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Technology, Safety and Costs of Decommissioning Nuclear Reactors At Multiple-Reactor Stations

Prepared by N. G. Wittenbrock

Pacific Northwest Laboratory
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FOREWORO

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] This report, eleventh in the series, addresses the decommissioning of nuclear reactors at multiple-reactor power stations.

Additional decommissioning topics will be reported on the tentative schedule as follows:

FY 1982 • Research/Test Reactors

FY 1982 • LWR Post-Accidents

FY 1982 • Independent Spent Fuel Storage Installations

FY 1983 • Fuel Cycle Post-Accidents

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.[12] The second is a review and analysis of current decommissioning regulations.[13] The third covers the facilitation of the decommissioning of light water reactors,[14] identifying modifications or design changes to facilities, equipment, and procedures that will improve safety and/or reduce costs. The fourth covers the establishment of an information base concerning monitoring for compliance with decommissioning survey criteria.[15] A fifth report on this same theme, entitled Technology and Cost of Termination Surveys Associated with Decommissioning of Nuclear Facilities, is intended for FY 1982.

The information provided in this report on multiple-reactor stations, 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
Division of Engineering Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

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2. Technology, Safety and Costs of Decommissioning a Reference Nuclear Fuel Reprocessing Plant. NUREG-0278, Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, October 1977.

3. Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station. NUREG/CR-0130, Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, June 1978.

4. Technology, Safety and Costs of Decommissioning a Reference Small Mixed Oxide Fuel Fabrication Plant. NUREG/CR-0129, Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, February 1979.

5. Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station. NUREG/CR-0130 Addendum, Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, August 1979.

6. Technology, Safety and Costs of Decommissioning a Reference Low-Level Waste Burial Ground. NUREG/CR-0570, Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, June 1980.

7. Technology, Safety and Costs of Decommissioning a Reference Boiling Water Reactor Power Station. NUREG/CR-0672, Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, June 1980.

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9. Technology, Safety and Costs of Decommissioning Reference Non-Fuel Cycle Nuclear Facilities. NUREG/CR-1754, Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, February 1981.

10. Technology, Safety and Costs of Decommissioning a Reference Low-Level Waste Burial Ground. NUREG/CR-0570 Addendum, Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, May 1981.

11. Technology, Safety and Costs of Decommissioning a Reference Uranium Hexafluoride Conversion Plant. NUREG/CR-1757, Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, October 1981.

12. Decommissioning of Nuclear Facilities - An Annotated Bibliography. NUREG/CR-0131, Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, August 1979.

13. Decommissioning of Nuclear Facilities - A Review and Analysis of Current Regulations. NUREG/CR-0671, Pacific Northwest Laboratory and Battelle Human Affairs Research Centers for U.S. Nuclear Regulatory Commission, August 1979.

14. Facilitation of Decommissioning of Light Water Reactors. NUREG/CR-0569, Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, December 1979.

15. Monitoring for Compliance with Decommissioning Termination Survey Criteria. NUREG/CR-2082, Oak Ridge National Laboratory for U.S. Nuclear Regulatory Commission, June 1981.

ABSTRACT

Safety and cost information is developed for the conceptual decommissioning of large (1175-MWe) pressurized water reactors (PWRs) and large (1155-MWe) boiling water reactors (BWRs) at multiple-reactor stations. Three decommissioning alternatives are studied: DECON (immediate decontamination), SAFSTOR (safe storage followed by deferred decontamination), and ENTOMB (entombment). Safety and costs of decommissioning are estimated by determining the impact of probable features of multiple-reactor-station operation that are considered to be unavailable at a single-reactor station, and applying these estimated impacts to the decommissioning costs and radiation doses estimated in previous PWR and BWR decommissioning studies. The multiple-reactor-station features analyzed are: the use of interim onsite nuclear waste storage with later removal to an offsite nuclear waste disposal facility, the use of permanent onsite nuclear waste disposal, the dedication of the site to nuclear power generation, and the provision of centralized services.

Five scenarios for decommissioning reactors at a multiple-reactor station are investigated. The number of reactors on a site is assumed to be either four or ten; nuclear waste disposal is varied between immediate offsite disposal, interim onsite storage, and immediate onsite disposal. It is assumed that the decommissioned reactors are not replaced in one scenario but are replaced in the other scenarios. Centralized service facilities are provided in two scenarios but are not provided in the other three.

Decommissioning of a PWR or a BWR at a multiple-reactor station probably will be less costly and result in lower radiation doses than decommissioning an identical reactor at a single-reactor station. Regardless of whether the light water reactor being decommissioned is at a single- or multiple-reactor station:

- the estimated occupational radiation dose for decommissioning an LWR is lowest for SAFSTOR and highest for DECON
- the estimated cost of decommissioning a PWR is lowest for ENTOMB and highest for SAFSTOR
- the estimated cost of decommissioning a BWR is lowest for DECON and highest for SAFSTOR.

In all cases, SAFSTOR has the lowest occupational radiation dose and the highest cost.

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1.0 INTRODUCTION

Much attention is being given in the United States today to concerns about nuclear electric power generation. Chief among these concerns are the safe design, construction, and operation of nuclear power reactors and other nuclear fuel-cycle facilities and the safe disposal of nuclear waste.

In its regulatory role, the Nuclear Regulatory Commission (NRC) is developing criteria and standards for decontamination of retired facilities in connection with plant design objectives, plant decommissioning, and license terminations. To provide background information for this effort, the NRC is sponsoring a series of studies on the decommissioning of nuclear fuel-cycle facilities.

This report, one in the series, presents the results of a study on decommissioning of reactors at a multiple-reactor nuclear power station. Its objective is to determine the impacts on both safety and cost of decommissioning a nuclear power reactor at a site where other reactors are operating, being built, or being decommissioned, compared with the safety and cost of decommissioning a nuclear power reactor at a single-reactor power station. The sensitivities of both safety and cost to onsite versus offsite nuclear waste disposal, number of reactors onsite, availability of onsite central services, and reactor type (PWR or BWR) are examined. Two earlier decommissioning studies in this series provide the principal technical bases for these analyses.[1,2]

Several likely scenarios for multiple-reactor nuclear power stations are examined. Decommissioning alternatives studied within these scenarios are DECON (immediate decontamination), SAFSTOR (safe storage followed by deferred decontamination), and ENTOMB (entombment).

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(1) R. I. Smith, G. J. Konzek, and W. E. Kennedy, Jr., Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station, NUREG/CR-0130, U.S. Nuclear Regulatory Commission Report by Pacific Northwest Laboratory, June 1978.

(2) H. D. Oak, G. M. Holter, W. E. Kennedy, Jr., and G. J. Konzek, Technology, Safety and Costs of Decommissioning a Reference Boiling Water Reactor Power Station, NUREG/CR-0672, U.S. Nuclear Regulatory Commission Report by Pacific Northwest Laboratory, June 1980.

2.0 SUMMARY

The purpose of this study is to determine the differences in the costs and the associated radiation doses for decommissioning a reactor at a multiple-reactor station compared with decommissioning an identical reactor at a single-reactor station. The study results are summarized in this section. This information is intended as background data for use in developing regulations and regulatory guides for decommissioning nuclear reactor power plants.

2.1 DECOMMISSIONING ALTERNATIVES AND STUDY APPROACH

Three alternatives for decommissioning the reactors at a multiple-reactor station are studied: DECON, SAFSTOR, and ENTOMB.

- DECON, called immediate dismantlement in previous studies on decommissioning of a PWR and a BWR at a single-reactor station,(1,2) is the prompt removal from the site of all materials containing or contaminated with radionuclides at levels greater than permitted for unrestricted use of the property.
- SAFSTOR, called safe storage followed by deferred dismantlement in the previous LWR decommissioning studies, is the establishment and maintenance of the LWR power plant in a condition that poses an acceptable risk to the public and safely stores the property for as long as desired to allow decay of some of the radioactivity, followed by decontamination of the facility to the unrestricted release level.
- ENTOMB, called entombment in the previous LWR decommissioning studies, is the encasement and maintenance of the nonreleasable radioactive materials in a monolithic structure to ensure retention of the radionuclides until they have decayed to levels that permit unrestricted release of the site.

The sensitivity of the safety and cost to several variables is investigated for each of these decommissioning alternatives. The variables examined are nuclear waste disposal, site dedication to nuclear power generation, centralized services, number of reactors at the site, and types of reactors being decommissioned. Cost and radiation doses are estimated for five possible multiple-reactor station scenarios.

2.2 REGULATORY CONSIDERATIONS FOR DECOMMISSIONING

Regulations are in place under which decommissioning of nuclear reactor power plants can be covered. In some cases (i.e., security, safeguards, quality assurance) the existing regulations do not speak specifically to the question of decommissioning, but they can readily be interpreted as being applicable.

Areas where more specific guidance could be helpful are:

- Clarification of the criteria defining allowable levels of contamination and dose rates for unrestricted release of decommissioned nuclear facilities.
- Definition of classes of radioactive waste, to more clearly indicate the acceptable disposition method for the highly radioactive neutron-activated components (i.e., disposal in shallow land burial sites or in deep geologic storage).
- Clarification of the financial qualifications and responsibility for decommissioning, to define the commitments of the facility owner for achieving the final status of unrestricted use of the property.

