NUREG/CR-0130
Addendum 3

Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station

Classification of Decommissioning Wastes

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Operated by
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Prepared for
U.S. Nuclear Regulatory
Commission

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ABSTRACT

The radioactive wastes expected to result from decommissioning of the reference pressurized water reactor power station are reviewed and classified in accordance with 10 CFR 61.

The 17,885 cubic meters of waste from DECON are classified as follows: Class A, 98.0%; Class B, 1.2%; Class C, 0.1%. About 0.7% (133 cubic meters) of the waste would be generally unacceptable for disposal using near-surface disposal methods.

CONTENTS

ABSTRACT iii

FOREWORD vii

STUDY CONTRIBUTORS xi

1.0 INTRODUCTION 1.1

2.0 SUMMARY 2.1

3.0 10 CFR 61 REQUIREMENTS 3.1

4.0 ALTERNATIVES FOR DECOMMISSIONING THE REFERENCE PWR 4.1

 4.1 THE REFERENCE PWR 4.1

 4.2 DECOMMISSIONING ALTERNATIVES 4.1

5.0 CHARACTERIZATION OF PWR DECOMMISSIONING WASTES 5.1

 5.1 NEUTRON-ACTIVATED MATERIALS 5.1

 5.2 CONTAMINATED MATERIALS 5.1

 5.3 RADIOACTIVE WASTES 5.8

6.0 CLASSIFICATION OF PWR DECOMMISSIONING WASTES 6.1

 6.1 NEUTRON-ACTIVATED MATERIALS 6.1

 6.2 CONTAMINATED MATERIALS 6.8

 6.3 RADIOACTIVE WASTES 6.8

7.0 CONCLUSIONS 7.1

8.0 REFERENCES 8.1

TABLES

2.1 Classification of Radioactive Wastes from PWR Decommissioning........ 2.3

3.1 Limiting Concentrations of Long-Lived Radionuclides Used as Bases for Waste Classification in 10 CFR 61.......................... 3.2

3.2 Limiting Concentrations of Short-Lived Radionuclides Used as Bases for Waste Classification in 10 CFR 61.......................... 3.2

5.1 Neutron-Activated Materials from DECON at the Reference PWR.......... 5.2

5.2 Neutron-Activated Materials from 30-Year Deferred Decontamination at the Reference PWR................................ 5.3

5.3 Neutron-Activated Materials from 50-Year Deferred Decontamination at the Reference PWR................................ 5.4

5.4 Neutron-Activated Materials from 100-Year Deferred Decontamination at the Reference PWR................................ 5.5

5.5 Neutron-Activated Materials from ENTOMB at the Reference PWR......... 5.6

5.6 Contaminated Materials from PWR Decommissioning...................... 5.7

5.7 Radioactive Wastes from Decommissioning at the Reference PWR......... 5.9

6.1 Classification of Radioactive Wastes from PWR Decommissioning........ 6.2

6.2 Waste Classifications of Neutron-Activated Materials from DECON at the Reference PWR.. 6.3

6.3 Waste Classifications of Neutron-Activated Materials from 30-Year Deferred Decontamination at the Reference PWR................ 6.4

6.4 Waste Classifications of Neutron-Activated Materials from 50-Year Deferred Decontamination at the Reference PWR................ 6.5

6.5 Waste Classifications of Neutron-Activated Materials from 100-Year Deferred Decontamination at the Reference PWR............... 6.6

6.6 Waste Classifications of Neutron-Activated Materials from ENTOMB at the Reference PWR.. 6.7

6.7 Waste Classifications of Radioactive Wastes from Decommissioning at the Reference PWR................................ 6.9

FOREWORD
BY
NUCLEAR REGULATORY COMMISSION STAFF

The NRC staff is reappraising its regulatory position relative to the decommissioning of nuclear facilities.[1] As a part of this activity, the NRC has initiated two series of studies through technical assistance contracts. These contracts are being undertaken to develop information to support the preparation of new standards covering decommissioning.

The basic series of studies covers the technology, safety, and costs of decommissioning reference nuclear facilities. Light water reactors and fuel-cycle and non-fuel-cycle facilities are included. Facilities of current design on typical sites are selected for the studies. Separate reports are prepared as the studies of the various facilities are completed.

The first report in this series covers a fuel reprocessing plant;[2] the second addresses a pressurized water reactor;[3] and the third deals with a small mixed oxide fuel fabrication plant.[4] The fourth report, an addendum to the pressurized water reactor report,[5] examines the relationship between reactor size and decommissioning cost, the cost of entombment, and the sensitivity of cost to radiation levels, contractual arrangements, and disposal site charges. The fifth report in this series deals with a low-level waste burial ground;[6] the sixth covers a large boiling water reactor power station;[7] and the seventh examines a uranium fuel fabrication plant.[8] The eighth report covers non-fuel-cycle nuclear facilities.[9] The ninth report, an addendum to the low-level waste burial ground report,[10] supplements the description of environmental radiological surveillance programs used in the parent document. The tenth report deals with a uranium hexafluoride conversion plant.[11] The eleventh report addresses the decommissioning of nuclear reactors at multiple-reactor power stations.[12] The twelfth report covers nuclear research and test reactors.[13] The thirteenth report examines the decommissioning of reference light water reactors that have been involved in serious accidents.[14] The fourteenth and fifteenth reports are addendums to the pressurized water reactor report and the boiling water reactor report, respectively, and examine the impacts on decommissioning of both of these plant types of a temporary inability to dispose of waste offsite at the time of decommissioning.[15,16] The sixteenth report, an addendum to the nuclear research and test reactors report, addresses the sensitivity of decommissioning radiation exposure and costs to selected parameters at nuclear research and test reactor facilities.[17] The seventeenth report deals with the decommissioning of independent spent fuel storage installations.[18] This addendum to the pressurized water reactor report examines the radioactive wastes expected to result from decommissioning the reference PWR and classifies those wastes in accordance with 10 CFR 61.

An additional decommissioning topic will be reported tentatively as follows:

FY 1984 • Post-Accident Decommissioning at Fuel Cycle and Non-Fuel Cycle Facilities

The second series of studies covers supporting information on the decommissioning of nuclear facilities. Four reports have been issued in the second series. The first consists of an annotated bibliography on the decommissioning of nuclear facilities.[19] The second is a review and analysis of current decommissioning regulations.[20] The third covers the facilitation of the decommissioning of light water reactors.[21] The fourth report covers the establishment of an information base concerning monitoring for compliance with decommissioning survey criteria.[22] The fifth report addresses the technology and cost of termination surveys associated with decommissioning of nuclear facilities.[23]

The information provided in this report on decommissioning of a pressurized water reactor, including any comments, will be included in the record for consideration by the Commission in establishing criteria and new standards for decommissioning. Comments on this report should be mailed to

Chief
Chemical Engineering Branch
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U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

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1.0 INTRODUCTION

In the analysis of the decommissioning of the reference pressurized water reactor power station (PWR) reported previously in NUREG/CR-0130,[1,2] it was assumed that all of the low-level radioactive waste from decommissioning could be disposed of by land disposal at licensed shallow-land burial grounds. The purpose of this addendum is to examine this assumption of waste suitability for shallow-land burial by classifying the decommissioning wastes from the reference PWR study in terms of waste classes defined in Title 10, Part 61 of the Code of Federal Regulations (10 CFR 61). This information is intended for use by the Nuclear Regulatory Commission (NRC) as background data and bases in the modification of existing regulations and the development of new regulations pertaining to decommissioning activities. This report should also be helpful to operators of nuclear power plants in estimating decommissioning waste management costs and to burial ground operators in planning for the land burial of decommissioning wastes.

By Federal Register notice dated December 27, 1982,[3] the NRC promulgated a new regulation (10 CFR 61) governing the land disposal of low-level radioactive waste (LLW). This new regulation establishes three classes of LLW, based on radiological hazard, and provides minimum waste form and stability requirements and near-surface disposal requirements for the land burial of these wastes. Wastes with radionuclide concentrations that do not meet the classification criteria of 10 CFR 61 are generally unacceptable for routine near-surface disposal. Licensees are required to safely store these wastes until a specific determination can be made on their disposition.

The principal results of this analysis of classification of decommissioning wastes from the reference PWR are summarized in Section 2. A summary of waste classification requirements from 10 CFR 61 is given in Section 3. The decommissioning alternatives evaluated in the reference PWR study are briefly summarized in Section 4. Information on quantities and radionuclide contents of the radioactive wastes from decommissioning the reference PWR is presented in Section 5. The classification of these wastes in terms of the waste classes defined in 10 CFR 61 is presented in Section 6. Conclusions and recommendations are given in Section 7.

2.0 SUMMARY

In the analysis of the decommissioning of a reference pressurized water reactor (PWR) reported previously in NUREG/CR-0130, it was assumed that the low-level radioactive wastes from decommissioning could be disposed of by near-surface burial at a licensed shallow-land burial ground. The purpose of this addendum is to reevaluate this assumption in terms of the recently established requirements for waste characterization published in Title 10, Part 61 of the Code of Federal Regulations (10 CFR 61). To accomplish this reevaluation, radioactive wastes from the conceptual decommissioning of the reference PWR are classified in terms of the waste classes specified in Section 61.55 of 10 CFR. Section 61.55 establishes three classes of low-level radioactive waste (LLW) based on radiological hazard, and defines limiting concentrations of long-lived and short-lived nuclides for each waste class. Minimum waste form and stability requirements are also defined for each waste class.

Class A waste has the lowest concentrations of radioactivity and must meet minimum requirements for burial designed to facilitate handling at the disposal site and provide protection of the health and safety of burial site personnel. Class B waste has higher concentrations of radioactivity and must meet more rigorous requirements on waste form to ensure stability after disposal. Class C waste must not only meet more rigorous requirements on waste form to ensure stability but also requires additional measures at the disposal facility to protect against inadvertent intrusion. Wastes with radionuclide concentrations that do not meet the classification criteria of 10 CFR 61 are generally unacceptable for routine near-surface disposal and must be safely stored by the licensee until a specific determination can be made on their disposition.

Radioactive materials that require disposal as a consequence of conceptual decommissioning of the reference PWR include 1) neutron-activated materials, 2) contaminated materials, and 3) radioactive wastes. Neutron-activated materials include the reactor pressure vessel, vessel internal components and structures, and the surrounding concrete biological shield. Significant amounts of the radioisotopes ^{59}Ni, ^{63}Ni, and ^{94}Nb are present in neutron-activated decommissioning wastes. The presence of these isotopes can affect the waste classification of neutron-activated material and could result in these wastes being unsuitable for shallow-land disposal.

Contaminated materials from PWR decommissioning include nearly all of the piping and equipment in the reactor containment and in the fuel, auxiliary, and control buildings, as well as many of the concrete surfaces of these buildings. There are no significant quantities of limiting long-lived isotopes in contaminated materials. The principal limiting short-lived isotopes in these materials are ^{60}Co and ^{137}Cs. Average concentrations of limiting short-lived radionuclides in contaminated materials are low enough that these materials constitute Class A waste.

Radioactive wastes from reactor decommissioning operations include both wet solid wastes and dry solid wastes. Wet solid wastes are the solidified wastes that result from the processing of chemical decontamination solutions and contaminated water volumes. Dry solid wastes include discarded contaminated materials such as rags and wipes, plastic sheeting, contaminated tools, and anti-contamination clothing. There are no significant quantities of limiting long-lived isotopes in either wet solid or dry solid radioactive wastes. The principal limiting short-lived isotopes in the waste are ^{60}Co and ^{137}Cs. Most of the radioactive waste from decommissioning operations can be classified as Class A waste, with only about 25% (by volume) being classified as Class B waste.

The alternative approaches to decommissioning a nuclear power station considered in the reference PWR study are DECON (immediate decontamination to unrestricted release), SAFSTOR (safe storage with deferred decontamination to unrestricted release), and ENTOMB (entombment of radioactive materials with decay to unrestricted release). The DECON alternative results in a greater quantity of radioactive waste being generated, and requires a greater commitment of disposal site space than either of the other two decommissioning alternatives. The nuclear waste generated during SAFSTOR operations includes radioactive waste from preparations for safe storage and waste generated during deferred decontamination. For safe storage periods of 50 years or longer, because of radioactive decay, the total waste from all SAFSTOR operations is significantly less than the waste volume generated during DECON. In the ENTOMB scenario analyzed in the reference PWR study, the long-lived reactor vessel internals are removed and shipped to a licensed burial site prior to entombment. The nuclear wastes resulting from ENTOMB operations include these long-lived reactor components, any contaminated material not accommodated within the confines of the entombment structure, and radioactive wastes resulting from ENTOMB activities. The total waste volume generated for offsite disposal in this alternative is substantially less than that generated for DECON.

