwaste shipments, and, as a result, repackaging of the wastes may be necessary.

The performance of polyethylene high integrity containers during handling after storage may also be affected by an extended storage period. Radiolytic cross-linking resulting in embrittlement of the container material and radiolytic oxidative degradation resulting in loss of strength of the material may compromise the ability of the container to meet the free drop and lifting load requirements for high integrity containers. Once again, repackaging of the wastes for shipment could become necessary. (It should be noted here that the rates of these radiolytic processes in polyethylene need to be determined under representative storage conditions in order to ascertain the validity of extrapolations by Dougherty et al.[19])

Radiolytic gas generation from waste, binder, or container material may result in pressurization, causing damage to the waste form, the container, or both. In additon, the gas itself may pose a flammability or explosion hazard. Biodegradative processes during storage may also result in container pressurization from gas production.

Other processes during storage may contribute to problems with waste package performance after storage. Agglomeration of spent ion-exchange resins stored for extended periods in resin holding tanks may result from either biodegradative or radolytic processes and can interfere with subsequent transfer and processing of the resins. Temperature fluctuations (freeze-thaw cycling) in unheated storage facilities may result in the loss of monolithic physical integrity of cement waste forms, especially if mitigative measures such as air entrainment have not been taken. The radiolytic production of corrosives from the wastes may also compromise the physical integrity of waste forms, especially cement.

Based on actual field experience and field studies with radwaste packages or similar systems, corrosion of carbon steel container material and radiolytic generation of flammable gases are the waste package performance problems of greatest concern. A review of the corrosion of steel containers of transuranic waste has been conducted by DOE[13] and contains atmospheric corrosion data for carbon steel in a wide range of environments, from the extremely corrosive marine atmosphere to the relatively benign desert environment. Unfortunately, with the exception of some preliminary studies alluded to above, primarily at BNL,[14,15] rates of corrosion of container materials by various low-level wastes and waste forms do not seem to be readily available. Because of all the possible combinations of waste forms, solidification agents, and container materials, obtaining such data could involve a long and expensive test program. There seems to be somewhat better data on the rate of radiolytic gas generation, at least from highly loaded ion-exchange resins, since calculations of the rate of gas generation from these resins have been verified by the observed rate of hydrogen gas generation from the Epicor-II pre-filter liners used in the TMI-2 cleanup.[25]

MITIGATIVE MEASURES

Mitigative measures to counteract potential waste package performance problems during and as a result of extended storage of LLW should be considered.

- The corrosion of carbon steel by aggressive constituents from either the low-level waste or the atmosphere may be reduced or prevented by use of protective coatings. An example of this practice is the use of galvanized steel drums, i.e., drums coated with zinc metal. Several kinds of organic coatings have been developed for the protection of metals, but proper preparation of the base metal -- e.g., removal of all corrosion products -- before application of these coatings is necessary in order to avoid later blistering and spalling of the coating.

- Atmospheric corrosion of steel containers may be reduced or eliminated by several methods. In enclosed structures this result may be achieved by lowering the relative humidity of the storage environment, e.g., by heating the air or by the use of hygroscopic drying agents. For more open storage areas the protection provided by a commercially available weather shield may suffice; this is basically an air-inflated fabric structure which protects against atmospheric corrosion by eliminating the exposure of the waste containers to rainfall and air-borne particles.

- The problems resulting from radiolytic gas generation may be alleviated by the use of catalysts to promote recombination of hydrogen and oxygen gases in situations where both gases might be generated -- e.g., from radiolysis of water in inorganic zeolites -- and by the use of getter materials to absorb hydrogen gas. The rate of radiolytic gas generation is likely to be small, probably only cubic centimeters of gas per day from some Class C waste packages. Pressurization may be avoided with a pressure-relieved container. Accumulations of hazardous gases may be avoided by storing

wastes which are likely to generate gases in an adequately ventilated area monitored for radionuclides and explosive gas mixtures.

- Biodegradative processes resulting in resin agglomeration, gas generation, or corrosion may be prevented by the addition of a suitable biocide to the waste at the start of the storage period.

- Radiolytic degradation of polyethylene, particularly radiation-induced cross-linking leading to loss of ductility and eventual embrittlement of the container material, may be avoided by storing the waste in an on-site holding tank, if practicable. The waste would not be transferred to a HIC until immediately before shipment for burial.

- The resistance of cement waste forms to freeze-thaw cycling may be increased by the use of appropriate additives, in particular, those which enhance air entrainment.

- Low-activity wastes (Class A) should not be stored adjacent to high-activity wastes (Class C) in order to avoid radiolytic degradation of the low-activity wastes by the γ-radiation field of the high-activity wastes.

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The views expressed in this paper are not necessarily those of the U.S. Nuclear Regulatory Commission.

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