2.3 FINANCING OF DECOMMISSIONING

The NRC is considering the following criteria for evaluation of the effectiveness of alternative decommissioning financing methods:

1. the degree of decommissioning assurance provided
2. the cost of providing the assurance
3. the extent to which the consumers of the plant's power equitably share the cost of decommissioning
4. the flexibility to respond to changes in inflation and interest rates, reactor life, and estimated decommissioning costs

5. the ability to accommodate different ownership and jurisdictional arrangements.

There are three principal financing alternatives for decommissioning a nuclear power station that meet these criteria to varying degrees:

- a prepaid decommissioning reserve controlled by an outside entity
- an internal decommissioning reserve, either funded or unfunded
- a funded reserve or sinking fund controlled by an outside entity.

The problem of providing assurance that adequate funds will be available for decommissioning a nuclear power reactor at a multiple-reactor station after final reactor shutdown is not significantly different from providing that assurance at a single-reactor station. The alternatives for accumulating funds for decommissioning a reactor appear equally applicable for a reactor at a single- or multiple-reactor station.

2.4 MULTIPLE-REACTOR STATION CONCEPTS

It is more likely that the reactors at a multiple-reactor station with a small number of reactors (i.e., four reactors) will be of the same type and design than it is for a station with a larger number of reactors. However, even at a multiple-reactor station with 10 or 20 reactors, it is probable that there will be several reactors of each type of LWR. Standardization of design gives the following advantages during the decommissioning of several identical reactors at a nuclear power station:

- It minimizes the planning effort for decommissioning the second and later reactors of an identical design.
- It improves the productivity of the decommissioning workers due to the experience gained on the first reactor.
- It improves the planning of decommissioning techniques and permits correction of mistakes.

If a site is dedicated to nuclear power generation, replacement reactors will be constructed on a schedule to result in startup of a replacement reactor just as an old reactor is retired. Such site dedication fosters a stable labor force for construction and decommissioning of the plants.

Significant savings can be achieved over the construction of a new plant, if structures and systems (other than the nuclear reactor equipment of an old nuclear power plant) are refurbished and reused with a new nuclear steam supply system. Since much of the old nuclear reactor plant would be decontaminated in place and refurbished for use with a new nuclear reactor, decommissioning of the old reactor plant would be simpler and less costly.

2.5 REFERENCE LIGHT WATER REACTORS

The reference light water reactors are the same as those described in References 1 and 2. The reference PWR plant is an 1175-MWe (3500-MWt) Westinghouse pressurized water reactor, specifically the Trojan Nuclear Plant at Rainier, Oregon, operated by the Portland General Electric Company. The reference BWR plant is an 1155-MWe (3320-MWt) General Electric boiling water reactor being built by the Washington Public Power Supply System; it is designated as the WPPSS Nuclear Project No. 2 and is located near Richland, Washington.

2.6 IMPACT OF MULTIPLE REACTORS ON DECOMMISSIONING COSTS

The impact of having more than one reactor at a nuclear reactor power station on the cost of decommissioning one of the reactors is estimated by comparison with costs previously estimated for decommissioning a reactor at a single-reactor power station. Factors experienced in this analysis include several different approaches to disposal of low-level nuclear waste, the dedication of the site to nuclear power generation, the availability of centralized services, and the type and number of reactors present at the station.

Waste Disposal

The three options considered for disposal of the low-level nuclear waste generated while decommissioning a reactor at a multiple-reactor station are:

1. disposal at an offsite licensed low-level waste disposal facility
2. interim onsite storage with transfer to an offsite licensed low-level waste disposal facility at a later date
3. disposal at a permanent onsite low-level nuclear waste disposal facility.

Decommissioning a single reactor at a multiple-reactor station results in the same quantity of nuclear waste for disposal and the same packaging, transportation and disposal-site handling and burial costs as decommissioning an identical reactor at a single-reactor station. Therefore, there is no impact on the cost of offsite nuclear waste disposal.

Storing nuclear waste from decommissioning onsite for a period of 30 to 100 years before transferring it to a permanent offsite waste disposal facility can result in cost savings. Interim onsite storage of nuclear waste with later permanent disposal offsite involves the following tasks:

- packaging
- transporting to interim onsite storage
- placing in interim storage
- retrieving from interim storage
- transporting to a permanent disposal facility
- placing in a permanent disposal facility.

Three categories of radioactive material, neutron-activated, contaminated, and radwaste, are considered in the nuclear waste disposal cost analyses. Costs of nuclear waste disposal with interim onsite storage are estimated for interim storage periods of 30, 50, and 100 years. Estimates of nuclear waste disposal costs for the three decommissioning alternatives are given in Table 2.6-1. These

TABLE 2.6-1. Summary of Estimated Costs for Interim Onsite Nuclear Waste Storage with Later Removal to Permanent Offsite Disposal

Decommissioning Alternative	Safe Storage Period (years)	Nuclear Waste Disposal Cost ($ thousands)[a]							
		Immediate Offsite Disposal		Interim Onsite Waste Storage					
				PWR			BWR		
		PWR	BWR	30 yr[b,c]	50 yr[b,c]	100 yr[b,c]	30 yr[b,c]	50 yr[b,c]	100 yr[b,c]
DECON	0	10 762	10 850	12 810	8 550	8 530	11 360	6 970	6 900
SAFSTOR	30	10 790	10 850	8 280	8 190	8 160	7 120	6 335	6 280
	50	4 270	4 700	3 450	3 370	3 340	1 900	1 690	1 650
	100	4 230	4 620	3 400	3 314	3 300	1 650	1 490	1 460
ENTOMB	0	4 580	7 140	3 390	2 840	2 820	6 000	4 010	3 930

(a) Costs are given in 1978 dollars and include a 25% contingency.
(b) Duration of the interim onsite waste storage period.
(c) Includes cost of placement of waste in interim onsite storage plus cost of removal at a later date to permanent offsite disposal.

costs include a 25% contingency and are given in 1978 dollars for easy comparability with cost estimates in the previous PNL reactor decommissioning studies.[1,2] With the exception of 30-year interim onsite storage of the nuclear waste from DECON, all of the nuclear waste disposal costs were reduced by using interim onsite storage of the nuclear waste, compared with immediate offsite disposal.

Factors that contribute to lower costs for onsite waste disposal than for offsite waste disposal are:

- lower transportation costs because of the short haul to the disposal site
- no overweight charges, since all travel is over private roads
- no relief driver charges, since only one driver is needed
- shielded cask liners may not be needed for some of the activated material, since the DOT maximum surface dose rate may be exceeded during travel over private roads.

Estimated nuclear waste disposal costs for permanent onsite disposal of the nuclear waste from decommissioning a PWR and a BWR are given in Table 2.6-2 for DECON, SAFSTOR, and ENTOMB. The costs of disposal at an offsite nuclear waste disposal facility are also given for comparison. All of the costs are in 1978 dollars and include a 25% contingency. Significant cost reductions are estimated in every instance. The estimated savings from using the different nuclear waste disposal options are summarized in Table 2.6-3.

TABLE 2.6-2. Summary of Estimated Costs for Permanent Onsite Nuclear Waste Disposal

	Cost of Waste Disposal ($ thousands)[a]										
			SAFSTOR								
			PWR			BWR					
Disposal Location	DECON PWR	DECON BWR	30 yr[b]	50 yr[b]	100 yr[b]	30 yr[b]	50 yr[b]	100 yr[b]	ENTOMB PWR	ENTOMB BWR
Offsite	10 760	10 850	10 990	4 460	4 400	10 850	4 700	4 620	4 580	7 140
Onsite	7 050	5 240	7 120	2 660	2 660	5 420	1 070	940	1 980	2 700
Cost Reduction	3 710	5 610	3 870	1 790	1 740	5 430	3 630	3 680	2 600	4 440

(a) Costs are given in 1978 dollars and include a 25% contingency.
(b) Duration of safe storage period.

TABLE 2.6-3. Summary of Estimated Nuclear Waste Disposal Cost Reductions at a Multiple-Reactor Station

Waste Disposal Option	Cost Reductions ($ thousands)[a]					
	DECON		SAFSTOR[b]		ENTOMB	
	PWR	BWR	PWR	BWR	PWR	BWR
Interim Onsite Storage for:[c]						
30 years	(2050)[d]	(510)[d]	2510	3730	1190	1140
50 years	2210	3880	2600	4520	1740	3130
100 years	2230	3950	2630	4570	1760	3210
Permanent Onsite Disposal	3710	5610	3870	5430	2600	4440

(a) A 25% contingency is included in all cost differences. Costs are in 1978 dollars.
(b) For deferred decontamination after 30 years of safe storage.
(c) Interim storage costs include costs of placement in interim onsite storage and removal to offsite disposal.
(d) Parentheses indicate a cost increase.

Site Dedication

Dedication of a site to nuclear power generation results in replacement reactors being constructed on a schedule to achieve startup of a replacement reactor as an old reactor is shut down. At such dedicated sites, either relatively long periods of construction activity will occur periodically or there will be continuous construction activity at the site if the startup of the reactors is spaced to occur over a 30-year period.

Dedication of a multiple-reactor site to nuclear power generation:

- fosters stable operating and construction labor forces
- favors the establishment of interim onsite low-level waste storage or permanent onsite low-level waste disposal
- results in improved efficiency of construction and decommissioning as management and the labor force accumulate onsite experience
- encourages the provision of centralized services.