A summary of the classification requirements for the radioactive wastes from conceptual decommissioning of the reference PWR is given in Table 2.1. Data used to define the burial volumes and radionuclide concentrations that form the bases for the waste classification results are from Reference 1. While the total nuclear waste volume varies by about a factor of 10, depending on the decommissioning alternative, the volumes of Class C waste and of waste that exceeds Class C limits are essentially independent of the decommissioning alternative.

Most of the radioactive waste from PWR decommissioning (86% to 98%, depending on the decommissioning alternative and the volume of waste generated for disposal) can be classified as Class A waste. To be acceptable for shallow-land disposal, this waste must meet the minimum packaging and waste form requirements given in 10 CFR 61.56(a).

TABLE 2.1. Classification of Radioactive Wastes from PWR Decommissioning

Decommissioning Alternative	Burial Volume[a] (m^3)	Waste Class Assignment[b]							
		Class A		Class B		Class C		Exceeds Class C Limits	
		Volume (m^3)	Percent	Volume (m^3)	Percent	Volume (m^3)	Percent	Volume (m^3)	Percent
DECON	17 885	17 521	98.0	214	1.2	17	0.1	133	0.7
30-YR SAFSTOR[c]	17 888	17 615	98.5	123	0.7	17	0.1	133	0.7
50-YR SAFSTOR[c]	1 830	1 565	85.5	115	6.3	17	0.9	133	7.3
100-YR SAFSTOR[c]	1 780	1 530	85.9	100	5.6	17	1.0	133	7.5
ENTOMB	3 060	2 696	88.1	214	7.0	17	0.5	133	4.4

(a) Data on burial volumes for decommissioning wastes are from Sections G.4, H.3, and H.5 of Reference 1, and Section 4.4 of Reference 2.

(b) Based on limiting concentrations of long- and short-lived radionuclides given in Table 1 and Table 2 of 10 CFR 61.55.

(c) Includes radioactive wastes from both preparations for safe storage and deferred decontamination.

A relatively small amount of the nuclear waste from PWR decommissioning is classified as Class B waste. This waste includes some neutron-activated stainless steel components with significant amounts of ^{63}Ni, spent resins and used particulate filters with high specific activity, and a fraction of the dry solid waste generated during decommissioning operations. Class B wastes must meet the stability requirements of 10 CFR 61.56(b) that are intended to provide protection against structural degradation following burial. Most of the Class B waste from PWR decommissioning would meet these structural stability requirements with little or no additional processing.

Approximately 17 m^3 of the radioactive waste from decommissioning the reference PWR is estimated to be Class C waste. This waste consists of the neutron-activated stainless steel upper core grid plate and the lower support columns from inside the reactor vessel, which contain high concentrations of ^{63}Ni and ^{94}Nb. Class C waste must meet the stability requirements of 10 CFR 61.56(b) and must also be disposed of by the burial site operator using methods that provide additional protection against inadvertent intrusion into the burial ground for at least 500 years. Hence, the disposal costs for Class C waste would probably be significantly higher than the disposal costs for Class A or Class B wastes. In this addendum, no attempt is made to estimate these additional costs.

The neutron activated stainless steel core shroud and the lower grid plate have such high concentrations of ^{59}Ni, ^{63}Ni, and ^{94}Nb that they exceed the Class C limits of 10 CFR 61. The radioactivity of the lower core barrel and the thermal shields also exceeds Class C limits by a small amount. Material that exceeds kClass C limits is generally unacceptable for routine near-surface disposal. The licensee is required to safely store this waste until a specific determination can be made on its disposition.

3.0 10 CFR 61 REQUIREMENTS

By Federal Register Notice dated December 27, 1982,[3] the NRC amended its regulations to provide specific requirements for licensing the land disposal of low-level radioactive wastes containing source, special nuclear, or byproduct material. The majority of these requirements are contained in a new Part 61 to Title 10 of the Code of Federal Regulations (10 CFR 61), "Licensing Requirements for Land Disposal of Radioactive Waste", which took effect on January 23, 1983. Some additional requirements directed primarily at waste generators and handlers were concurrently published as a new Section 20.311 of Part 20, "Standards for Protection Against Radiation." The effective date of 10 CFR 20.311 is December 27, 1983.

Although the new requirements apply primarily to disposal site operators, they also include provisions that pertain to persons who generate waste that will be disposed of at land disposal facilities. Licensees generating waste have a responsibility to determine the presence and concentrations of various nuclides listed in Section 61.55, and thereby to classify the waste. Packaging and waste stability requirements for waste destined for shallow-land burial depend on the waste classification. Wastes that do not meet the classification requirements of Section 61.55 require special provisions for their disposal and would, in most instances, require interim storage pending identification of a suitable disposal alternative.

Section 61.55 defines radioactive waste suitable for land disposal as falling into one of three categories, i.e., Class A waste, Class B waste, and Class C waste. Wastes are determined to fall into one of these classes by comparison to limiting concentrations of particular long-lived and short-lived radionuclides. Class A waste contains the lowest radionuclide concentrations and must meet only minimum waste form requirements. Class B and C wastes contain higher radionuclide concentrations and must meet both the minimum waste form and the stability requirements of Section 61.56. Class C waste must be disposed of by use of methods that provide added protection against inadvertent intrusion into the burial ground.

The basis for classification of LLW in terms of long-lived radionuclide concentrations is shown in Table 3.1, reproduced from Table 1 of 10 CFR 61.55. The basis for classification of LLW in terms of short-lived radionuclide concentrations is shown in Table 3.2, reproduced from Table 2 of 10 CFR 61.55.

TABLE 3.1. Limiting Concentrations of Long-Lived Radionuclides Used as Bases for Waste Classification in 10 CFR 61[(a)]

Radionuclide	Concentration (curies/m^3)
^{14}C	8
^{14}C in activated metal	80
^{59}Ni in activated metal	220
^{94}Nb in activated metal	0.2
^{99}Tc	3
^{129}I	0.08
Alpha-emitting transuranic nuclides with half-life greater than five years	100[(b)]
^{241}Pu	3 500[(b)]
^{242}Cm	20 000[(b)]

(a) Reproduced from Table 1 of 10 CFR 61.55
(b) Units are nanocuries per gram.

TABLE 3.2. Limiting Concentrations of Short-Lived Radionuclides Used as Bases for Waste Classification in 10 CFR 61[(a)]

Radionuclide	Concentration (curies/m^3) Column 1	Column 2	Column 3
Total of all nuclides with half-life less than five years	700	(b)	(b)
^{3}H	40	(b)	(b)
^{60}Co	700	(b)	(b)
^{63}Ni	3.5	70	700
^{63}Ni in activated metal	35	700	7 000
^{90}Sr	0.04	150	7 000
^{137}Cs	1	44	4 600

(a) Reproduced from Table 2 of 10 CFR 61.55
(b) There are no limits established for these radionuclides in Class B or C waste. Practical considerations such as the effects of external radiation and internal heat generation on transportation, handling, and disposal will limit the concentrations for these wastes. These wastes shall be Class B unless the concentrations of other nuclides in Table 3.2 determine the waste to be Class C independent of these nuclides.

If the radioactive waste contains only radionuclides listed in Table 3.1 (long-lived radionuclides), classification is determined using the following guidelines. If the concentration does not exceed 0.1 times the value in the table, the waste is Class A. If the concentration exceeds 0.1 times the value in Table 3.1 but does not exceed the value in the table, the waste is Class C. If the concentration exceeds the value in Table 3.1, the waste is generally unacceptable for near-surface disposal. For example, for Class A wastes the limiting concentration of long-lived alpha-emitting transuranic nuclides is 10 nCi/gram. For Class C wastes, the disposal limit for transuranic waste is set at 100 nCi/gram.

If the radioactive waste contains only radionuclides listed in Table 3.2 (short-lived radionuclides), classification is determined using the following guidelines. If the concentration does not exceed the value in Column 1, the waste is Class A. If the concentration exceeds the value in Column 1 but does not exceed the value in Column 2, the waste is Class B. If the concentration exceeds the value in Column 2 but does not exceed the value in Column 3, the waste is Class C. If the concentration exceeds the value in Column 3, the waste is generally acceptable for near-surface disposal.

If radioactive waste does not contain any of the radionuclides in either Table 3.1 or Table 3.2, it is Class A.

If radioactive waste contains a mixture of both long-lived and short-lived nuclides, some of which are listed in Table 3.1 and some in Table 3.2, the waste classification is determined in the following manner. If the concentration of a nuclide listed in Table 3.1 does not exceed 0.1 times the value given in Table 3.1, the class is determined by the concentration of nuclides listed in Table 3.2. If the concentration of a nuclide listed in Table 3.1 exceeds 0.1 times the value listed in Table 3.1 but does not exceed the value in Table 3.1, the waste is Class C, provided the concentration of nuclides listed in Table 3.2 does not exceed the values shown in Column 3 of Table 3.2.

For determining the classification of waste that contains a mixture of radionuclides, the sum-of-fractions rule described in 10 CFR 61.55(a)(7) is used. To use the sum-of-fractions rule, it is necessary to divide each nuclide's concentration by the appropriate limit and add the resulting values. The appropriate limits must all be taken from the same column of the same table. The sum of the fractions for the column must be less than 1.0 if the waste class is to be determined by that column.

The NRC has prepared a technical position(4) describing procedures acceptable to the regulatory staff which may be used by licensees to determine the presence and concentrations of radionuclides listed in Table 3.1 and Table 3.2, thereby classifying wastes for near-surface disposal. The basic methods for identifying radionuclide concentrations in nuclear waste include the following:

- materials accountability
- classification by source
- gross radioactivity measurements
- direct measurement of individual radionuclides.

Materials accountability refers to the process whereby a given quantity (and resulting concentration) of radioactive material may be known to be contained within a given waste, or may be inferred by determining the difference between the quantities of radioactive material entering and exiting a particular process. Classification by source is similar to materials accountability and involves determining the radionuclide content and classification of waste through knowledge and control of its source. Gross radioactivity measurement entails the establishment of a program to correlate specific radionuclide concentrations in the waste with gross measurements of radioactivity levels. Radionuclide concentrations may also be measured directly or may be inferred by ratioing the concentrations of radioisotopes that can be readily measured.

The NRC technical position[4] also provides guidance on determining the waste volumes to be used in calculating radionuclide concentrations. In many cases the volume used for waste classification purposes may be taken to be the volume of the waste container. This would be true of trash waste streams compacted into shipping containers. If a particular waste is stabilized within a waste container using a solidification medium such as cement or bitumen, the classification volume may be considered to be the volume of the solidified mass. The waste classification volume of large unpackaged components such as contaminated pumps, heat exchangers, etc., may be taken to be the overall volume of the component.

If the volume of the waste container is significantly larger (i.e., more than 10% larger) than the volume of the contaminated waste, the volume used for classification purposes should be that of the waste. For example, for wastes such as ion exchange resins or filter media contained within a disposable demineralizer or liner, the volume used for waste classification should be the volume of the contained waste rather than the gross volume of the container. For neutron-activated materials such as the reactor pressure vessel or the vessel internals that are cut into sections and packaged for disposal, the volume for waste classification should be the full-density volume of the material (i.e., the weight divided by the density) rather than the container volume.

Section 10 CFR 61.55(a)(8) states that in determining radionuclide concentrations in nuclear waste, the concentrations may be averaged over the volume of the waste, or over the weight if the concentration units are expressed in nanocuries per gram. In the averaging process, consideration should be given to 1) whether the distribution of radionuclides within the waste can be considered to be reasonably homogeneous, and 2) whether the volume of the waste container is significantly larger than the volume of the waste itself and the differential volume consists largely of void space. Most waste forms may be considered homogeneous for purposes of waste classification. Examples of homogeneous wastes include spent ion exchange resins, filter media, solidified liquids, contaminated dirt, contaminated concrete, and contaminated trash when compacted in waste containers.

4.0 ALTERNATIVES FOR DECOMMISSIONING THE REFERENCE PWR

The quantities and curie contents of the radioactive wastes from light-water reactor decommissioning depend on several factors, including the reactor operating history, decontamination activities performed during the operating life, and the alternative chosen for decommissioning of the reactor. Three decommissioning alternatives, DECON, SAFSTOR, and ENTOMB, are analyzed in the reference study of PWR decommissioning. These alternatives are briefly described in this section. The characteristics of the radioactive wastes that result when each alternative is conceptually applied to the decommissioning of the reference PWR are summarized in Section 5.

4.1 THE REFERENCE PWR

The reference PWR is an 1175-MWe (3500-MWt) reactor, specifically the Trojan Nuclear Plant at Rainier, Oregon, operated by the Portland General Electric Company. The nuclear steam supply system is a four-loop pressurized water reactor manufactured by the Westinghouse Electric Company, and is generally representative of the current generation of large PWRs. Descriptive information about the reference plant is presented in Chapter 7 and Appendix A of Reference 1.