It is expected that the efficiency of decommissioning the reactors at a multiple-reactor station will improve after the first reactor is decommissioned due to the learning process. Cost and dose reduction factors are estimated using the following assumptions:

1. The reduction factor for planning and preparation for the second and each succeeding reactor of a particular type (PWR or BWR) is 0.50.
2. The reduction factor for decommissioning operations for the second reactor of a particular type is 0.95.
3. The reduction factor for decommissioning operations for the third and each succeeding reactor of a particular type is 0.90.

Centralized Services

A number of centralized services that may be available at a multiple-reactor station are:

- health physics services
- security forces
- solid waste processing
- equipment decontamination services
- maintenance shops and services
- laundry services
- transportation services
- central stores.

Centralized health physics services and a station-wide central security force could significantly reduce the cost of providing these services. The cost reductions derive largely from:

- the reduced staff overhead for each of these services
- the reduced peak-load staffing requirements per reactor, by providing a pool of personnel for each service.

In the decommissioning studies of the reference PWR[1] and the reference BWR[2] at single-reactor stations, it was assumed that the dry solid radioactive waste was mechanically compacted to achieve a five-fold volume reduction.

A central waste incinerator at a multiple-reactor station can further reduce the volume of combustible radioactive waste by at least a factor of 5, giving an overall volume reduction factor of 25. Such an incinerator can yield significant reductions in waste disposal costs for both the operating and decommissioning phases of reactor life. The savings from using the incinerator, with capital and operating costs considered, compared to merely compacting the combustible radioactive waste, are 65 to 70% of the compacted waste disposal cost for the PWR and 55 to 70% for the BWR.

Equipment decontamination services can be more fully utilized at a multiple-reactor station than at a single-reactor station. The several types of equipment decontamination services considered are:

- decontamination of special tools and equipment used for decommissioning, allowing maintenance and reuse of these items
- mobile decontamination systems for in-situ chemical decontamination of piping and components
- central electropolishing and chemical decontamination facilities for improved decontamination of piping sections and components.

Development work on decontamination of metals by electropolishing indicates that much of the contaminated metal in piping and vessels at a nuclear power plant can be salvaged and sold for scrap. Electropolishing is an effective process for decontaminating piping, valves, and other equipment for refurbishment and reuse. Salvage of releasable decontaminated stainless steel, assuming 80% recovery, represents the largest component of the savings from the use of central decontamination services when decommissioning a PWR. For decommissioning a BWR, the decontamination and refurbishment of special tools and equipment for reuse generates most of the savings from the use of central decontamination services.

Central laundry services, central transportation services, and central stores provide a convenience for the operating and decommissioning phases of reactor life at a multiple-reactor station, but they do not generate significant savings during reactor decommissioning.

The savings from use of central services are summarized in Table 2.6-4.

TABLE 2.6-4. Summary of Cost Reductions Resulting from Centralized Services at a Multiple-Reactor Station

Central Service	Cost Reductions ($ thousands)[a]					
	DECON		SAFSTOR[b]		ENTOMB	
	PWR	BWR	PWR	BWR	PWR	BWR
Radiation Monitoring	580	770	900	1320	580	820
Security	570	650	1010	1330	570	760
Solid Waste Processing	170	280	180	320	170	280
Equipment Decontamination	1420	1750	1430	1800	1420	1750

(a) A 25% contingency is included in all cost differences. Costs are in 1978 dollars.
(b) For deferred decontamination after 30 years of safe storage.

Type of Reactor

The differences in the estimated decommissioning costs for PWRs and BWRs given in studies for single-reactor stations[1,2] are also experienced in decommissioning reactors at a multiple-reactor station. Decommissioning costs for PWRs are impacted to about the same extent as for BWRs when costs at a multiple-reactor station are compared to costs at a single-reactor station.

Number of Reactors

The number of reactors at a multiple-reactor station influences how the nuclear waste is disposed of, whether there is a continuing stable construction labor force, and whether, or which, centralized services are provided. With a small number of reactors at the station, it is not likely that nuclear waste could be disposed of onsite. It is also improbable that centralized services would be provided; however, special decommissioning tools and equipment probably would be shared. Improvement and economies in planning the decommissioning of successive reactors would be realized for a few as well as many reactors at a multiple-reactor station. If only a few reactors are located at the station, the continuing stability of the labor force would not be assured. Therefore, there would not be a continuing availability of experienced decommissioning workers.

2.7 IMPACT OF MULTIPLE REACTORS ON RADIATION DOSE

The same factors examined in the cost analysis are considered in estimating the impact on the occupational and public radiation doses from decommissioning a reactor at a multiple-reactor station. Occupational radiation dose impacts consider the doses received by the decommissioning workers at the reactor plant, the transportation workers, and the burial ground workers. The impacts on the occupational doses of waste disposal options, site dedication, and centralized services are given in Table 2.7-1. The impacts on the public radiation doses of these same factors are given in Table 2.7-2.

TABLE 2.7-1. Summary of Estimated Occupational Radiation Dose Reductions from Decommissioning One Reactor at a Multiple- vs. a Single-Reactor Station

	Occupational Radiation Dose Reductions (man-rem)					
	DECON		SAFSTOR[a]		ENTOMB	
Factor	PWR	BWR	PWR	BWR	PWR	BWR
Waste Disposal						
Interim Onsite Storage for:						
30 years	(72)[b]	(47)[b]	74	68	(6)[b]	(33)[b]
50 years	72	55	77	87	12	26
100 years	75	60	78	88	13	29
Permanent Onsite Disposal	90	101	90	101	23	67
Site Dedication[c]	75	129	21	29	65	118
Centralized Services	4	5	2	3	4	5

(a) For preparations for safe storage and deferred decontamination after 30 years of safe storage.
(b) Parentheses indicate a dose increase.
(c) For a multiple-reactor station with five reactors of one type.

TABLE 2.7-2. Summary of the Estimated Public Radiation Dose Reductions from Decommissioning One Reactor at a Multiple- vs. a Single-Reactor Station

Factor	Public Radiation Dose Reductions (man-rem)					
	DECON		SAFSTOR[a]		ENTOMB	
	PWR	BWR	PWR	BWR	PWR	BWR
Waste Disposal						
Interim Onsite Storage for:						
30 years	3	5	18	17	1	<1
50 years	18	19	18	20	3	7
100 years	18	19	18	20	3	7
Centralized Services	1	1	<1	<1	1	1

(a) For preparations for safe storage and deferred decontamination after 30 years of safe storage.

2.8 MULTIPLE-REACTOR STATION DECOMMISSIONING SCENARIOS

Five scenarios for multiple-reactor stations are investigated to determine the impact of the variables discussed in Subsection 2.6 on decommissioning costs and safety. These variables, the number of reactors at the station, the type of reactors, the nuclear waste disposal option, the dedication of the site to nuclear power generation, and the provision of central services are varied for the different scenarios. Details of the five scenarios are indicated in Figure 2.8-1.

Scenarios 1 and 2 are for 4-reactor stations and scenarios 3, 4, and 5 are for 10-reactor stations. Scenario 2 does not have a site dedicated to nuclear power generation, while the other four scenarios are at dedicated sites. Scenarios 4 and 5 are at dedicated sites with central facilities and have either interim onsite nuclear waste storage or permanent onsite nuclear waste disposal.

Summaries of the decommissioning costs for the five scenarios and the decommissioning cost reductions compared to single-reactor station decommissioning

SCENARIO NUMBER	NUMBER OF REACTORS	TYPE OF REACTOR		RETIRED AFTER 40 YR		OLD REACTOR REPLACED		WASTE DISPOSAL			CENTRAL FACILITIES	
		PWR	BWR	1 REACTOR EVERY 2 YR	1 REACTOR EVERY 4 YR	YES	NO	IMMEDIATE OFFSITE	ONSITE INTERIM STORAGE	ONSITE PERMANENT DISPOSAL	YES	NO
1	4	X		X		X			X			X
2	4		X		X		X	X				X
3	10	X	X		X	X		X				X
4	10	X	X		X	X			X		X	
5	10	X	X	X		X				X	X	

FIGURE 2.8-1. Multiple-Reactor Station Scenarios

costs are given in Table 2.8-1. Except for Scenario 1 (interim onsite nuclear waste storage for 30 years), the estimated decommissioning costs at a multiple-reactor station are reduced, compared to single-reactor stations.

Table 2.8-2 gives a summary of the estimated occupational radiation doses for decommissioning one reactor at the multiple-reactor stations of the five scenarios. The dose reductions compared to the occupational doses for decommissioning a reactor at a single-reactor station are also given.

2.9 FACILITATION OF DECOMMISSIONING

The several alternatives or techniques for facilitating the decommissioning of nuclear power plants that are discussed are: improved documentation, improved access, substitution and purification of materials, design of the biological shield for easy removal, improved protection of concrete, improved removal of concrete, special shielded maintenance shop, improved shielding for maintenance and decommissioning, remote maintenance and decommissioning, and special tools and techniques. All of these alternatives and techniques are equally applicable to reactors at single- or multiple-reactor stations.

Features of multiple-reactor station operation such as site dedication, onsite waste storage or disposal, and provision of centralized services are decommissioning facilitation options in and of themselves.

TABLE 2.8-1. Summary of the Estimated Costs for Multiple-Reactor Station Decommissioning Scenarios

Decommissioning Alternative	Safe Storage Period	Interim Waste Storage Period	Decommissioning Cost ($ thousands)(a) Single Reactor Station PWR	Single Reactor Station BWR	Scenario No. 1 PWR	Scenario No. 2 BWR	Scenario No. 3 PWR	Scenario No. 3 BWR	Scenario No. 4 PWR	Scenario No. 4 BWR	Scenario No. 5 PWR	Scenario No. 5 BWR	Decommissioning Cost Reductions ($ thousands)(a) Scenario No. 1 PWR	Scenario No. 2 BWR	Scenario No. 3 PWR	Scenario No. 3 BWR	Scenario No. 4 PWR	Scenario No. 4 BWR	Scenario No. 5 PWR	Scenario No. 5 BWR
DECON		0	31 026	43 550	--	41 848	30 096	41 628	--	--	23 645	32 568	--	1 703	930	1 923	--	--	7 381	10 983
		30	--	--	32 281	--	--	--	29 405	38 686	--	--	(1 255)(b)	--	--	--	1 621	4 864	--	--
		50	--	--	28 019	--	--	--	25 143	34 299	--	--	3 008	--	--	--	5 884	9 251	--	--
		100	--	--	28 006	--	--	--	25 130	34 224	--	--	3 020	--	--	--	5 896	9 326	--	--
SAFSTOR	30	0	40 750	58 890	--	54 863	39 214	54 468	--	--	31 826	44 341	--	4 028	1 536	4 423	--	--	8 924	14 611
		30	--	--	36 943	--	--	--	33 193	45 976	--	--	3 808	--	--	--	7 558	12 914	--	--
		50	--	--	36 849	--	--	--	33 099	45 193	--	--	3 901	--	--	--	7 651	13 698	--	--
		100	--	--	36 818	--	--	--	33 068	45 136	--	--	3 933	--	--	--	7 683	13 754	--	--
	50	0	35 750	51 325	--	47 561	34 139	47 213	--	--	28 954	38 856	--	3 764	1 536	4 113	--	--	6 796	12 469
		30	--	--	33 624	--	--	--	29 919	39 688	--	--	2 126	--	--	--	5 831	11 638	--	--
		50	--	--	33 549	--	--	--	29 844	39 481	--	--	2 201	--	--	--	5 906	11 844	--	--
		100	--	--	33 511	--	--	--	29 806	39 439	--	--	2 239	--	--	--	5 944	11 886	--	--
	100	0	39 750	55 040	--	51 276	38 214	50 928	--	--	33 030	42 578	--	3 764	1 536	4 113	--	--	6 720	12 463
		30	--	--	37 611	--	--	--	33 935	43 289	--	--	2 139	--	--	--	5 815	11 751	--	--
		50	--	--	37 536	--	--	--	33 860	43 135	--	--	2 214	--	--	--	5 890	11 905	--	--
		100	--	--	37 511	--	--	--	33 835	43 100	--	--	2 239	--	--	--	5 915	11 940	--	--
ENTOMB(c)		0	29 732	45 581	--	43 859	28 846	43 619	--	--	23 510	35 584	--	1 723	886	1 963	--	--	6 223	9 998
		30	--	--	27 793	--	--	--	24 923	38 883	--	--	1 940	--	--	--	4 810	6 699	--	--
		50	--	--	27 235	--	--	--	24 365	36 890	--	--	2 498	--	--	--	5 368	8 691	--	--
		100	--	--	27 219	--	--	--	24 349	36 816	--	--	2 514	--	--	--	5 384	8 765	--	--

(a) Costs given in 1978 dollars and include a 25% contingency.
(b) Parenthese indicate a cost increase.
(c) These estimates include no costs that may be associated with final actions necessary for termination of the license.

TABLE 2.8-2. Summary of the Estimated Occupational Radiation Doses for Multiple-Reactor Station Decommissioning Scenarios

Decommissioning Alternative	Safe Storage Period	Interim Waste Storage Period	Decommissioning Occupational Radiation Dose (man-rem)										Decommissioning Occupational Radiation Dose Reduction (man-rem)							
			Single Reactor Station		Scenario No. 1	Scenario No. 2	Scenario No. 3		Scenario No. 4		Scenario No. 5		Scenario No. 1	Scenario No. 2	Scenario No. 3		Scenario No. 4		Scenario No. 5	
			PWR	BWR	PWR	BWR	PWR	BWR	PWR	BWR	PWR	BWR	PWR	BWR	PWR	BWR	PWR	BWR	PWR	BWR
DECON		0	1324	1954	--	1843	1239	1825	--	--	1145	1719	--	111	85	129	--	--	179	235
		30	--	--	1320	--	--	--	1304	1867	--	--	4	--	--	--	20	87	--	--
		50	--	--	1179	--	--	--	1163	1765	--	--	145	--	--	--	161	189	--	--
		100	--	--	1176	--	--	--	1160	1760	--	--	148	--	--	--	164	194	--	--
SAFSTOR	30	0	554	527	--	503	523	498	--	--	431	395	--	24	31	29	--	--	123	132
		30	--	--	454	--	--	--	447	427	--	--	100	--	--	--	107	100	--	--
		50	--	--	451	--	--	--	444	409	--	--	103	--	--	--	110	118	--	--
		100	--	--	450	--	--	--	443	408	--	--	104	--	--	--	111	119	--	--
	50	0	456	429	--	407	427	403	--	--	403	362	--	22	29	26	--	--	53	67
		30	--	--	426	--	--	--	420	374	--	--	30	--	--	--	36	55	--	--
		50	--	--	423	--	--	--	417	369	--	--	33	--	--	--	39	60	--	--
		100	--	--	422	--	--	--	417	368	--	--	34	--	--	--	39	61	--	--
	100	0	455	427	--	405	426	401	--	--	403	359	--	22	29	26	--	--	52	68
		30	--	--	424	--	--	--	419	382	--	--	31	--	--	--	36	45	--	--
		50	--	--	422	--	--	--	416	377	--	--	33	--	--	--	39	50	--	--
		100	--	--	421	--	--	--	416	377	--	--	34	--	--	--	39	50	--	--
ENTOMB[a]		0	992	1756	--	1655	860	1638	--	--	833	1566	--	101	62	118	--	--	89	190
		30	--	--	873	--	--	--	862	1666	--	--	49	--	--	--	60	90	--	--
		50	--	--	855	--	--	--	845	1607	--	--	67	--	--	--	77	149	--	--
		100	--	--	854	--	--	--	843	1603	--	--	68	--	--	--	79	153	--	--

(a) These estimates do not include any doses that may be associated with actions necessary for the termination of the license.

One of the alternatives for reactor retirement is conversion to a new nuclear- or fossil-fueled steam supply system. Reuse of those facilities at a nuclear power station that can be refurbished makes good economic sense. Based on capital cost studies for PWRs[3] and BWRs,[4] the structures and equipment other than the nuclear steam supply system account for about 70% of the initial direct construction cost. Analyses of removing the old reactor vessel and replacing it with a new vessel indicate that such action is feasible, but difficult, in the reference PWR and BWR nuclear power plants. Removal of a reactor vessel intact for disposal is also feasible but is generally more costly in terms of money and radiation dose than segmentation and disposal of the vessel.

Design features that should be incorporated to facilitate the removal or replacement of the reactor pressure vessel and other large equipment pieces are:

- an equipment hatch in the reactor containment building large enough to accommodate the intact reactor pressure vessel
- an equipment hatch located so that there is sufficient lay-down area in front of it, both in the containment building and in the adjacent building, so that the reactor vessel can be lined up with the hatch
- adequate supports in the containment building to handle the special cranes needed for very heavy loads such as the reactor pressure vessel and steam generators
- a readily removable roof section in the fuel building of a PWR and in the reactor building of a BWR that is large enough to accommodate the reactor pressure vessel
- an inner shield of modular design that can be removed and/or replaced.

2.10 CONCLUSIONS

Decommissioning of a PWR or BWR at a multiple-reactor station probably will be less costly and result in lower radiation doses than decommissioning of an identical reactor at a single-reactor station. Regardless of whether the light water reactor being decommissioned is at a single- or multiple-reactor station:

- the estimated occupational radiation dose for decommissioning an LWR is lowest for SAFSTOR and highest for DECON
- the estimated cost of decommissioning a PWR is lowest for ENTOMB[(a)] and highest for SAFSTOR
- the estimated cost of decommissioning a BWR is lowest for DECON and highest for SAFSTOR.

Decommissioning costs and occupational radiation doses for the two types of reactors are impacted in about the same way by the factors studied at multiple-reactor stations. In determining if there is a cost advantage for decommissioning nuclear reactors at a multiple-reactor station versus a single-reactor station, the type of reactor, PWR or BWR, has little influence on the result.

The number of reactors at a multiple-reactor station may influence the availability of interim onsite nuclear waste storage, permanent onsite nuclear waste storage, or centralized services. Four or more reactors of a single type, along with dedication of the site to nuclear power generation, can lead to a relatively stable construction labor force and, with successive decommissioning of the reactors, lead to improvements in the efficiency of planning and execution of the decommissioning activities.

Interim onsite nuclear waste storage with later relocation to permanent offsite disposal or permanent onsite nuclear waste disposal can contribute to reduced decommissioning costs and occupational doses.

Providing centralized services, particularly health physics services, security force, central waste incineration, central equipment decontamination facilities, and special maintenance services can reduce decommissioning costs. Of the central services studied, only waste volume reduction by incineration yields a significant reduction of the occupational radiation dose.