4.2 DECOMMISSIONING ALTERNATIVES

The alternative approaches to decommissioning a nuclear power station that are considered in the reference PWR study are DECON (immediate decontamination to unrestricted release), SAFSTOR (safe storage with deferred decontamination to unrestricted release), and ENTOMB (entombment of radioactive materials with decay to unrestricted release.[5,6] These alternatives can be defined as follows.

DECON is the prompt removal from the facility and site of all materials with residual radioactivity levels greater than those permitted for unrestricted use of the property. DECON meets the requirements for termination of the facility license and, under present regulatory requirements, is the only decommissioning alternative that renders the facility and site available for unrestricted use within a short time period. DECON requires the removal of all equipment, structures, and site materials that are radioactively activated or contaminated to levels greater than acceptable residual contamination levels. This alternative results in a greater quantity of radioactive waste being generated for offsite disposal and requires a greater commitment of disposal site space than either of the other two decommissioning alternatives.

SAFSTOR comprises those activities required to prepare and maintain the facility in a condition that poses an acceptable risk to the public and safely stores the property for a period to allow some decay of the onsite radioactivity, followed by decontamination of the facility to an unrestricted level. SAFSTOR includes three phases of activity: 1) preparations for safe storage, 2) safe storage, and 3) deferred decontamination. Preparations for safe storage include comprehensive cleanup and decontamination activities sufficient to allow shutdown of all plant systems and installation of security barriers and remotely monitored surveillance devices. Preparations for safe storage are followed by a period of continuing care (safe storage) to permit some decay of the residual radioactivity. Requirements during the continuing-care period include activities to maintain the structural integrity and prevent intrusion into the facility. Since materials having radioactivity levels above unrestricted release levels are still onsite, an amended nuclear license remains in force until the deferred decontamination is complete. At the conclusion of the safe storage period, deferred decontamination is accomplished to remove from the site any materials with residual radioactivity greater than that permitted for release of the property for unrestricted use. In the reference study, decommissioning requirements for continuing-care periods of 30, 50, and 100 years are analyzed. For continuing-care periods of 50 years or longer, because of radioactive decay, the total for the volume of nuclear waste generated during deferred decontamination plus the waste volume generated during preparations for safe storage is significantly less than the waste volume generated during DECON.

ENTOMB is the encasement and maintenance of nonreleasable radioactive materials in a monolithic structure of concrete or other structural material with long-term surveillance until the radioactivity has decayed to levels suitable for unrestricted use. The structure should be sufficiently strong and long-lived to ensure retention of the radionuclides during the long-term surveillance period. In the reference PWR study, the entombment structure is that portion of the reactor containment building located below the operating floor level.[2] A concrete barrier is postulated to be poured at this level to seal the building below the operating floor.

Two approaches to ENTOMB at a PWR are possible: 1) the reactor vessel internals, which have extremely long-lived radioactivity, are removed and shipped to a nuclear waste repository, and 2) the reactor vessel internals are left in place. In each case, as much of the contaminated equipment from outside the entombment structure as can be stored in the entombment structure is moved there. In the first case, because of the relatively short half-lives of the entombed radioactivity, it may be possible, without dismantling the structure, to terminate the amended nuclear license and release the structure for unrestricted use after a period of about 100 years. In the second case, existing regulations require the amended nuclear license to remain in force for an indefinite period.

The entombment scenario analyzed in the reference PWR study is the first approach, in which the long-lived reactor vessel internals are removed prior to entombment. The nuclear wastes generated for disposal include these long-lived reactor components, any contaminated material not accommodated within the confines of the entombment structure, and radioactive wastes resulting from ENTOMB activities. The total waste volume generated for offsite disposal in this alternative is substantially less than that generated for DECON.

5.0 CHARACTERIZATION OF PWR DECOMMISSIONING WASTES

The radioactive materials that require disposal as a consequence of light-water reactor decommissioning operations include 1) neutron-activated materials, 2) contaminated materials, and 3) radioactive wastes. Information on waste volumes, curie contents, and major radionuclides in the wastes from decommissioning the reference PWR is given in Reference 1. Waste characterization data from Reference 1 are summarized in this section to provide a basis for the waste classification discussion of Section 6.

5.1 NEUTRON-ACTIVATED MATERIALS

All of the neutron-activated materials from PWR decommissioning are contained in the reactor pressure vessel, vessel internal components and structures, and in the surrounding concrete biological shield. Tables 5.1 through 5.5 summarize data on volumes, radioactivity (curie) contents, and fractional radioactivity of limiting long-lived and short-lived radionuclides for neutron-activated materials. Table 5.1 shows data on neutron-activated wastes from DECON at the reference PWR. Tables 5.2 through 5.4 show data on neutron-activated wastes from deferred decontamination after shutdown periods of 30, 50, and 100 years. Table 5.5 shows data on neutron-activated wastes from ENTOMB. Burial volumes and curie contents are taken from Table G.4-3 of Reference 1. Full-density volumes are calculated by dividing the mass by the density where the mass is from Table G.4-3 of Reference 1. The radioactivities of activated components from deferred decontamination are corrected for decay on the basis of radionuclide inventory data presented in Tables 7.3-3, 7.3-4, and 7.3-6 of Reference 1. These tables are also the source of the data on fractional radioactivity of the limiting radionuclides. Limiting radionuclides are those nuclides whose concentrations in the waste provide the bases for the classification of the radioactive waste for burial. (See Tables 3.1 and 3.2 of this addendum.)

An important characteristic of the neutron-activated material from PWR decommissioning is the presence of the radioisotopes ^{59}Ni, ^{63}Ni, and ^{94}Nb. As shown in Tables 3.1 and 3.2, these isotopes can affect the waste classification of the material. If significant amounts of these isotopes are present, the material may be Class B or Class C or may exceed the Class C limits.

5.2 CONTAMINATED MATERIALS

Contaminated materials from PWR decommissioning include nearly all of the piping and equipment in the reactor containment and the fuel, auxiliary, and

TABLE 5.1. Neutron-Activated Materials from DECON of Reference PWR

Reactor Component	Material	Radioactivity (Ci)[a]	Burial Volume (m^3)[a]	Full-Density Volume[b] (m^3)	Ci/m^3[c]	Fractional Radioactivity of Limiting Long-Lived Nuclides[d]: ^{14}C	^{59}Ni	^{94}Nb	^{99}Tc	Fractional Radioactivity of Limiting Short-Lived Nuclides[d]: ^{60}Co	^{63}Ni	Less Than 5-Year Half-Life
Pressure Vessel Cylindrical Wall	Carbon Steel	19 170	108	37.0	518	--	3.6×10^{-5}	--	--	8.5×10^{-2}	4.3×10^{-3}	9.1×10^{-1}
Vessel Head	Carbon Steel	10	57	12.1	0.8	--	3.6×10^{-5}	--	--	8.5×10^{-2}	4.3×10^{-3}	9.1×10^{-1}
Vessel Bottom	Carbon Steel	10	57	5.3	1.9	--	3.6×10^{-5}	--	--	8.5×10^{-2}	4.3×10^{-3}	9.1×10^{-1}
Upper Core Support Assembly	Stainless Steel	10	11	1.5	6.7	--	2.8×10^{-4}	2.0×10^{-6}	--	3.6×10^{-1}	4.5×10^{-2}	5.9×10^{-1}
Upper Support Columns	Stainless Steel	100	11	1.4	72	--	2.8×10^{-4}	2.0×10^{-6}	--	3.6×10^{-1}	4.5×10^{-2}	5.9×10^{-1}
Upper Core Barrel	Stainless Steel	1 000	6	0.4	2 500	--	2.8×10^{-4}	2.0×10^{-6}	--	3.6×10^{-1}	4.5×10^{-2}	5.9×10^{-1}
Upper Core Grid Plate	Stainless Steel	24 310	14	0.6	40 500	--	2.8×10^{-4}	2.0×10^{-6}	--	3.6×10^{-1}	4.5×10^{-2}	5.9×10^{-1}
Guide Tubes	Stainless Steel	100	17	1.9	53	--	2.8×10^{-4}	2.0×10^{-6}	--	3.6×10^{-1}	4.5×10^{-2}	5.9×10^{-1}
Lower Core Barrel	Stainless Steel	651 000	91	5.4	121 000	--	2.8×10^{-4}	2.0×10^{-6}	--	3.6×10^{-1}	4.5×10^{-2}	5.9×10^{-1}
Thermal Shields	Stainless Steel	146 100	17	1.3	112 000	--	2.8×10^{-4}	2.0×10^{-6}	--	3.6×10^{-1}	4.5×10^{-2}	5.9×10^{-1}
Core Shroud	Stainless Steel	3 431 000	11	1.6	2 145 000	--	2.8×10^{-4}	2.0×10^{-6}	--	3.6×10^{-1}	4.5×10^{-2}	5.9×10^{-1}
Lower Grid Plate	Stainless Steel	553 400	14	0.5	1 107 000	--	2.8×10^{-4}	2.0×10^{-6}	--	3.6×10^{-1}	4.5×10^{-2}	5.9×10^{-1}
Lower Support Columns	Stainless Steel	10 000	3	0.4	25 000	--	2.8×10^{-4}	2.0×10^{-6}	--	3.6×10^{-1}	4.5×10^{-2}	5.9×10^{-1}
Lower Core Forging	Stainless Steel	2 500	31	4.7	532	--	2.8×10^{-4}	2.0×10^{-6}	--	3.6×10^{-1}	4.5×10^{-2}	5.9×10^{-1}
Miscellaneous Internals	Stainless Steel	2 000	23	4.6	435	--	2.8×10^{-4}	2.0×10^{-6}	--	3.6×10^{-1}	4.5×10^{-2}	5.9×10^{-1}
Bio-Shield Concrete	Concrete	2 000	707	707.0	3	--	3.4×10^{-5}	--	--	1.9×10^{-2}	4.0×10^{-3}	9.8×10^{-1}
Reactor Cavity Liner	Carbon Steel	10	14	2.0	5	--	3.6×10^{-5}	--	--	8.5×10^{-2}	4.3×10^{-3}	9.1×10^{-1}
Totals		4 842 720	1 192	787.7								

(a) Based on Table G.4-3 of Reference 1.
(b) Mass divided by density where mass is from Table G.4-3 of Reference 1.
(c) Radioactivity (Ci) divided by full-density volume.
(d) Based on Tables 7.3-3, 7.3-4, and 7.3-6 of Reference 1.

TABLE 5.2. Neutron-Activated Materials from 30-Year Deferred Decontamination at the Reference PWR