(a) ENTOMB cost estimates do not include the costs that may be associated with actions required for termination of the license.

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3. Capital Cost: Pressurized Water Reactor Plant, prepared for the U.S. Nuclear Regulatory Commission and the Energy Research and Development Administration by United Engineers and Constructors, Inc., NUREG-0241, June 1977.

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3.0 DECOMMISSIONING: ALTERNATIVES, CONSIDERATIONS, AND STUDY APPROACH

Once a nuclear reactor reaches the end of its useful life, it must be placed in a condition that assures that the impact of the facility upon public health and safety will be within acceptable bounds; achieving this condition is termed "decommissioning." Conditions that satisfy the requirements of decommissioning range from 1) minimal cleanup and subsequent physical security under licensing restrictions to 2) complete cleanup and removal of all radioactivity and release of the plant from all licensing restrictions. Alternatives for decommissioning are discussed in Section 3.1; considerations for decommissioning are discussed in Section 3.2; and the approach taken for this study is discussed in Section 3.3.

3.1 DECOMMISSIONING ALTERNATIVES

Three alternatives available for decommissioning a nuclear power station are: DECON, immediate decontamination; SAFSTOR, safe storage followed by deferred decontamination; and ENTOMB, entombment.[a] Each of these alternatives is defined and discussed in the following subsections.

Before starting decommissioning by any of the three alternatives, the facility operating license may be amended to authorize possession but not operation of the facility.[3]

3.1.1 DECON

DECON is the prompt removal from the site of all materials containing or contaminated with radionuclides at levels greater than permitted for unrestricted use of the property. Under present regulatory requirements, DECON is the only decommissioning alternative that allows termination of the facility license in a short time period. Demolition and removal of the decontaminated and uncontaminated structures, following DECON, is at the option of the owner and local government agencies.

(a) The terms "immediate decontamination" and "deferred decontamination" used in this study are the current terms for "immediate dismantlement" and "deferred dismantlement" used in the previous decommissioning studies of a PWR and a BWR at a single-reactor station.[1,2]

DECON meets the requirements for termination of the facility operating license and renders the LWR facility and site available for unrestricted use within a short period of time following final reactor shutdown. In this decommissioning alternative, large commitments of money (in a relatively short time frame), personnel radiation exposure, and disposal site space are made in exchange for prompt availability of the facility and site for other purposes. Additional considerations include the elimination of continuing security, maintenance, and surveillance requirements (i.e., for SAFSTOR or ENTOMB), and the availability of the facility operations staff to form a decommissioning work force that is highly knowledgeable about the facility. Early termination of the license also satisfies the desirable objective of minimizing the number of sites dedicated to radioactive material storage.

3.1.2 SAFSTOR

SAFSTOR is the establishment and maintenance of the reference LWR power station in a condition that poses an acceptable risk to the public and safely stores the property to allow decay of some of the radioactivity, followed by decontamination of the facility to an unrestricted level. Since materials having radioactivity levels above unrestricted release levels are still onsite, the amended nuclear license remains in force throughout the safe storage period.

Two categories[a] of safe storage are possible:

- Custodial safe storage - minimum cleanup and decontamination is made and preventive maintenance of life-support and protection systems is performed to prepare the facility. The storage period requires fulltime, onsite surveillance crews to maintain the structure, the operating equipment, and the security of the property.
- Passive safe storage - comprehensive cleanup and decontamination sufficient to allow shutdown of all plant systems and installation of strong security barriers and remotely monitored electronic surveillance systems constitute the facility preparations. The storage period requirements include maintenance of structural integrity and prevention of intrusion into the facility.

(a) In this study, we consider only passive SAFSTOR, which is referred to only as "SAFSTOR."

SAFSTOR satisfies the requirements for protection of the public while minimizing, to various degrees, the initial commitments of time, money, occupational radiation exposure, and waste disposal space. This advantage is offset by the need to maintain the amended nuclear license, by the associated restrictions placed on the use of the property, and by the increase in the number of sites dedicated to storage of radioactive materials. This approach requires continuing physical security, surveillance, and maintenance of structural integrity sufficient to ensure public protection. The level of security necessary will depend on the type and quantity of nuclear materials left and the safeguards needs of adjacent units with common "vital areas."

A storage period of 50 years makes possible a large reduction in personnel exposure and a decrease in the need for remote or shielded operations while removing the remaining radioactive material to make the property available for unrestricted use. However, the neutron activation products ^{59}Ni and ^{94}Nb in the reactor internals will not have decayed to acceptable levels even after a storage period of 100 years. Therefore, eventual dismantlement of at least the activated reactor components will be necessary to achieve a level of radioactivity that can meet the criteria for unrestricted use of the facility and termination of the possession-only license.

Deferred decontamination includes whatever actions are required at the end of a period of continuing care to terminate the licensee's amended nuclear license and to release the property for unrestricted use. Some disassembly and disposal of activated components are still required, but the personnel radiation exposure and the disposal-site space requirements are potentially diminished. Deferred decontamination cannot, however, rely on the facility operations staff for personnel familiar with the facility.

3.1.3 ENTOMB

ENTOMB is the encasement and maintenance of nonreleasable radioactive materials in a monolithic structure of concrete or other structural material. The structure should be sufficiently strong and long-lived to ensure retention of the radionuclides until they have decayed to levels that permit unrestricted release of the site. Depending on the approach taken, the entombment period can range from about 100 years to many thousands of years.

ENTOMB is similar in nature to SAFSTOR in that it also consists of a period of facility and site preparation followed by a period of continuing care that includes security, surveillance, and maintenance activities. The level of security necessary will depend on the type and quantity of nuclear materials left and the safeguards needs of adjacent units with common "vital areas." ENTOMB also requires the amended nuclear license to remain in force. The facility and site preparations include comprehensive cleanup and decontamination of equipment and structures outside of the entombment structure and confinement of nonreleasable materials within the monolithic structure. Continuing care activities are minimal.

Two approaches to ENTOMB are possible: 1) the reactor vessel internals, which have extremely long-lived radioactivity, are removed and shipped to a nuclear waste depository 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 entombment structure for unrestricted use after a continuing care period of about 110 years. (However, present regulations and regulatory guidance do not allow such action without a comprehensive survey to establish that radioactive contamination is within acceptable release limits.) In the second case, existing regulations require the amended nuclear license to remain in force for an indefinite period of continuing care, unless the reactor vessel internals are removed at a later date.

When it becomes desirable to terminate the amended nuclear license for ENTOMB, dismantling of the entombment structure <u>may</u> be required in the first entombment approach and <u>is</u> required in the second approach. This represents a task that is much more difficult than dismantling the unentombed facility, since the entombment structure is built to endure for a long period of time. Therefore, the second approach to ENTOMB, and perhaps the first approach also, must be viewed as an almost irreversible commitment to long-term maintenance of the amended nuclear license. However, dismantlement of the entombment structure is not impossible, only very difficult.

3.2 CONSIDERATIONS FOR DECOMMISSIONING

Many considerations must be taken into account in choosing the appropriate decommissioning alternative for a specific situation. This section deals with many of the considerations in qualitative terms according to the following broad categories: economic, licensing, societal, safety, and schedule. It must be recognized that these cateogories are highly interrelated, but the interrelationships are only alluded to here.

3.2.1 Economic

While safety during decommissioning is the principal concern of the NRC, economic matters are probably the foremost consideration to stockholders (if a private utility), customers, utility managements, and utility rate commissions. The following factors that control the economics of decommissioning are discussed:

- property utilization potential
- staffing
- radioactive material disposition
- waste disposal capabilities
- planning and preparation requirements
- taxation
- license and insurance fees
- funding availability.

3.2.1.1 Property Utilization Potential

The potential use of the deactivated plant is a principal economic concern. The site is certified for industrial purposes, and the structures and systems are licensed for nuclear power production. As such, they represent a significan investment in time and money. Although retrofitting of some auxiliary systems may be necessary to meet the extant licensing requirements, refurbishing of the primary systems to meet code requirements could facilitate the reactivation of the facility for power production.

However, if reactivation is not desirable or is not possible, use of the property for other purposes should be studied. The results could dictate the decommissioning alternative selected.

3.2.1.2 Staffing

The availability of a sufficient number of properly trained and skilled personnel is a significant cost factor in decommissioning. For decommissioning activities that commence immediately following final reactor shutdown, it is desirable to draw the personnel from the ranks of the plant operating staff. These personnel are very familiar with the structures, systems, radiation work procedures, and specific areas of radiation exposure potential. Specifically, supervisory personnel, health physics personnel, maintenance craft personnel, and personnel trained in conventional decontamination methods and in the operation of the systems required during decommissioning should be recruited prior to plant shutdown. The supervisory personnel are largely responsible for formulating the plans and making the preparations for decommissioning and, therefore, should be available to begin these duties approximately 2 years before plant shutdown. The other personnel should be available as necessary to augment the planning and preparation effort, to become trained in the operation of any special decommissioning equipment, and, then, to implement the plans.

Personnel transferred from elsewhere within the company or hired from outside labor pools will probably require training in radiation work procedures, as well as in special equipment operation, and this will constitute an added expense.

For decommissioning activities performed a significant length of time after final reactor shutdown, personnel must be selected from elsewhere within the company or from the outside labor pool; however, at a multiple-reactor station there may be personnel available who are familiar with the reactor plant. Again, training becomes a cost factor. Alternatively, the job could be contracted with a firm that specializes in decommissioning work.

3.2.1.3 Radioactive Material Disposition

Two factors pertaining to radioactive material disposition help determine the cost of decommissioning. They are: 1) the amounts and kinds of radioactive materials on the property when decommissioning activities proceed and 2) the existing regulatory requirements concerning personnel radiation exposure, unrestricted release levels, and radioactive material handling and disposal. These factors directly affect the following aspects: decontamination and decommissioning procedures, packaging and transportation procedures, and time requirements for implementation. These aspects, in turn, help determine the kind, number, utilization, and efficiency of staff personnel.

3.2.1.4 Nuclear Waste Disposal Capabilities

A current major concern of nuclear facility owners is the availability of nuclear waste disposal sites.(4) It is still unclear whether components containing long-lived radioactivity in high concentrations, removed from, in, and around the reactor vessel, will require deep geologic disposal or only shallow-land burial.

Another area of concern in this respect is the location and accessibility of operable nuclear waste disposal sites. The cost of shipping decommissioning wastes to disposal sites is determined in part by the distance traveled and in part by requirements imposed by states through which the radioactive materials must travel.

Although federal agencies dominate the regulatory process in the shipment of radioactive materials, state highway departments regulate gross vehicle weights and dimensions, as well as some other aspects of radioactive shipments. Currently, about half of the states have adopted the DOT Hazardous Materials Regulations to cover intrastate radioactive materials shipments. In addition, several states have adopted or proposed additional regulations for other aspects of radioactive materials shipments.(5,6) These aspects include:

- special routing
- advance notification for shipments of large quantities
- state inspections of some types
- prohibition of certain types
- prior approval
- requirements of exclusive-use vehicles
- use of pilot vehicles
- speed restrictions
- specific hours of movement
- accompaniment of all shipments by radiation monitoring personnel.

The variation of regulations between adjacent states often requires special considerations for interstate shipments.

There is a potential conflict between some of the proposed state laws and the provisions of the National Transportation Act of 1974 (Public Law 93-633, signed in 1975). This law prohibits states from adopting laws or regulations more stringent than federal regulations unless state regulations improve transportation safety. Even in this case, such rules can be adopted only if they do not unreasonably burden commerce.

3.2.1.5 Planning and Preparation Requirements

The cost of preparing the detailed decommissioning plans, the technical specifications, the safety analyses, and the documentation may be different for each of the decommissioning alternatives and should be considered. For example, a comprehensive decommissioning plan is required for DECON and ENTOMB, but for the first phase of SAFSTOR (preparations for safe storage), a somewhat less comprehensive initial plan maybe acceptable. A complete decommissioning plan is required prior to deferred decontamination (the final phase of SAFSTOR).

3.2.1.6 Taxation

A factor that could have considerable influence on the choice of alternative and time frame for decommissioning is the way that the facility is viewed by the local taxing authorities for property tax purposes. For example, it is possible that the plant in SAFSTOR or ENTOMB could be taxed at one of the following values: 1) an operating plant, 2) unimproved land, or 3) the land and structures minus the expected additional decommissioning costs (since the retired plant is a negative asset). The first alternative (which is unlikely) would force DECON of the plant, since the accumulated tax costs would, in a few years, exceed the cost of DECON. The third approach wou'd reduce the taxes to a very nominal amount, since the additional decommissioning costs could exceed the value of the land and structures. In practice, the tax rate will be negotiated between the local tax assessor and the plant owner. It will likely be based on a combination of the second and third situations given above, with land outside the exclusion area assessed at a value comparable with adjacent similar property and property within the exclusion area assessed at essentially zero value. Since the outer area of the site may be released for unrestricted use when the reactor has been placed in safe storage or entombment, it may be put to productive use to pay its property taxes.

3.2.1.7 License and Insurance Fees

Other economic factors that could have a role in determining the decommissioning alternative are the costs of licensing and the costs of nuclear liability insurance. Both, as presently applied, require a significant initial outlay and then diminish as the amount of residual radioactivity is reduced.

Licensing fees are required for amending the facility operating license to allow possession but not operation of the facility. Thereafter, inspection fees are levied based on the NRC inspection requirements. Presently, while any spent fuel remains on the site, safeguards inspections must continue as during operation. In addition, annual health, safety, and environmental inspections must continue until the amended nuclear license is terminated.

The cost of nuclear liability insurance depends on the level of coverage required by the NRC as proof of financial protection during decommissioning. If the level must remain the same regardless of the plant condition, timely termination of the possession-only license is desirable.

3.2.1.8 Funding Availability

As with all projects, there are certain fixed costs during decommissioning (i.e., salaries, services, utilities, and maintenance) that continue once the project begins, regardless of the progress made towards project completion. If insufficient funding delays decommissioning activities, these fixed costs, plus the effect of inflation over the delay period, increase the overall decommissioning cost. Therefore, it is important that sufficient funds are available to complete the planned decommissioning activities as scheduled.

3.2.2 Licensing

Licensing in the nuclear industry is basically a question of responsibility for the protection of the workers and the public from undue exposure to regulated radioactive materials. In this respect, an organization is licensable only as it can demonstrate a continued ability and willingness to abide by the license requirements imposed by the NRC. Once the license is granted, the licensee agrees to accept the associated responsibilities until such time as the license is terminated (or transferred to another licensed organization, as allowed by regulation).

Termination of an amended nuclear license is conditional on the removal and proper disposal of nonreleasable radioactive materials. While the higher occupational exposure from DECON is undesirable, the requirements and responsibilities of maintaining the license may overshadow the exposure aspect and make this alternative desirable. The dynamic nature of government regulation may also make termination of the license desirable.

Another aspect of licensing that must be considered is the license duration and the license renewal process and cost. Licenses are presently subject to a 40-year time limit, at which time they must be renewed. The renewal review requirements comprise financial, safety, and environmental considerations similar to those for a license amendment situation. The costs of documenting these considerations and the NRC review costs for each required license renewal must be taken into account when choosing the decommissioning alternative.

3.2.3 Societal

Another consideration is that of public acceptance of the long-term presence of a retired facility. There is a reasonable probability that once the plant is no longer providing tax revenue and payroll to the community, the public may view the single-reactor station structures as an eyesore, a perceived hazard, or, at the least, an unproductive use of an otherwise useful site. Thus, pressures may mount for the removal of the retired structures. At a multiple-reactor station such public pressure could be less, or nonexistent, since the shutdown facility is located with other operating nuclear power reactors. While it is beyond the scope of this study to evaluate the likelihood of this concern, the plant owner should sample local public opinion on this question well in advance of setting his plans for decommissioning.

In the same vein, the NRC presently desires to minimize the number of sites permanently committed to the containment of radioactive materials. Removal and disposal of the reactor vessel internals is the only method whereby this desire can be fulfilled for the reference LWRs, even in the long run. Existing regulations allow the various decommissioning alternatives that are detailed in Section 3.1. But regulations are dynamic in nature and are subject to societal pressures; and, even though new regulations or changes to present regulations may never forbid the use of a particular decommissioning alternative, they could discourage or make impractical its use.

3.2.4 Safety

Radiological, industrial, and environmental safety play an important role in decommissioning. Each is regulated by the federal government or the state government, or both, to provide the amount of protection from hazards that is deemed necessary. The selected decommissioning approach should provide the required safety for the workers and for the public, and should have minimal adverse impact on the environment.

3.2.4.1 Radiological Safety

In decommissioning an LWR, ^{60}Co is the prime contributor to the total accumulated occupational radiation dose. It appears as activated corrosion product contamination in and on equipment and structural surfaces and as an activation product in structural materials in and around the reactor vessel. Each decommissioning alternative results in a different accumulated occupational dose because of different exposure requirements.

Dose rates throughout the plant, largely determined by the amount and decay of ^{60}Co, decay to approximately 10% of the original shutdown values after about 17.5 years and 1% after about 35 years, assuming no decontamination. Therefore, deferring the major decommissioning activity by even 17.5 years decreases the accumulated occupational dose. The reduction depends on the required decommissioning activities prior to that point in time and those necessary to complete the license-termination process. Relatively little reduction in total accumulated occupational dose is assumed to result from deferring decontamination beyond 30 years after placing a PWR in safe storage (Reference 1, p. 11-21). This is also assumed to be the case for a BWR (Reference 2, p. 11-15).

3.2.4.2 Industrial Safety

Hazardous situations having the potential for occupational injuries and fatalities will arise during normal activities of each decommissioning alternative. The quantity and severity of occurrences associated with a given decommissioning alternative depend on the kinds of activities performed and the manpower and time requirements for that alternative. As with every industrial operation, proper industrial safety practices during decommissioning will minimize accidents.

3.2.4.3 Environmental Safety

Many of the environmental effects of plant operation will also be evident during decommissioning, but in most cases at greatly diminished levels. The environmental effects that pertain to decommissioning are radiation exposure, liquid and airborne radioactive release, and solid radwaste disposal. No thermal discharge is required during decommissioning except, perhaps, that associated with operation of an auxiliary boiler.

At final shutdown of a reference LWR, large volumes of water requiring disposal are present throughout the plant. Some of these volumes are in presumably noncontaminated systems and, after sampling, can be released directly to the environs via the blowdown line. Others, notably those contained in the spent fuel pool, the reactor vessel, etc., are contaminated in varying degrees and may require processing through the liquid radwaste system prior to discharge.