Reactor Component	Material	Radioactivity (Ci)[a]	Burial Volume (m^3)[a]	Full-Density Volume[b] (m^3)	Ci/m^3[c]	Fractional Radioactivity of Limiting Long-Lived Nuclides[d,e]				Fractional Radioactivity of Limiting Short-Lived Nuclides[d,e]		
						^{14}C	^{59}Ni	^{94}Nb	^{99}Tc	^{60}Co	^{63}Ni	Less Than 5-Year Half-Life
Pressure Vessel Cylindrical Wall	Carbon Steel	105	108	37.0	2.9	--	$6.6x10^{-3}$	--	--	$2.9x10^{-1}$	$6.4x10^{-1}$	$6.7x10^{-2}$
Vessel Head	Carbon Steel	0.06	57	12.1	0.005	--	$6.6x10^{-3}$	--	--	$2.9x10^{-1}$	$6.4x10^{-1}$	$6.7x10^{-2}$
Vessel Bottom	Carbon Steel	0.06	57	5.3	0.01	--	$6.6x10^{-3}$	--	--	$2.9x10^{-1}$	$6.4x10^{-1}$	$5.7x10^{-2}$
Upper Core Support Assembly	Stainless Steel	0.4	11	1.5	0.3	--	$6.5x10^{-3}$	$4.5x10^{-5}$	--	$1.6x10^{-1}$	$8.3x10^{-1}$	--
Upper Support Columns	Stainless Steel	4.3	11	1.4	3.1	--	$6.5x10^{-3}$	$4.5x10^{-5}$	--	$1.6x10^{-1}$	$8.3x10^{-1}$	--
Upper Core Barrel	Stainless Steel	43	6	0.4	108	--	$6.5x10^{-3}$	$4.5x10^{-5}$	--	$1.6x10^{-1}$	$8.3x10^{-1}$	--
Upper Core Grid Plate	Stainless Steel	1 045	14	0.6	1 740	--	$6.5x10^{-3}$	$4.5x10^{-5}$	--	$1.6x10^{-1}$	$8.3x10^{-1}$	--
Guide Tubes	Stainless Steel	4.3	17	1.9	2.3	--	$6.5x10^{-3}$	$4.5x10^{-5}$	--	$1.6x10^{-1}$	$8.3x10^{-1}$	--
Lower Core Barrel	Stainless Steel	27 990	91	5.4	5 180	--	$6.5x10^{-3}$	$4.5x10^{-5}$	--	$1.6x10^{-1}$	$8.3x10^{-1}$	--
Thermal Shields	Stainless Steel	6 280	17	1.3	4 830	--	$6.5x10^{-3}$	$4.5x10^{-5}$	--	$1.6x10^{-1}$	$8.3x10^{-1}$	--
Core Shroud	Stainless Steel	147 450	11	1.6	92 200	--	$6.5x10^{-3}$	$4.5x10^{-5}$	--	$1.6x10^{-1}$	$8.3x10^{-1}$	--
Lower Grid Plate	Stainless Steel	23 800	14	0.5	47 600	--	$6.5x10^{-3}$	$4.5x10^{-5}$	--	$1.6x10^{-1}$	$8.3x10^{-1}$	--
Lower Support Columns	Stainless Steel	430	3	0.4	1 075	--	$6.5x10^{-3}$	$4.5x10^{-5}$	--	$1.6x10^{-1}$	$8.3x10^{-1}$	--
Lower Core Forging	Stainless Steel	110	31	4.7	23.4	--	$6.5x10^{-3}$	$4.5x10^{-5}$	--	$1.6x10^{-1}$	$8.3x10^{-1}$	--
Miscellaneous Internals	Stainless Steel	86	23	4.6	18.7	--	$6.5x10^{-3}$	$4.5x10^{-5}$	--	$1.6x10^{-1}$	$8.3x10^{-1}$	--
Bio-Shield Concrete	Concrete	11	707	707.0	0.02	--	$6.4x10^{-3}$	--	--	$7.0x10^{-2}$	$6.2x10^{-1}$	$3.1x10^{-1}$
Reactor Cavity Liner	Carbon Steel	0.06	14	2.0	0.03	--	$6.6x10^{-3}$	--	--	$2.9x10^{-1}$	$6.4x10^{-1}$	$6.7x10^{-2}$
Totals		207 450	1 192	787.7								

(a) Based on Table G.4-3 of Reference 1.
(b) Mass divided by density where mass is from Table G.4-3 of Reference 1.
(c) Radioactivity (Ci) divided by full-density volume.
(d) Based on Tables 7.3-3, 7.3-4, and 7.3-6 of Reference 1.
(e) Corrected for radioactive decay on the bases of radionuclide inventories in Tables 7.3-3, 7.3-4 and 7.3.6 of Reference 1.

TABLE 5.3. Neutron-Activated Materials from 50-Year Deferred Decontamination of Reference PWR

Reactor Component	Material	Radioactivity (Ci)[a]	Burial Volume (m^3)[a]	Full-Density Volume[b] (m^3)	Ci/m^3[c]	Fractional Radioactivity of Limiting Long-Lived Nuclides[d,e]				Fractional Radioactivity of Limiting Short-Lived Nuclides[d,e]		
						^{14}C	^{59}Ni	^{94}Nb	^{99}Tc	^{60}Co	^{63}Ni	Less Than 5-Year Half-Life
Pressure Vessel Cylindrical Wall	Carbon Steel	62	108	37.0	1.7	--	$1.1x10^{-2}$	--	--	$3.8x10^{-2}$	$9.4x10^{-1}$	$6.6x10^{-4}$
Vessel Head	Carbon Steel	0.03	57	12.1	0.003	--	$1.1x10^{-2}$	--	--	$3.8x10^{-2}$	$9.4x10^{-1}$	$6.6x10^{-4}$
Vessel Bottom	Carbon Steel	0.03	57	5.3	0.01	--	$1.1x10^{-2}$	--	--	$3.8x10^{-2}$	$9.4x10^{-1}$	$6.6x10^{-4}$
Upper Core Support Assembly	Stainless Steel	0.3	11	1.5	0.2	--	$8.5x10^{-3}$	$6.1x10^{-5}$	--	$1.5x10^{-2}$	$9.7x10^{-1}$	--
Upper Support Columns	Stainless Steel	3.3	11	1.4	2.4	--	$8.5x10^{-3}$	$6.1x10^{-5}$	--	$1.5x10^{-2}$	$9.7x10^{-1}$	--
Upper Core Barrel	Stainless Steel	33	6	0.4	82	--	$8.5x10^{-3}$	$6.1x10^{-5}$	--	$1.5x10^{-2}$	$9.7x10^{-1}$	--
Upper Core Grid Plate	Stainless Steel	802	14	0.6	1 340	--	$8.5x10^{-3}$	$6.1x10^{-5}$	--	$1.5x10^{-2}$	$9.7x10^{-1}$	--
Guide Tubes	Stainless Steel	3.3	17	1.9	1.8	--	$8.5x10^{-3}$	$6.1x10^{-5}$	--	$1.5x10^{-2}$	$9.7x10^{-1}$	--
Lower Core Barrel	Stainless Steel	21 480	91	5.4	3 980	--	$8.5x10^{-3}$	$6.1x10^{-5}$	--	$1.5x10^{-2}$	$9.7x10^{-1}$	--
Thermal Shields	Stainless Steel	4 820	17	1.3	3 710	--	$8.5x10^{-3}$	$6.1x10^{-5}$	--	$1.5x10^{-2}$	$9.7x10^{-1}$	--
Core Shroud	Stainless Steel	113 220	11	1.6	70 800	--	$8.5x10^{-3}$	$6.1x10^{-5}$	--	$1.5x10^{-2}$	$9.7x10^{-1}$	--
Lower Grid Plate	Stainless Steel	18 260	14	0.5	36 500	--	$8.5x10^{-3}$	$6.1x10^{-5}$	--	$1.5x10^{-2}$	$9.7x10^{-1}$	--
Lower Support Columns	Stainless Steel	330	3	0.4	825	--	$8.5x10^{-3}$	$6.1x10^{-5}$	--	$1.5x10^{-2}$	$9.7x10^{-1}$	--
Lower Core Forging	Stainless Steel	85	31	4.7	18.1	--	$8.5x10^{-3}$	$6.1x10^{-5}$	--	$1.5x10^{-2}$	$9.7x10^{-1}$	--
Miscellaneous Internals	Stainless Steel	65	23	4.6	14.1	--	$8.5x10^{-3}$	$6.1x10^{-5}$	--	$1.5x10^{-2}$	$9.7x10^{-1}$	--
Bio-Shield Concrete	Concrete	8	707	707.0	0.01	--	$8.3x10^{-3}$	--	--	$6.5x10^{-3}$	$6.9x10^{-1}$	$2.9x10^{-1}$
Reactor Cavity Liner	Carbon Steel	0.3	14	2.0	0.02	--	$1.1x10^{-2}$	--	--	$3.8x10^{-2}$	$9.4x10^{-1}$	$6.6x10^{-4}$
Totals		159 170	1 192	787.7								

(a) Based on Table G.4-3 of Reference 1.
(b) Mass divided by density where mass is from Table G.4-3 of Reference 1.
(c) Radioactivity (Ci) divided by full-density volume.
(d) Based on Tables 7.3-3, 7.3-4, and 7.3-6 of Reference 1.
(e) Corrected for radioactive decay on the bases of radionuclide inventories in Tables 7.3-3, 7.3-4 and 7.3.6 of Reference 1.

TABLE 5.4. Neutron-Activated Materials from 100-Year Deferred Decontamination at the Reference PWR

Reactor Component	Material	Radioactivity (Ci)[a]	Burial Volume (m^3)[a]	Full-Density Volume[b] (m^3)	Ci/m^3[c]	Fractional Radioactivity of Limiting Long-Lived Nuclides[d,e]: ^{14}C	^{59}Ni	^{94}Nb	^{99}Tc	Fractional Radioactivity of Limiting Short-Lived Nuclides[d,e]: ^{60}Co	^{63}Ni	Less Than 5-Year Half-Life
Pressure Vessel Cylindrical Wall	Carbon Steel	40	108	37.0	1.1	--	$1.7x10^{-2}$	--	--	$7.6x10^{-5}$	$9.9x10^{-1}$	--
Vessel Head	Carbon Steel	0.02	57	12.1	0.002	--	$1.7x10^{-2}$	--	--	$7.6x10^{-5}$	$9.9x10^{-1}$	--
Vessel Bottom	Carbon Steel	0.02	57	5.3	0.004	--	$1.7x10^{-2}$	--	--	$7.6x10^{-5}$	$9.9x10^{-1}$	--
Upper Core Support Assembly	Stainless Steel	0.2	11	1.5	0.13	--	$1.3x10^{-2}$	$9.1x10^{-5}$	--	$3.1x10^{-5}$	$9.8x10^{-1}$	--
Upper Support Columns	Stainless Steel	2.2	11	1.4	1.6	--	$1.3x10^{-2}$	$9.1x10^{-5}$	--	$3.1x10^{-5}$	$9.8x10^{-1}$	--
Upper Core Barrel	Stainless Steel	22	6	0.4	55	--	$1.3x10^{-2}$	$9.1x10^{-5}$	--	$3.1x10^{-5}$	$9.8x10^{-1}$	--
Upper Core Grid Plate	Stainless Steel	535	14	0.6	892	--	$1.3x10^{-2}$	$9.1x10^{-5}$	--	$3.1x10^{-5}$	$9.8x10^{-1}$	--
Guide Tubes	Stainless Steel	2.2	17	1.9	1.2	--	$1.3x10^{-2}$	$9.1x10^{-5}$	--	$3.1x10^{-5}$	$9.8x10^{-1}$	--
Lower Core Barrel	Stainless Steel	14 330	91	5.4	2 650	--	$1.3x10^{-2}$	$9.1x10^{-5}$	--	$3.1x10^{-5}$	$9.8x10^{-1}$	--
Thermal Shields	Stainless Steel	3 220	17	1.3	2 480	--	$1.3x10^{-2}$	$9.1x10^{-5}$	--	$3.1x10^{-5}$	$9.8x10^{-1}$	--
Core Shroud	Stainless Steel	75 480	11	1.6	47 200	--	$1.3x10^{-2}$	$9.1x10^{-5}$	--	$3.1x10^{-5}$	$9.8x10^{-1}$	--
Lower Grid Plate	Stainless Steel	12 180	14	0.5	24 400	--	$1.3x10^{-2}$	$9.1x10^{-5}$	--	$3.1x10^{-5}$	$9.8x10^{-1}$	--
Lower Support Columns	Stainless Steel	220	3	0.4	550	--	$1.3x10^{-2}$	$9.1x10^{-5}$	--	$3.1x10^{-5}$	$9.8x10^{-1}$	--
Lower Core Forging	Stainless Steel	55	31	4.7	11.7	--	$1.3x10^{-2}$	$9.1x10^{-5}$	--	$3.1x10^{-5}$	$9.8x10^{-1}$	--
Miscellaneous Internals	Stainless Steel	45	23	4.6	9.8	--	$1.3x10^{-2}$	$9.1x10^{-5}$	--	$3.1x10^{-5}$	$9.8x10^{-1}$	--
Bio-Shield Concrete	Concrete	6	707	707.0	0.01	--	$1.1x10^{-2}$	--	--	$1.2x10^{-5}$	$6.4x10^{-1}$	$3.5x10^{-1}$
Reactor Cavity Liner	Carbon Steel	0.02	14	2.0	0.01	--	$1.7x10^{-2}$	--	--	$7.6x10^{-5}$	$9.9x10^{-1}$	--
Totals		106 140	1 192	787.7								

(a) Based on Table G.4-3 of Reference 1.
(b) Mass divided by density where mass is from Table G.4-3 of Reference 1.
(c) Radioactivity (Ci) divided by full-density volume.
(d) Based on Tables 7.3-3, 7.3-4, and 7.3-6 of Reference 1.
(e) Corrected for radioactive decay on the bases of radionuclide inventories in Tables 7.3-3, 7.3-4 and 7.3.6 of Reference 1.