Airborne radioactive releases that result from normal decommissioning activities are small in comparison to normal plant operation.[(1)] Of the various decommissioning alternatives, SAFSTOR releases the least amount of airborne radioactivity, since much radioactivity has decayed by the start of deferred decontamination.

DECON generates the largest amount of solid radioactive wastes that must be placed in a licensed disposal facility. ENTOMB produces less, although the entombed structure becomes a waste disposal site, and SAFSTOR (including deferred decontamination), the least. The major environmental impact of solid radioactive waste disposal is the land area that must be committed to this activity. In addition, shipping these wastes to the disposal site produces the normal transportation noises, exhaust noises, exhaust fumes, and radiation doses.

3.2.5 Schedule

A large percentage of the facility decommissioning cost is a fixed level of expenditure that is associated with the time span of the work rather than with the specific tasks. Therefore, the optimum schedule for any decommissioning alternative is one where the total time involved is the time required to efficiently complete the longest sequence of tasks. This dictates the necessary length of time (the critical path) to complete the entire job, and all other work should be completed within this time span. An optimum-sized, well-trained staff is essential: too many or too few people, as well as undertrained people, hamper the efficient completion of the work, thus increasing both the total cost and the total accumulated occupational radiation exposure. As previously discussed, insufficient funding to complete the work within the critical-path time span also drives these totals upward.

3.3 STUDY APPROACH

The study identifies and quantifies the different technologies and the impacts on safety and costs of decommissioning a nuclear power reactor at a multiple-reactor site as compared to a single-reactor site. For each of the three decommissioning alternatives, DECON, SAFSTOR, and ENTOMB, the sensitivity of the safety and cost to several variables is explored. Five scenarios for multiple-reactor stations are investigated. Detailed decommissioning analyses for a PWR and a BWR are presented in NUREG/CR-0130[1] and NUREG/CR-0672,[2] respectively, and provide the bases for the sensitivity analyses. These detailed analyses are not repeated in this study.

3.3.1 Variables

At a multiple-reactor site some facilities may be shared and some services may be centralized for more economical reactor operation. These and other variables are discussed in the following subsections.

3.3.1.1 Nuclear Waste Disposal

Nuclear waste disposal is the major contributor to the public radiation dose from decommissioning a nuclear reactor and is a significant item in the decommissioning cost. In the studies of decommissioning LWRs at single-reactor stations, disposal of nuclear waste was considered only at an offsite, licensed nuclear waste disposal facility. Variations considered in this study include temporary onsite storage of nuclear waste, with eventual removal to a licensed disposal site, and permanent onsite disposal of low-level nuclear waste.

3.3.1.2 Site Dedication

Whether or not the site is dedicated to nuclear electric energy production can have an impact on the safety and cost of decommissioning of reactors. If the site is dedicated to nuclear generation of electricity, construction of the replacement reactor will be completed before final shutdown of the old reactor. The effect of the presence of the construction forces on the available skilled labor pool for the decommissioning crew is explored. Rotation of construction craftsmen between new reactor construction and decommissioning could help keep individual radiation exposures within regulatory limits, with minimal financial impact.

3.3.1.3 Centralized Services

Onsite, centralized services available during decommissioning of a reactor could facilitate the decommissioning program. Centralized services that may be available onsite are safety, security, fire protection, radiation monitoring, laundry, facilities and personnel for decontamination, central shops, and transportation.

3.3.1.4 Number of Reactors Onsite

The number of reactors onsite will probably have a direct bearing on the extent of centralized services provided. In this study, sites with four and ten reactors are considered. Several nuclear reactor stations with three reactors are in operation at this time and other stations are planned for four reactors. Several studies of nuclear energy centers have concluded that centers containing 10 to 20 or more nuclear reactors are technically feasible.[7-9]

3.3.1.5 Type of Reactor Being Decommissioned

The impact of whether the reactor being decommissioned is a PWR or a BWR is investigated. The PNL decommissioning studies of a PWR[1] and of a BWR[2] show that there are differences in occupational exposure and cost for the two reactor types; in this study, however, the only effect of reactor type explored is that of the differences between decommissioning a reactor at a single-reactor site and at a multiple-reactor site.

3.3.2 Multiple-Reactor Station Scenarios

The five scenarios investigated for multiple-reactor stations are described below:

Scenario No. 1

- 4 reactors onsite
- only pressurized water reactors are located onsite
- after 40 years of operation of the oldest reactor, one reactor is shut down every 2 years
- a replacement reactor is started up as each old reactor is shut down
- nuclear waste is temporarily stored onsite and moved later to an offsite, licensed disposal facility
- central facilities are not provided onsite.

Scenario No. 2

- 4 reactors onsite
- only boiling water reactors are located onsite
- after 40 years of operation of the oldest reactor, one reactor is shut down every 4 years
- the shutdown reactor is not replaced
- nuclear waste is sent to an offsite, licensed disposal facility
- central facilities are not provided onsite.

Scenario No. 3

- 10 reactors onsite
- both PWR and BWR reactors are located onsite
- after 40 years of operation of the oldest reactor, one reactor is shut down every 4 years
- a replacement reactor is started up as each old reactor is shut down
- nuclear waste is sent to an offsite, licensed disposal facility
- central facilities are not provided onsite.

Scenario No. 4

- 10 reactors onsite
- both PWR and BWR reactors are located onsite
- after 40 years of operation of the oldest reactor, one reactor is shut down every 4 years
- a replacement reactor is started up as each old reactor is shut down
- nuclear waste is temporarily stored onsite and moved later to an offsite, licensed disposal facility
- central facilities are provided onsite.

Scenario No. 5

- 10 reactors onsite
- both PWR and BWR reactors are located onsite
- after 40 years of operation of the oldest reactor, one reactor is shut down every 2 years
- a replacement reactor is started up as each old reactor is shut down
- low-level nuclear waste is disposed of onsite
- central facilities are provided onsite.

REFERENCES

1. R. I. Smith, G. J. Konzek and W. E. Kennedy, Jr., Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station, NUREG/CR-0130, U.S. Nuclear Regulatory Commission Report by Pacific Northwest Laboratory, June 1978.

2. H. D. Oak, G. M. Holter, W. E. Kennedy, Jr and G. J. Konzek, Technology, Safety, and Costs of Decommissioning a Reference Boiling Water Reactor Power Station, NUREG/CR-0672, U.S. Nuclear Regulatory Commission Report by Pacific Northwest Laboratory, June 1980.

3. Regulatory Guide 1.86, Termination of Operating Licenses for Nuclear Reactors, U.S. Atomic Energy Commission, June 1974.

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5. C. K. Beck, "Intergovernmental Relationships in the Transport of Radioactive Materials," Proceedings of the Second Annual Legislative Workshop, CONF-730588, Oak Ridge, Tennessee, May 1973.

6. W. A. Brobst, "The State of State Regulations," Proceedings of the 4th International Symposium on Packaging and Transportation of Radioactive Material, CONF-840901, Miami Beach, Florida, September 1974.

7. Nuclear Energy Center Site Survey - 1975, U.S. Nuclear Regulatory Commission, NUREG-0001-ES, January 1974.

8. H. Harty, The Hanford Nuclear Energy Center, a Conceptual Study, PNL-2640, Pacific Northwest Laboratory, Richland, Washington, September 1978.

9. C. C. Burwell, M. J. Ohanian and A. M. Weinberg, "A Siting Policy for an Acceptable Nuclear Future," Science, 204:1043-1051, 1979.

4.0 REGULATORY CONSIDERATIONS FOR DECOMMISSIONING

Decommissioning of a nuclear reactor power plant must be accomplished in compliance with the applicable regulations, guides, and standards. In this section, current regulations, guides, and standards that apply to decommissioning a nuclear power reactor are cited. In addition, currently developing Nuclear Regulatory Commission (NRC) decommissioning policy is discussed.

Regulations and guidelines for nuclear facility decommissioning are dynamic. National policy relating to decommissioning of LWRs is changing, and new regulations are forthcoming. The NRC is developing a more explicit overall policy for decommissioning nuclear facilities.(1)

A comprehensive review and analysis of current regulations related to decommissioning of licensed nuclear facilities was completed by Schilling, et al.,(2) and detailed discussions of the regulations and guides that apply to decommissioning PWRs and BWRs are given in References 3 and 4.

4.1 CURRENT FEDERAL REGULATIONS AND GUIDES

Several references to decommissioning are contained in Title 10 Code of Federal Regulations (10 CFR). These references are:

- 10 CFR 50.33(f)[a] - relates to the financial qualifications of the applicant for a license to construct, operate, and shut down and maintain the facility in a safe condition.
- 10 CFR 50.82 - outlines information and procedures necessary for the termination of any type of facility license.
- 10 CFR 51 - pertains to licensing and regulatory policy and procedures for environmental protection. Section 51.5(b)(7) provides guidance for determining whether an environmental impact statement is needed for decommissioning a nuclear facility.

Regulatory Guide 1.86, Termination of Operating Licenses for Nuclear Reactors, amplifies 10 CFR 50.82 and describes the acceptable decommissioning alternatives as well as the methods for satisfying 10 CFR 50.82.

(a) Abbreviation for Section 50.33(f) of Title 10, Code of Federal Regulations, Part 50 (typical).