TABLE 5.5. Neutron-Activated Materials from ENTOMB at the Reference PWR

Reactor Component	Material	Radioactivity (Ci)[a]	Burial Volume (m^3)[a]	Full-Density Volume[b] (m^3)	Ci/m^3[c]	Fractional Radioactivity of Limiting Long-Lived Nuclides[d]				Fractional Radioactivity of Limiting Short-Lived Nuclides[d]		
						^{14}C	^{59}Ni	^{94}Nb	^{99}Tc	^{60}Co	^{63}Ni	Less Than 5-Year Half-Life
Pressure Vessel Cylindrical Wall	Carbon Steel	19 170	108	37.0	518	--	$3.6x10^{-5}$	--	--	$8.5x10^{-2}$	$4.3x10^{-3}$	$9.1x10^{-1}$
Vessel Head	Carbon Steel	10	57	12.1	0.8	--	$3.6x10^{-5}$	--	--	$8.5x10^{-2}$	$4.3x10^{-3}$	$9.1x10^{-1}$
Vessel Bottom	Carbon Steel	10	57	5.3	1.9	--	$3.6x10^{-5}$	--	--	$8.5x10^{-2}$	$4.3x10^{-3}$	$9.1x10^{-1}$
Upper Core Support Assembly	Stainless Steel	10	11	1.5	6.7	--	$2.8x10^{-4}$	$2.0x10^{-6}$	--	$3.6x10^{-1}$	$4.5x10^{-2}$	$5.9x10^{-1}$
Upper Support Columns	Stainless Steel	100	11	1.4	72	--	$2.8x10^{-4}$	$2.0x10^{-6}$	--	$3.6x10^{-1}$	$4.5x10^{-2}$	$5.9x10^{-1}$
Upper Core Barrel	Stainless Steel	1 000	6	0.4	2 500	--	$2.8x10^{-4}$	$2.0x10^{-6}$	--	$3.6x10^{-1}$	$4.5x10^{-2}$	$5.9x10^{-1}$
Upper Core Grid Plate	Stainless Steel	24 310	14	0.6	40 500	--	$2.8x10^{-4}$	$2.0x10^{-6}$	--	$3.6x10^{-1}$	$4.5x10^{-2}$	$5.9x10^{-1}$
Guide Tubes	Stainless Steel	100	17	1.9	53	--	$2.8x10^{-4}$	$2.0x10^{-6}$	--	$3.6x10^{-1}$	$4.5x10^{-2}$	$5.9x10^{-1}$
Lower Core Barrel	Stainless Steel	651 000	91	5.4	121 000	--	$2.8x10^{-4}$	$2.0x10^{-6}$	--	$3.6x10^{-1}$	$4.5x10^{-2}$	$5.9x10^{-1}$
Thermal Shields	Stainless Steel	146 100	17	1.3	112 000	--	$2.8x10^{-4}$	$2.0x10^{-6}$	--	$3.6x10^{-1}$	$4.5x10^{-2}$	$5.9x10^{-1}$
Core Shroud	Stainless Steel	3 431 000	11	1.6	2 145 000	--	$2.8x10^{-4}$	$2.0x10^{-6}$	--	$3.6x10^{-1}$	$4.5x10^{-2}$	$5.9x10^{-1}$
Lower Grid Plate	Stainless Steel	553 400	14	0.5	1 107 000	--	$2.8x10^{-4}$	$2.0x10^{-6}$	--	$3.6x10^{-1}$	$4.5x10^{-2}$	$5.9x10^{-1}$
Lower Support Columns	Stainless Steel	10 000	3	0.4	25,000	--	$2.8x10^{-4}$	$2.0x10^{-6}$	--	$3.6x10^{-1}$	$4.5x10^{-2}$	$5.9x10^{-1}$
Lower Core Forging	Stainless Steel	2 500	31	4.7	532	--	$2.8x10^{-4}$	$2.0x10^{-6}$	--	$3.6x10^{-1}$	$4.5x10^{-2}$	$5.9x10^{-1}$
Miscellaneous Internals	Stainless Steel	2 000	23	4.6	435	--	$2.8x10^{-4}$	$2.0x10^{-6}$	--	$3.6x10^{-1}$	$4.5x10^{-2}$	$5.9x10^{-1}$
Totals		4 840 710	471	78.7								

(a) Based on Table G.4-3 of Reference 1.
(b) Mass divided by density where mass is from Table G.4-3 of Reference 1.
(c) Radioactivity (Ci) divided by full-density volume.
(d) Based on Tables 7.3-3, 7.3-4, and 7.3-6 of Reference 1.

control buildings. In addition, many of the concrete surfaces of these buildings are assumed to be contaminated and to require surface removal to a depth of about 50 millimeters.

Contaminated material burial volumes for each of the decommissioning alternatives (DECON, SAFSTOR, and ENTOMB) are summarized in Table 5.6. The total volume of contaminated material from DECON is estimated to be about 16,100 m^3 at the disposal site. The radioactivity in this material is not expected to be great, probably less than 1000 curies total. The average specific activity of this material is therefore estimated to be about 0.062 Ci/m^3. The principal short-lived isotopes are ^{60}Co (half-life = 5.27 years) and ^{137}Cs (half-life = 30.0 years).

TABLE 5.6. Contaminated Materials from PWR Decommissioning

Decommissioning Alternative	Contaminated Material Volume (m^3)	Average Specific Activity (Ci/m^3)
DECON[a]	16 078	0.062
SAFSTOR[a]		
Preparations for Safe Storage	--	--
Deferred Dismantlement After 30 Years	16 078	<0.06
Deferred Dismantlement After 50 Years	100	<0.03
Deferred Dismantlement After 100 Years	100	<0.03
ENTOMB[b]	1 974	0.062

(a) Contaminated material volumes from DECON and SAFSTOR are from Table H.5-1 of Reference 1.
(b) The contaminated material volume shipped offsite for burial from the ENTOMB alternative is estimated on the basis of information in Section 4.4 of Reference 2. See text for details.

The contaminated material volumes shown in Table 5.6 for deferred dismantlement are from Table H.5-1 of Reference 1. Since deferred dismantlement takes place several years after reactor shutdown, which allows for some decay of the ^{60}Co and ^{137}Cs radioactivity, the average specific activity of contaminated material from deferred dismantlement is postulated to be less than 0.060 Ci/m^3.

The volume of contaminated material shipped offsite for burial in the ENTOMB scenario is based on information in Section 4.4 of Reference 2. For the ENTOMB alternative, all of the contaminated concrete is assumed to be entombed. In addition, all of the contaminated equipment and piping from the reactor building (the steam generators, pressurizer, coolant pumps, reactor cavity liner, reactor coolant piping, etc.) and half of the contaminated equipment and piping from the other buildings are entombed. The total volume of contaminated material from outside the reactor building, other than concrete, is estimated to be 3948 m^3. Thus, the volume of contaminated material shipped for burial in the ENTOMB scenario is estimated to be about 1974 m^3. The average specific activity of this material is assumed to be the same as that for the contaminated material from DECON, about 0.062 Ci/m^3.

5.3 RADIOACTIVE WASTES

Radioactive wastes from reactor decommissioning operations may be either wet solid wastes or dry solid wastes. Wet solid wastes result from the processing of chemical decontamination solutions and contaminated water volumes. These wastes include used ion exchange resins, cartridge filters, and evaporator bottom liquids. Wet solid wastes are mixed with or encapsulated in solid materials such as cement or urea formaldehyde to assure retention of radioactive materials within the shipping containers after disposal. Dry solid wastes include discarded contaminated materials such as rags and wipes, plastic sheeting, contaminated tools, and disposable protective clothing. Table 5.7 gives a summary of data on waste volumes, curies, and fractional radioactivity of limiting short-lived radionuclides for radioactive wastes from decommissioning at the reference PWR.

The operations of system decontamination, draining of contaminated water systems, and handling of the resultant radioactive liquids are assumed to be undertaken regardless of the alternative chosen for decommissioning of the reference PWR. Consequently, the volume of wet solid wastes from decommissioning operations is assumed to be the same for each alternative (DECON, SAFSTOR, or ENTOMB). Waste volume and curie data for wet solid wastes are taken from Section G.4.2.3 of Reference 1. Data on fractional radioactivity of limiting short-lived nuclides for these wastes are taken from Table 7.3-7 of Reference 1. The processing of contaminated water and chemical decontamination solutions results in a total of 133 m^3 of evaporator bottom liquids. These liquids are solidified and packaged in 94 steel cask liners. Each liner has a volume of 2.84 m^3, and the volume of concreted waste in each liner is assumed to be 2.30 m^3. Twenty-two containers have assumed surface radiation dose rates of 50 R/hr (600 Ci/container); 45 containers have assumed surface radiation dose rates of 1 R/hr (12 Ci/container); and 27 containers have assumed surface radiation dose rates of 0.2 R/hr (2.4 Ci/container). The volume of spent ion exchange resins for disposal is estimated to be 30 m^3, containing 42,000 Ci of radioactivity. The resins are assumed to be mixed with a solidifying agent and packaged for disposal in twenty 2.84-m^3 steel containers. (The total volume of solidified waste material is assumed to be 46 m^3.) Forty-two cartridge filters for fluid streams are assumed to be packaged in concrete-lined 0.21-m^3 drums

TABLE 5.7. Radioactive Wastes from Decommissioning at the Reference PWR

Waste Type	Radioactivity (Ci)	Burial Volume[(a)] (m^3)	Ci/m^3	Fractional Radioactivity of Limiting Short-Lived Nuclides: ^{60}Co	^{63}Ni	^{90}Sr	^{137}Cs	Other Short-Lived
Wet Solid Wastes								
Evaporator Bottoms	13 200	62 (51)	259	$3.2x10^{-1}$	--	--	$1.2x10^{-3}$	$6.8x10^{-1}$
Evaporator Bottoms	540	128 (104)	5.2	$3.2x10^{-1}$	--	--	$1.2x10^{-3}$	$6.8x10^{-1}$
Evaporator Bottoms	65	76 (62)	1.0	$3.2x10^{-1}$	--	--	$1.2x10^{-3}$	$6.8x10^{-1}$
Spent Resins	42 000	57 (46)	913	$3.2x10^{-1}$	--	--	$1.2x10^{-3}$	$6.8x10^{-1}$
Used Particulate Filters	5 040	9 (6.3)	800	$3.2x10^{-1}$	--	--	$1.2x10^{-3}$	$6.8x10^{-1}$
Dry Solid Wastes								
DECON								
Shielded Drums	525	88	6.0	$7.5x10^{-2}$	--	$7.0x10^{-4}$	$7.5x10^{-1}$	$1.7x10^{-1}$
Unshielded Drums	232	195	1.2	$7.5x10^{-2}$	--	$7.0x10^{-4}$	$7.5x10^{-1}$	$1.7x10^{-1}$
Preparations for Safe Storage								
Shielded Drums	166	28	6.0	$7.5x10^{-2}$	--	$7.0x10^{-4}$	$7.5x10^{-1}$	$1.7x10^{-1}$
Unshielded Drums	33	28	1.2	$7.5x10^{-2}$	--	$7.0x10^{-4}$	$7.5x10^{-1}$	$1.7x10^{-1}$
30-Year Deferred Decontamination								
Shielded Drums	138	23	6.0	$4.0x10^{-3}$	--	$7.9x10^{-4}$	$9.9x10^{-1}$	$1.3x10^{-3}$
Unshielded Drums	72	207	0.35	$4.0x10^{-3}$	--	$7.9x10^{-4}$	$9.9x10^{-1}$	$1.3x10^{-3}$
50-Year Deferred Decontamination								
Shielded Drums	90	15	6.0	$4.2x10^{-4}$	--	$8.4x10^{-4}$	$1.0x10^{0}$	$8.4x10^{-4}$
Unshielded Drums	42	135	0.31	$4.2x10^{-4}$	--	$8.4x10^{-4}$	$1.0x10^{0}$	$8.4x10^{-4}$
100-Year Deferred Decontamination								
Shielded Drums	--	--	--	--	--	--	--	--
Unshielded Drums	42	100	0.42	--	--	$1.3x10^{-3}$	$1.0x10^{0}$	--
ENTOMB								
Shielded Drums	525	88	6.0	$7.5 x 10^{-2}$	--	$7.0x10^{-4}$	$7.5x10^{-1}$	$1.7x10^{-1}$
Unshielded Drums	232	195	1.2	$7.5 x 10^{-2}$	--	$7.0x10^{-4}$	$7.5x10^{-1}$	$1.7x10^{-1}$

(a) Values in parentheses for wet solid wastes are actual solidified waste volumes used to calculate Ci/m^3.

for shipment to a burial site. Each filter is assumed to have a volume of 0.15 m^3 and an average curie content of 120 Ci. Cobalt-60 (half-life = 5.27 years) is the principal short-lived radionuclide in wet solid wastes.

Dry solid wastes from PWR decommissioning are assumed to be compacted and packaged in 0.21-m^3 standard steel drums for shipment to a burial ground. Some of the drums have surface dose rates that result in a requirement for shielding of the drums during transport. Shielded drums are assumed to have maximum surface dose rates of 1.0 R/hr (1.25 Ci/drum). Unshielded drums are assumed to have maximum surface dose rates of 0.2 R/hr (0.25 Ci/drum). Dry solid waste volumes shown in Table 5.7 are from Section G.4.2 (DECON and ENTOMB), Section H.3.2 (preparations for safe storage), and Section H.5.1 (deferred decontamination) of Reference 1. The principal short-lived nuclides in contaminated dry solid wastes are ^{60}Co and ^{137}Cs (half-life = 30.0 years). Because of the relatively large concentration of ^{137}Cs in dry solid wastes, it is assumed in this study that approximately 10% of the drums of dry waste from 30 and 50 years of deferred decontamination still require shielding for shipment to a burial ground. After 100 years, all of the dry solid wastes from deferred decontamination can be shipped in unshielded drums.

6.0 CLASSIFICATION OF PWR DECOMMISSIONING WASTES

A summary of waste class assignments for the radioactive wastes from conceptual decommissioning of the reference PWR is given in Table 6.1. Both the actual volumes of waste and the percentages of total waste volume in each waste class are shown in the table. Waste class assignments are based on waste characterization data for the reference PWR summarized in Section 5 and on waste category definitions given in 10 CFR 61 and summarized in Tables 3.1 and 3.2 of this addendum.

Most of the radioactive waste from PWR decommissioning may be classified as Class A waste. For the reference PWR, approximately 85% to 98% of the waste from decommissioning (the actual waste volume depends on the decommissioning alternative) is estimated to be Class A waste. Approximately 17 m^3 of waste (less than one percent of the total volume of waste from any decommissioning alternative) is estimated to be Class C waste. Approximately 133 m^3 of waste (from 0.7% to 7.5% of the waste volume, depending on decommissioning alternative) is estimated to exceed the Class C limits of 10 CFR 61. The Class C and "not classifiable" wastes are neutron-activated stainless steel components that contain high concentrations of ^{59}Ni, ^{63}Ni, and ^{94}Nb.

Details of the waste class assignments for neutron-activated materials, contaminated materials, and radioactive wastes from conceptual decommissioning of the reference PWR are given in the following sections.

6.1 NEUTRON-ACTIVATED MATERIALS

Waste class assignments for the neutron-activated materials from conceptual decommissioning of the reference PWR are given in Tables 6.2 through 6.6. Table 6.2 shows waste classes for neutron-activated materials removed from the reactor containment building during DECON. Tables 6.3 through 6.5 show waste classes for neutron-activated materials removed during deferred decontamination after shutdown periods of 30, 50, and 100 years. Table 6.6 shows waste classes for neutron-activated materials removed during ENTOMB at the reference PWR. Waste class assignments are determined by comparing the estimated concentrations of limiting long-lived and short-lived radionuclides in the waste with the concentrations used to define the different waste classes shown in Tables 3.1 and 3.2 of Section 3. The estimated activity concentrations of limiting radionuclides shown in Tables 6.2 through 6.6 are determined by multiplying the specific activity (Ci/m^3) of each activated component by the fractional radioactivity of the limiting radionuclides in the component. As explained in Section 5.1, the specific activity of neutron-activated material is based on the full-density volume rather than the burial volume of the

TABLE 6.1. Classification of Radioactive Wastes from PWR Decommissioning

Waste Category	Burial Volume (m^3)	Waste Class Assignment: Class A Volume (m^3)	Class A Percent	Class B Volume (m^3)	Class B Percent	Class C Volume (m^3)	Class C Percent	Exceeds Class C Limits Volume (m^3)	Exceeds Class C Limits Percent
DECON									
Neutron-Activated	1 192	982	82.4	60	5.0	17	1.4	133	11.2
Contaminated	16 078	16 078	100.0	--	--	--	--	--	--
Radwaste	615	461	75.0	154	25.0	--	--	--	--
Total Decommissioning Waste	17 885	17 521	98.0	214	1.2	17	0.1	133	0.7
30-YR SAFSTOR									
Neutron-Activated	1 192	1 036	86.9	6	0.5	17	1.4	133	11.2
Contaminated	16 078	16 078	100.0	--	--	--	--	--	--
Radwaste									
Prep. for Safe Storage	388	294	75.8	94	24.2	--	--	--	--
Deferred Decontamination	230	207	90.0	23	10.0	--	--	--	--
Total Decommissioning Waste	17 888	17 615	98.5	123	0.7	17	0.1	133	0.7
50-YR SAFSTOR									
Neutron-Activated	1 192	1 036	86.9	6	0.5	17	1.4	133	11.2
Contaminated	100	100	100.0	--	--	--	--	--	--
Radwaste									
Prep. for Safe Storage	388	294	75.8	94	24.2	--	--	--	--
Deferred Decontamination	150	135	90.0	15	10.0	--	--	--	--
Total Decommissioning Waste	1 830	1 565	85.5	115	6.3	17	0.9	133	7.3
100-YR SAFSTOR									
Neutron-Activated	1 192	1 036	86.9	6	0.5	17	1.4	133	11.2
Contaminated	100	100	100.0	--	--	--	--	--	--
Radwaste									
Prep. for Safe Storage	388	294	75.8	94	24.2	--	--	--	--
Deferred Decontamination	100	100	100.0	--	--	--	--	--	--
Total Decommissioning Waste	1 780	1 530	85.9	100	5.6	17	1.0	133	7.5
ENTOMB									
Neutron-Activated	471	261	55.4	60	12.8	17	3.6	133	28.2
Contaminated	1 974	1 974	100.0	--	--	--	--	--	--
Radwaste	615	461	75.0	154	25.0	--	--	--	--
Total Decommissioning Waste	3 060	2 696	88.1	214	7.0	17	0.5	133	4.4

TABLE 6.2. Waste Classifications of Neutron-Activated Materials from DECON at the Reference PWR

Reactor Component	Burial Volume (m^3)	Full-Density Volume (m^3)	Total Specific Activity[(a)] (Ci/m^3)	Specific Activity (Ci/m^3): Limiting Long-Lived Nuclides				Limiting Short-Lived Nuclides			Waste Class
				^{14}C	^{59}Ni	^{94}Nb	^{99}Tc	^{60}Co	^{63}Ni	Less Than 5-Year Half-Life	
Pressure Vessel Cylindrical Wall	108	37.0	518	-	$1.9x10^{-2}$	--	--	$4.4x10^{1}$	$2.2x10^{0}$	$4.7x10^{2}$	A
Vessel Head	57	12.1	0.8	-	$2.9x10^{-5}$	--	--	$6.8x10^{-2}$	$3.4x10^{-3}$	$7.3x10^{-1}$	A
Vessel Bottom	57	5.3	1.9	-	$6.8x10^{-5}$	--	--	$1.6x10^{-1}$	$8.2x10^{-3}$	$1.7x10^{0}$	A
Upper Core Support Assembly	11	1.5	6.7	-	$1.9x10^{-3}$	$1.3x10^{-5}$	--	$2.4x10^{0}$	$3.0x10^{-1}$	$4.0x10^{0}$	A
Upper Support Columns	11	1.4	72	-	$2.0x10^{-2}$	$1.4x10^{-4}$	--	$2.6x10^{1}$	$3.2x10^{0}$	$4.2x10^{1}$	A
Upper Core Barrel	6	0.4	2 500	-	$7.0x10^{-1}$	$5.0x10^{-3}$	--	$9,0x10^{2}$	$1.1x10^{2}$	$1.5x10^{3}$	B
Upper Core Grid Plate	14	0.6	40 500	-	$1.1x10^{1}$	$8.1x10^{-2}$	--	$1.5x10^{4}$	$1.8x10^{3}$	$2.4x10^{4}$	C
Guide Tubes	17	1.9	53	-	$1.5x10^{-2}$	$1.1x10^{-4}$	--	$1.9x10^{1}$	$2.4x10^{0}$	$3.1x10^{1}$	A
Lower Core Barrel	91	5.4	121 000	-	$3.4x10^{1}$	$2.4x10^{-1}$	--	$4.4x10^{4}$	$5.4x10^{3}$	$7.1x10^{4}$	(b,c)
Thermal Shields	17	1.3	112 000	-	$3.1x10^{1}$	$2.2x10^{-1}$	--	$4.0x10^{4}$	$5.0x10^{3}$	$6.6x10^{4}$	(b,c)
Core Shroud	11	1.6	2 145 000	-	$6.0x10^{2}$	$4.3x10^{0}$	--	$7.7x10^{5}$	$9.7x10^{4}$	$1.3x10^{6}$	(b)
Lower Grid Plate	14	0.5	1 107 000	-	$3.1x10^{2}$	$2.2x10^{0}$	--	$4.0x10^{5}$	$5.0x10^{4}$	$6.5x10^{5}$	(b)
Lower Support Columns	3	0.4	25 000	-	$7.0x10^{0}$	$5.0x10^{-2}$	--	$9,0x10^{3}$	$1.1x10^{3}$	$1.5x10^{4}$	C
Lower Core Forging	31	4.7	532	-	$1.5x10^{-1}$	$1.1x10^{-3}$	--	$1.9x10^{2}$	$2.4x10^{1}$	$3.1x10^{2}$	B
Miscellaneous Internals	23	4.6	435	-	$1.2x10^{-1}$	$8.7x10^{-4}$	--	$1.6x10^{2}$	$2.0x10^{1}$	$2.6x10^{2}$	B
Bio-Shield Concrete	707	707.0	3	-	$1.0x10^{-4}$	--	--	$5.7x10^{-2}$	1.2×10^{-2}	$2.9x10^{0}$	A
Reactor Cavity Liner	14	2.0	5	-	$1.8x10^{-4}$	--	--	$4.2x10^{-1}$	$2.2x10^{-2}$	$4.6x10^{0}$	A

(a) From Table 5.1.

(b) Waste exceeds Class C limits because of high concentrations of ^{59}Ni, ^{63}Ni, and ^{94}Nb.

(c) By placing this waste in a container with other waste of low specific activity it might be possible to dispose of the container under Class C restrictions.

TABLE 6.3. Waste Classifications of Neutron-Activated Materials from 30-Year Deferred Decontamination at the Reference PWR

Reactor Component	Burial Volume (m^3)	Full-Density Volume (m^3)	Total Specific Activity[a] (Ci/m^3)	Specific Activity (Ci/m^3): Limiting Long-Lived Nuclides: ^{14}C	^{59}Ni	^{94}Nb	^{99}Tc	Limiting Short-Lived Nuclides: ^{60}Co	^{63}Ni	Less Than 5-Year Half-Life	Waste Class
Pressure Vessel Cylindrical Wall	108	37.0	2.9	-	$1.9x10^{-2}$	--	--	$8.4x10^{-1}$	$1.9x10^{0}$	$1.9x10^{-1}$	A
Vessel Head	57	12.1	0.005	-	$3.3x10^{-5}$	--	--	$1.5x10^{-3}$	$3.2x10^{-3}$	$3.4x10^{-4}$	A
Vessel Bottom	57	5.3	0.01	-	$6.6x10^{-5}$	--	--	$2.9x10^{-3}$	$6.4x10^{-3}$	$6.7x10^{-4}$	A
Upper Core Support Assembly	11	1.5	0.3	-	$2.0x10^{-3}$	$1.4x10^{-5}$	--	$4.8x10^{-2}$	$2.5x10^{-1}$	--	A
Upper Support Columns	11	1.4	3.1	-	$2.0x10^{-2}$	$1.4x10^{-4}$	--	$5.0x10^{-1}$	$2.6x10^{0}$	--	A
Upper Core Barrel	6	0.4	108	-	$7.0x10^{-1}$	$4.9x10^{-3}$	--	$1.7x10^{1}$	$9.0x10^{1}$	--	B
Upper Core Grid Plate	14	0.6	1 740	-	$1.1x10^{1}$	$7.8x10^{-2}$	--	$2.8x10^{2}$	$1.4x10^{3}$	--	C
Guide Tubes	17	1.9	2.3	-	$1.5x10^{-2}$	$1.0x10^{-4}$	--	$3.7x10^{-1}$	$1.9x10^{0}$	--	A
Lower Core Barrel	91	5.4	5 180	-	$3.4x10^{1}$	$2.3x10^{-1}$	--	$8.3x10^{2}$	$4.3x10^{3}$	--	(b,c)
Thermal Shields	17	1.3	4 830	-	$3.1x10^{1}$	$2.2x10^{-1}$	--	$7.7x10^{2}$	$4.0x10^{3}$	--	(b,c)
Core Shroud	11	1.6	92 200	-	$6.0x10^{2}$	$4.1x10^{0}$	--	$1.5x10^{4}$	$7.7x10^{4}$	--	(b)
Lower Grid Plate	14	0.5	47 600	-	$3.1x10^{2}$	$2.1x10^{0}$	--	$7.6x10^{3}$	$4.0x10^{4}$	--	(b)
Lower Support Columns	3	0.4	1 075	-	$7.0x10^{0}$	$4.8x10^{-2}$	--	$1.7x10^{2}$	$8.9x10^{2}$	--	C
Lower Core Forging	31	4.7	23.4	-	$1.5x10^{-1}$	$1.1x10^{-3}$	--	$3.7x10^{0}$	$1.9x10^{1}$	--	A
Miscellaneous Internals	23	4.6	18.7	-	$1.2x10^{-1}$	$8.4x10^{-4}$	--	$3.0x10^{0}$	$1.6x10^{1}$	--	A
Bio-Shield Concrete	707	707.0	0.02	-	$1.3x10^{-4}$	--	--	$1.4x10^{-3}$	$1.2x10^{-2}$	$6.2x10^{-3}$	A
Reactor Cavity Liner	14	2.0	0.03	-	$2.0x10^{-4}$	--	--	$8.7x10^{-3}$	$1.9x10^{-2}$	$2.0x10^{-3}$	A

(a) From Table 5.2.
(b) Waste exceeds Class C limits because of high concentrations of ^{59}Ni, ^{63}Ni, and ^{94}Nb.
(c) By placing this waste in a container with other waste of low specific activity it might be possible to dispose of the container under Class C restrictions.

TABLE 6.4. Waste Classifications of Neutron-Activated Materials from 50-Year Deferred Decontamination at the Reference PWR

				Specific Activity (Ci/m^3)							
				Limiting long-Lived Nuclides				Limiting Short-Lived Nuclides			
Reactor Component	Burial Volume (m^3)	Full-Density Volume (m^3)	Total Specific Activity(a) (Ci/m^3)	^{14}C	^{59}Ni	^{94}Nb	^{99}Tc	^{60}Co	^{63}Ni	Less Than 5-Year Half-Life	Waste Class
Pressure Vessel Cylindrical Wall	108	37.0	1.7	-	1.9×10^{-2}	--	--	6.5×10^{-2}	1.6×10^{0}	1.1×10^{-3}	A
Vessel Head	57	12.1	0.003	-	3.3×10^{-5}	--	--	1.1×10^{-4}	2.8×10^{-3}	2.0×10^{-6}	A
Vessel Bottom	57	5.3	0.01	-	1.1×10^{-4}	--	--	3.8×10^{-4}	9.8×10^{-3}	6.6×10^{-6}	A
Upper Core Support Assembly	11	1.5	0.2	-	1.7×10^{-3}	1.2×10^{-5}	--	3.0×10^{-3}	1.9×10^{-1}	--	A
Upper Support Columns	11	1.4	2.4	-	2.0×10^{-2}	1.5×10^{-4}	--	3.6×10^{-2}	2.3×10^{0}	--	A
Upper Core Barrel	6	0.4	82	-	7.0×10^{-1}	5.0×10^{-3}	--	1.2×10^{0}	8.0×10^{1}	--	B
Upper Core Grid Plate	14	0.6	1 340	-	1.1×10^{1}	8.2×10^{-2}	--	2.0×10^{1}	1.3×10^{3}	--	C
Guide Tubes	17	1.9	1.8	-	1.5×10^{-2}	1.1×10^{-4}	--	2.7×10^{-2}	1.7×10^{0}	--	A
Lower Core Barrel	91	5.4	3 980	-	3.4×10^{1}	2.4×10^{-1}	--	6.0×10^{1}	3.9×10^{3}	--	(b,c)
Thermal Shields	17	1.3	3 710	-	3.2×10^{1}	2.3×10^{-1}	--	5.6×10^{1}	3.6×10^{3}	--	(b,c)
Core Shroud	11	1.6	70 800	-	6.0×10^{2}	4.3×10^{0}	--	1.1×10^{3}	6.9×10^{4}	--	(b)
Lower Grid Plate	14	0.5	36 500	-	3.1×10^{2}	2.2×10^{0}	--	5.5×10^{2}	3.5×10^{4}	--	(b)
Lower Support Columns	3	0.4	825	-	7.0×10^{0}	5.0×10^{-2}	--	1.2×10^{1}	8.0×10^{2}	--	C
Lower Core Forging	31	4.7	18.1	-	1.5×10^{-1}	1.1×10^{-3}	--	2.7×10^{-1}	1.8×10^{1}	--	A
Miscellaneous Internals	23	4.6	14.1	-	1.2×10^{-1}	8.6×10^{-4}	--	2.1×10^{-1}	1.4×10^{1}	--	A
Bio-Shield Concrete	707	707.0	0.01	-	8.3×10^{-5}	--	--	6.5×10^{-5}	6.9×10^{-3}	2.9×10^{-3}	A
Reactor Cavity Liner	14	2.0	0.02	-	2.2×10^{-4}	--	--	7.6×10^{-4}	1.9×10^{-2}	1.3×10^{-5}	A

(a) From Table 5.3.

(b) Waste exceeds Class C limits because of high concentrations of ^{59}Ni, ^{63}Ni, and ^{94}Nb.

(c) By placing this waste in a container with other waste of low specific activity it might be possible to dispose of the container under Class C restrictions.

TABLE 6.5. Waste Classifications of Neutron-Activated Materials from 100-Year Deferred Decontamination at the Reference PWR

Reactor Component	Burial Volume (m^3)	Full-Density Volume (m^3)	Total Specific Activity[(a)] (Ci/m^3)	Specific Activity (Ci/m^3): Limiting Long-Lived Nuclides: ^{14}C	^{59}Ni	^{94}Nb	^{99}Tc	Limiting Short-Lived Nuclides: ^{60}Co	^{63}Ni	Less Than 5-Year Half-Life	Waste Class
Pressure Vessel Cylindrical Wall	108	37.0	1.1	--	1.9×10^{-2}	--	--	8.4×10^{-5}	1.1×10^{0}	--	A
Vessel Head	57	12.1	0.002	--	3.3×10^{-5}	--	--	1.5×10^{-7}	2.0×10^{-3}	--	A
Vessel Bottom	57	5.3	0.004	--	6.8×10^{-5}	--	--	3.0×10^{-7}	4.0×10^{-3}	--	A
Upper Core Support Assembly	11	1.5	0.13	--	1.7×10^{-3}	1.2×10^{-5}	--	4.0×10^{-6}	1.3×10^{-1}	--	A
Upper Support Columns	11	1.4	1.6	--	2.0×10^{-2}	1.5×10^{-4}	--	5.0×10^{-5}	1.6×10^{0}	--	A
Upper Core Barrel	6	0.4	55	--	7.2×10^{-1}	5.0×10^{-3}	--	1.7×10^{-3}	5.4×10^{1}	--	B
Upper Core Grid Plate	14	0.6	892	--	1.2×10^{1}	8.1×10^{-2}	--	2.8×10^{-2}	8.7×10^{2}	--	C
Guide Tubes	17	1.9	1.2	--	1.6×10^{-2}	1.1×10^{-4}	--	3.7×10^{-5}	1.2×10^{0}	--	A
Lower Core Barrel	91	5.4	2 650	--	3.4×10^{1}	2.4×10^{-1}	--	8.2×10^{-2}	2.6×10^{3}	--	(b,c)
Thermal Shields	17	1.3	2 480	--	3.2×10^{1}	2.2×10^{-1}	--	7.7×10^{-2}	2.4×10^{3}	--	(b,c)
Core Shroud	11	1.6	47 200	--	6.0×10^{2}	4.3×10^{0}	--	1.5×10^{0}	4.6×10^{4}	--	(b)
Lower Grid Plate	14	0.5	24 400	--	3.2×10^{2}	2.2×10^{0}	--	7.6×10^{-1}	2.4×10^{4}	--	(b)
Lower Support Columns	3	0.4	550	--	7.2×10^{0}	5.0×10^{-2}	--	1.7×10^{-2}	5.4×10^{2}	--	C
Lower Core Forging	31	4.7	11.7	--	1.5×10^{-1}	1.1×10^{-3}	--	3.6×10^{-4}	1.1×10^{1}	--	A
Miscellaneous Internals	23	4.6	9.8	--	1.3×10^{-1}	8.9×10^{-4}	--	3.0×10^{-4}	9.6×10^{0}	--	A
Bio-Shield Concrete	707	707.0	0.01	--	1.1×10^{-4}	--	--	1.2×10^{-7}	6.4×10^{-3}	3.5×10^{-3}	A
Reactor Cavity Liner	14	2.0	0.01	--	1.7×10^{-4}	--	--	7.6×10^{-7}	9.9×10^{-3}	--	A

(a) From Table 5.4.
(b) Waste exceeds Class C limits because of high concentrations of ^{59}Ni, ^{63}Ni, and ^{94}Nb.
(c) By placing this waste in a container with other waste of low specific activity it might be possible to dispose of the container under Class C restrictions.

TABLE 6.6. Waste Classification of Neutron-Activated Materials from ENTOMB at the Reference PWR

Reactor Component	Burial Volume (m^3)	Full-Density Volume (m^3)	Total Specific Activity(a) (Ci/m^3)	Specific Activity (Ci/m^3): Limiting Long-Lived Nuclides				Limiting Short-Lived Nuclides			Waste Class
				^{14}C	^{59}Ni	^{94}Nb	^{99}Tc	^{60}Co	^{63}Ni	Less Than 5-Year Half-Life	
Pressure Vessel Cylindrical Wall	108	37.0	518	-	$1.9x10^{-2}$	--	--	$4.4x10^{1}$	$2.2x10^{0}$	$4.7x10^{2}$	A
Vessel Head	57	12.1	0.8	-	$2.9x10^{-5}$	--	--	$6.8x10^{-2}$	$3.4x10^{-3}$	$7.3x10^{-1}$	A
Vessel Bottom	57	5.3	1.9	-	$6.8x10^{-5}$	--	--	$1.6x10^{-1}$	$8.2x10^{-3}$	$1.7x10^{0}$	A
Upper Core Support Assembly	11	1.5	6.7	-	$1.9x10^{-3}$	$1.3x10^{-5}$	--	$2.4x10^{0}$	$3.0x10^{-1}$	$4.0x10^{0}$	A
Upper Support Columns	11	1.4	72	-	$2.0x10^{-2}$	$1.4x10^{-4}$	--	$2.6x10^{1}$	$3.2x10^{0}$	$4.2x10^{1}$	A
Upper Core Barrel	6	0.4	2 500	-	$7.0x10^{-1}$	$5.0x10^{-3}$	--	$9.0x10^{2}$	$1.1x10^{2}$	$1.5x10^{3}$	B
Upper Core Grid Plate	14	0.6	40 500	-	$1.1x10^{1}$	$8.1x10^{-2}$	--	$1.5x10^{4}$	$1.8x10^{3}$	$2.4x10^{4}$	C
Guide Tubes	17	1.9	53	-	$1.5x10^{-2}$	$1.1x10^{-4}$	--	$1.9x10^{1}$	$2.4x10^{0}$	$3.1x10^{1}$	A
Lower Core Barrel	91	5.4	121 000	-	$3.4x10^{1}$	$2.4x10^{-1}$	--	$4.4x10^{4}$	$5.4x10^{3}$	$7.1x10^{4}$	(b,c)
Thermal Shields	17	1.3	112 000	-	$3.1x10^{1}$	$2.2x10^{-1}$	--	$4.0x10^{4}$	$5.0x10^{3}$	$6.6x10^{4}$	(b,c)
Core Shroud	11	1.6	2 145 000	-	$6.0x10^{2}$	$4.3x10^{0}$	--	$7.7x10^{5}$	$9.7x10^{4}$	$1.3x10^{6}$	(b)
Lower Grid Plate	14	0.5	1 107 000	-	$3.1x10^{2}$	$2.2x10^{0}$	--	$4.0x10^{5}$	$5.0x10^{4}$	$6.5x10^{5}$	(b)
Lower Support Columns	3	0.4	25 000	-	$7.0x10^{0}$	$5.0x10^{-2}$	--	$9.0x10^{3}$	$1.1x10^{3}$	$1.5x10^{4}$	C
Lower Core Forging	31	4.7	532	-	$1.5x10^{-1}$	$1.1x10^{-3}$	--	$1.9x10^{2}$	$2.4x10^{1}$	$3.1x10^{2}$	B
Miscellaneous Internals	23	4.6	435	-	$1.2x10^{-1}$	$8.7x10^{-4}$	--	$1.6x10^{2}$	$2.0x10^{1}$	$2.6x10^{2}$	B
Bio-Shield Concrete	--	--	--	-	--	--	--	--	--	--	--
Reactor Cavity Liner	--	--	--	-	--	--	--	--	--	--	--

(a) From Table 5.5.

(b) Waste exceeds Class C limits because of high concentrations of ^{59}Ni, ^{63}Ni, and ^{94}Nb.

(c) By placing this waste in a container with other waste of low specific activity it might be possible to dispose of the container under Class C restrictions.

material. Values for fractional radioactivity of limiting long-lived and short-lived radionuclides for the various neutron-activated components are given in Tables 5.1 through 5.5 of Section 5.

As shown in Tables 6.2 through 6.6, the concentrations of limiting radionuclides in much of the neutron-activated material from decommissioning of the reference PWR are low enough to permit the classification of this material as either Class A or Class B waste. However, the concentrations of ^{63}Ni and ^{94}Nb in the upper grid plate and the lower support columns require that this material be classified as Class C waste. The concentrations of ^{59}Ni, ^{63}Ni, and ^{94}Nb in the lower core barrel, thermal shield, lower grid plate, and core shroud exceed the values for Class C waste. Because of the long half-lives of these nickel and niobium isotopes, the radioactivity of the neutron-activated material is not significantly reduced by deferring its removal for periods of up to 100 years.

The neutron-activated material from PWR decommissioning that is classified as Class C waste is estimated to have a burial volume of 17 m^3, constituting about 1.4% of the activated material from DECON and SAFSTOR and about 3.6% of the activated material from ENTOMB. The neutron-activated material that exceeds Class C limits is estimated to have a burial volume of 133 m^3, constituting about 11.2% of the activated material from DECON and SAFSTOR and about 28.2% of the activated material from ENTOMB. (For the ENTOMB alternative, some activated components with low specific activity such as the bioshield concrete and the reactor cavity liner remain in the entombment enclosure.)

6.2 CONTAMINATED MATERIALS

As noted in Section 5.2, the estimated average radioactivity concentration in contaminated materials from conceptual decommissioning of the reference PWR is not greater than 0.062 Ci/m^3. The principal short-lived isotopes in this material are ^{60}Co and ^{137}Cs. Comparison of the estimated average radioactivity concentration in the contaminated materials with activity concentrations for limiting short-lived nuclides given in Table 3.2 of Section 3 shows that this material can be classified as Class A waste.

6.3 RADIOACTIVE WASTES

Waste class assignments for the radioactive wastes from conceptual decommissioning of the reference PWR are given in Table 6.7. Waste classes are determined by comparing the estimated concentrations of limiting short-lived radionuclides in the waste with the concentrations used to define the different waste classes shown in Table 3.2 of Section 3. The estimated radioactivity concentrations shown in Table 6.7 are obtained by multiplying the specific activity of a given waste type by the fractional radioactivity of the short-lived radionuclides in the waste as shown in Table 5.7 of Section 5.

TABLE 6.7. Waste Classifications of Radioactive Wastes from Decommissioning at the Reference PWR

Waste Type	Burial Volume[(a)] (m^3)	Total Specific Activity (Ci/m^3)	Specific Activity of Limiting Short-Lived Nuclides (Ci/m^3): ^{60}Co	^{63}Ni	^{90}Sr	^{137}Cs	Other Short-Lived	Waste Class
Wet Solid Wastes								
Evaporator Bottoms	62 (51)	259	8.3×10^{1}	--	--	2.6×10^{-1}	1.8×10^{2}	A
Evaporator Bottoms	128 (104)	5.2	1.7×10^{0}	--	--	5.2×10^{-3}	3.5×10^{0}	A
Evaporator Bottoms	76 (62)	1.0	3.2×10^{-1}	--	--	1.0×10^{-3}	6.8×10^{-1}	A
Spent Resins	57 (46)	913	2.8×10^{2}	--	--	8.7×10^{-1}	5.9×10^{2}	B
Used Particulate Filters	9 (6.3)	800	2.6×10^{2}	--	--	8.0×10^{-1}	5.4×10^{2}	B
Dry Solid Wastes								
DECON								
Shielded Drums	88	6.0	4.5×10^{-1}	--	4.2×10^{-3}	4.5×10^{0}	1.0×10^{0}	B
Unshielded Drums	195	1.2	9.0×10^{-2}	--	8.4×10^{-4}	9.0×10^{-1}	2.0×10^{-1}	A
Preparation for Safe Storage								
Shielded Drums	28	6.0	4.5×10^{-1}	--	4.2×10^{-3}	4.5×10^{0}	1.0×10^{0}	B
Unshielded Drums	28	1.2	9.0×10^{-2}	--	8.4×10^{-4}	9.0×10^{-1}	2.0×10^{-1}	A
30-Year Deferred Decontamination								
Shielded Drums	23	6.0	2.4×10^{-2}	--	4.7×10^{-3}	6.0×10^{0}	7.8×10^{-3}	B
Unshielded Drums	207	0.35	1.4×10^{-3}	--	2.8×10^{-4}	3.5×10^{-1}	4.6×10^{-4}	A
50-Year Deferred Decontamination								
Shielded Drums	15	6.0	2.5×10^{-3}	--	5.0×10^{-3}	6.0×10^{0}	5.0×10^{-3}	B
Unshielded Drums	135	0.31	1.3×10^{-4}	--	2.6×10^{-4}	3.1×10^{-1}	2.6×10^{-4}	A
100-Year Deferred Decontamination								
Shielded Drums	--	--	--	--	--	--	--	--
Unshielded Drums	100	0.42	--	--	5.5×10^{-4}	4.2×10^{-1}	--	A
ENTOMB								
Shielded Drums	88	6.0	4.5×10^{-1}	--	4.2×10^{-3}	4.5×10^{0}	1.0×10^{0}	B
Unshielded Drums	195	1.2	9.0×10^{-2}	--	8.4×10^{-4}	9.0×10^{-1}	2.0×10^{-1}	A

(a) Values in parentheses for wet solid wastes are actual solidified waste volumes used to calculate Ci/m^3.

As discussed previously in Section 5, the operations of system decontamination and processing of radioactive liquids are assumed to be undertaken regardless of the alternative chosen to decommission the facility. Consequently, the burial volumes and specific activities of the wet solid wastes from decommissioning operations are the same for each decommissioning alternative (DECON, SAFSTOR, and ENTOMB). Approximately 80% (by volume) of the wet solid wastes from PWR decommissioning are estimated to be Class A wastes. The remaining wet solid wastes (spent resins and used particulate filters) are Class B wastes.

Most of the dry solid wastes from PWR decommissioning operations can be classified as Class A wastes. Because of high concentrations of ^{137}Cs, approximately 31% (by volume) of the dry solid waste from DECON and ENTOMB and 50% of the dry solid waste from preparations for safe storage is estimated to be Class B waste. Approximately 10% of the dry solid waste from 30-year and 50-year deferred decontamination is estimated to be Class B waste. Because of radioactive decay, all of the dry solid waste from 100-year deferred decontamination is assumed to be Class A waste.

7.0 CONCLUSIONS

The nuclear wastes from conceptual decommissioning of a reference PWR are classified, in this addendum, in terms of the waste classes specified in 10 CFR 61. The results are tabulated in Table 6.1 of Section 6.

Most of the nuclear waste from PWR decommissioning (approximately 86% to 98% of the total waste volume, depending on the decommissioning alternative) is considered to have such low radionuclide concentrations that it can be classified as Class A waste. To be acceptable for shallow-land disposal, Class A waste must meet the minimum packaging and waste form requirements given in paragraph 61.56(a) of 10 CFR. The waste processing and packaging methods described in the reference PWR study (Reference 1) provide sufficient protection to permit the handling and disposal of these wastes at a licensed shallow-land disposal site without further packaging requirements.

A small fraction of the nuclear waste from PWR decommissioning (approximately 0.7% to 7% of the total waste volume, depending on the decommissioning alternative) is classified as Class B waste. For the reference PWR, the Class B waste includes some neutron-activated stainless steel components with ^{63}Ni concentrations that exceed Class A limits, spent resins and used particulate filters with high specific activity, and some dry solid waste with concentrations of short-lived radionuclides that exceed Class A limits. Class B waste must meet the stability requirements of 10 CFR 61.56(b) that are intended to provide protection against structural degradation following burial. Structural stability can be provided by the waste form itself, by processing the waste to a stable form, or by placing the waste in a disposable container that provides stability after disposal. The processing and packaging methods described in the reference study provide adequate stability for most of the Class B waste identified in the study. However, in processing Class B wet or liquid waste, care must be taken to ensure that the residual liquid does not exceed 1% of the volume of the waste when the waste is in a disposal container designed to ensure stability, or 0.5% of the volume of the waste for waste processed to a stable form.

Some of the neutron-activated stainless steel components removed from the reactor pressure vessel during decommissioning are considered to have such high concentrations of ^{59}Ni, ^{63}Ni, and ^{94}Nb that they exceed the classification criteria for Class A and Class B waste. For the reference PWR, the upper core grid plate (burial volume 14 m^3) and the lower support columns (burial volume 3 m^3) are classified as Class C waste. The lower core barrel (burial volume 91 m^3), the thermal shields (burial volume 17 m^3), the core shroud (burial volume 11 m^3), and the lower grid plate (burial volume 14 m^3) are all considered to be nonclassifiable in terms of the limiting concentrations of long-lived radionuclides specified in 10 CFR 61. The radioactivity of the lower core barrel and the thermal shields exceeds Class C limits by a relatively small amount. By adding low-activity waste such as contaminated concrete to the containers in which sections of the core barrel and the thermal shields are placed for disposal, it might be possible to dispose of these waste packages as Class C wastes or as wastes of lower classification.

Class C waste must meet the stability requirements of 10 CFR 61.56(b) and must also be disposed of by a burial site operator using methods that provide additional protection against inadvertent intrusion into the burial ground. Class C waste must be buried so that the top of the waste is a minimum of 5 meters below the top surface of the cover, or must be placed within intruder barriers that are designed to protect against an inadvertent intrusion for at least 500 years. The disposal costs for Class C waste could be significantly higher than the disposal costs for Class A and Class B wastes. An estimate of these higher costs is beyond the scope of this addendum and is not given here.

Nuclear waste that exceeds Class C limits according to the provisions of 10 CFR 61 is not acceptable for routine near-surface disposal. The licensee is required to safely store this waste until a specific determination can be made on its disposition. Onsite storage of decommissioning waste would prevent termination of the nuclear license and release of the site until the waste was subsequently removed to an offsite disposal facility. The prospect of onsite storage of nuclear waste for a protracted period could therefore affect the choice of an alternative to decommission the reactor.

Two recent PNL experimental studies[7,8] that characterized the radioactivity concentrations in contaminated and activated materials from nuclear power plants provide data for comparison with the waste classification results summarized above.

In one of the these studies,[7] onsite sampling and measurement programs were conducted at 7 nuclear power plants (3 PWRs and 4 BWRs) to assess residual radionuclide concentrations and inventories in contaminated piping, hardware, equipment, concrete, and soils. The residual radionuclide concentrations observed in these contaminated materials were compared with guidelines for shallow-land burial of low-level radioactive waste contained in 10 CFR 61. The study concluded that the entire components of a decommissioned nuclear power plant (exclusive of the reactor pressure vessel and internals) could be disposed of at a shallow-land burial site as Class A waste, either directly or by mixing the relatively small quantities of highly contaminated concrete with lower-activity wastes. (The study did not address the question of wastes from the processing of contaminated water volumes or decontamination solutions, some of which are considered in this addendum to be Class B wastes.)

In the second study,[8] a program was carried out to assess the problems posed to reactor decommissioning by long-lived activation products in reactor construction materials. Reactor components investigated included the bio-shield, the pressure vessel, the vessel cladding, and the stainless steel internals. The program included the following three steps:

1. Samples of stainless steel, vessel steel, concrete, and concrete ingredients were analyzed to develop a data base of major, minor, and trace elements capable of being activated.

2. Calculations were performed using average values of the measured compositions of the appropriate materials to predict the levels of activation products expected in reactor internals, vessel walls, and bio-shield materials for both PWRs and BWRs.

3. Selected samples of activated steel and concrete were subjected to limited radiochemical analyses as a verification of the computer model used for the calculations of Step 2.

A comparison was made between calculated activation levels and regulatory guidelines for shallow-land disposal according to 10 CFR 61. It was concluded that the PWR shroud does not appear to be suitable for disposal as low-level waste and that the core barrel is questionable. From an activation standpoint, the remaining components were determined to be either Class A or Class B waste, with the bio-shield clearly Class A, even at its highest point of activation.

The results of these two studies are in substantial agreement with the results reported in this addendum for the conceptual decommissioning of a reference PWR.

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16. ABSTRACT (200 words or less)

The radioactive wastes expected to result from decommissioning of the reference pressurized water reactor power station are reviewed and classified in accordance with 10 CFR 61. The 17,885 cubic meters of waste from DECON are classified as follows: Class A, 98.0%; Class B, 1.2%; Class C, 0.1%. About 0.7% (133 cubic meters) of the waste would be generally unacceptable for disposal using near-surface disposal methods.

17. KEY WORDS AND DOCUMENT ANALYSIS

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17b. IDENTIFIERS/OPEN-ENDED TERMS

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