A number of other federal regulations contain requirements that must be complied with during the decommissioning of a nuclear power plant. The following regulations contain requirements that are applicable to decommissioning a nuclear reactor:

10 CFR Part 19.	Notices, Instructions, and Reports to Workers; Inspections
10 CFR Part 20.	Standards for Protection Against Radiation
10 CFR Part 30.	Rules of General Applicability to Domestic Licensing of Byproduct Material
10 CFR Part 40.	Domestic Licensing of Source Material
10 CFR Part 51.	Licensing and Regulatory Policy and Procedures for Environmental Protection
10 CFR Part 70.	Domestic Licensing of Special Nuclear Material
10 CFR Part 71.	Packaging of Radioactive Material for Transport and Transportation of Radioactive Material Under Certain Conditions
10 CFR Part 73.	Physical Protection of Plants and Materials
10 CFR Part 140.	Financial Protection Requirements and Indemnity Agreements
10 CFR Part 150.	Exemption and Continued Regulatory Authority in Agreement States Under Section 274
10 CFR Part 170.	Fees for Facilities and Material Licenses and Other Regulatory Services Under the Atomic Energy Act of 1954, As Amended
40 CFR Part 190.	Environmental Protection Agency. Environmental Radiation Protection Standards for Nuclear Power Operation
49 CFR Parts 170-199	Department of Transportation. Hazardous Material Regulations

The following NRC Regulatory Guides are perceived to provide generic guidance for activities undertaken in decommissioning a nuclear reactor power plant:

1.8	Personnel Qualification and Training
1.16	Reporting of Operating Information
1.17	Protection of Nuclear Power Plants Against Industrial Sabotage
1.143	Design Guidance for Radioactive Waste Management Systems, Structures, and Components Installed in Light-Water-Cooled Nuclear Power Plants
4.2	Preparation of Environmental Reports for Nuclear Power Stations
8.2	Guide for Administrative Practices in Radiation Monitoring
8.3	Film Badge Performance Criteria
8.4	Direct-Reading and Indirect-Reading Pocket Dosimeters
8.6	Standard Test Procedures for Geiger-Müller Counters
8.8	Information Relevent to Ensuring that Occupational Radiation Exposures at Nuclear Power Stations will be as Low As Reasonably Achievable
8.9	Acceptable Concepts, Models, Equations, and Assumptions for a Bioassay Program
8.10	Operating Philosophy for Maintaining Occupational Radiation Exposure As Low As Reasonably Achievable

Several American National Standards Institute standards that are perceived applicable are:

ANSI N13.12	Control of Radioactive Surface Contamination of Material, Equipment, and Facilities to be Released for Uncontrolled Use

ANSI N18.7-1972	Standards for Administrative Control of Nuclear Power Plants
ANSI Z88.2-1969	Procedures for Respiratory Protection

4.2 MAJOR REGULATORY CONSIDERATIONS

At the end of the useful life of a nuclear power reactor, prompt termination of the NRC license is a desired objective. Removal of the radioactivity to levels permitting unrestricted use of the facility and site is mandatory for full license termination. Present policy and regulatory guidance that addresses nuclear facility decommissioning is not specific enough to adequately effect this objective in a manner consistent with protection of the public health and safety.[5] The NRC is currently reevaluating its policy on decommissioning of nuclear facilities,[1,6,7] and its draft generic environmental impact statement on decommissioning, issued in January 1981, concludes that the major adverse environmental impact of decommissioning is the commitment of small amounts of land for waste burial in exchange for reuse of the facility for other nuclear or nonnuclear purposes.[5]

REFERENCES

1. Plan for Reevaluation of NRC Policy on Decommissioning of Nuclear Facilities, NUREG-0436, Revision 1, Office of Standards Development, U.S. Nuclear Regulatory Commission, December 1978.

2. A. H. Schilling, et al., Decommissioning Commercial Nuclear Facilities: A Review and Analysis of Current Regulations, NUREG/CR-0671, U.S. Nuclear Regulatory Commission Report by Pacific Northwest Laboratory and Battelle Human Affairs Research Centers, August 1979.

3. R. I. Smith, G. J. Konzek and W. E. Kennedy, Jr., Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station, NUREG/CR-0130, U.S. Nuclear Regulatory Commission Report by Pacific Northwest Laboratory, June 1978.

4. H. D. Oak, et al., Technology, Safety, and Costs of Decommissioning a Reference Boiling Water Reactor Power Station, NUREG/CR-0672, U.S. Nuclear Regulatory Commission Report by Pacific Northwest Laboratory, June 1980.

5. Draft Generic Environmental Impact Statement on Decommissioning of Nuclear Facilities, NUREG-0586, U.S. Nuclear Regulatory Commission, January 1981.

6. G. D. Calkins, Plan for Reevaluation of NRC Policy on Decommissioning of Nuclear Facilities, NUREG-0436, Revision 1, Supplement 1, U.S. Nuclear Regulatory Commission, August 1980.

7. G. D. Calkins, Draft Thoughts on Regulation Changes for Decommissioning, NUREG-0590, U.S. Nuclear Regulatory Commission, Rev. 2, August 1980.

5.0 FINANCING OF DECOMMISSIONING

Alternatives for providing funds for decommissioning a nuclear power station are discussed in this section. This discussion is offered to highlight current regulatory approaches to funding decommissioning and NRC thinking on the subject.

Both federal and state governments have a responsibility to protect the health and safety of their citizens. In connection with this responsibility, a state in which a nuclear power plant is located is concerned that the operating utility has sufficient funds to decommission the plant after shutdown and that funds are available for unexpected contingencies during both plant operation and plant decommissioning. If the utility defaults or goes bankrupt, the state may have to assume financial responsibility for decommissioning.

Before the Three Mile Island accident two factors were presumed to provide a reasonably high degree of certainty that a utility will be financially capable of decommissioning a nuclear power plant. First, utilities generally have significant assets and, because of their regulated monopoly status, are allowed to recover their expenses and earn a reasonable return on their capital investment. Second, public-interest considerations relating to utilities' essential services to society suggest that a utility would not be allowed to become insolvent except in very rare instances. The very heavy financial strain on the Metropolitan Edison Company following the accident at TMI-2 is cause for further consideration of this presumption. For certain non-investor-owned utilities able to set their own rates (e.g., certain municipal utilities), the argument against insolvency is especially convincing. Nevertheless, some form of financial assurance for decommissioning may be desirable. First, since most nuclear power plants are expected to operate 30 to 40 years and ultimate decommissioning may be delayed 50 to 100 years following final shutdown, predicting the financial stability of the utility involved is uncertain at best. Second, the utility may postpone decommissioning because it has no direct economic incentive to decommission a shutdown plant. Finally, a severe accident such as occurred at TMI-2 may financially cripple even a large, well-insured utility. For these reasons, steps need to be taken to ensure that funds are available for decommissioning.

5.1 ALTERNATIVES FOR PROVIDING DECOMMISSIONING FUNDS

The eventual cost of decommissioning should be considered as much a part of nuclear power generation costs as is the construction cost or cost of fuel, and decommissioning cost should be borne equitably by the consumers of the power produced during plant operation.

The NRC is considering five criteria to evaluate the relative effectiveness of alternative decommissioning financing methods.(1) These criteria are:

1. the degree of assurance provided that funds will be available
2. the cost of providing the assurance
3. the extent to which the consumers of the plant's power equitably share the costs of decommissioning
4. the flexibility to respond to changes in inflation and interest rates, reactor life, and estimated decommissioning costs
5. the ability to accommodate different ownership and jurisdictional arrangements.

Criterion 1 is considered most important; criteria 2 and 3 are next in importance; and criteria 4 and 5 must be met for a financing alternative to receive further consideration.(1)

There are three principal financing alternatives for decommissioning a nuclear power station that satisfy the above criteria to varying degrees:

- a prepaid decommissioning reserve controlled by an outside entity
- an internal decommissioning reserve, either funded or unfunded
- a funded reserve or sinking fund controlled by an outside entity.

Combinations of these alternatives can also be used. These alternatives are discussed in the following subsections. A fourth alternative, payment of decommissioning costs from utility revenues when the funds are required, is considered in less detail because it fails to meet criteria 1 and 3. Other alternatives, such as bonding or insurance pools, are considered briefly, principally in regard to decommissioning after a premature shutdown.

5.1.1 Prepaid Decommissioning Reserve

This alternative involves payment of the total expected decommissioning cost (in year-of-startup dollars) to an outside entity prior to the start of operations at the nuclear power plant. The funds remain completely outside the control of the utility during the operating lifetime of the plant. The outside entity invests and manages the funds until needed for decommissioning. No states are known to now use this financing approach.

Ideally, the outside entity would be an agency of the state. This arrangement not only provides stability in the care and management of the funds but could also provide a significant tax advantage. The Internal Revenue Service does not tax income accruing to the government of any political subdivision of the U.S.[(2)]

The prepayment financing alternative meets the five-selection criteria reasonably well. Of the three discussed financing alternatives, this alternative provides the greatest assurance that decommissioning funds will be available. If the fund is not subject to federal taxes, the return realized could exceed the utility's after-tax cost of capital, suggesting that the consumer may benefit more by having the funds in an outside escrow account than by having the funds reinvested in the utility's capital structure. This approach is equitable to electricity consumers because the revenues to recover the prepaid expense are collected over the entire operating life of the plant. The prepaid financing approach seems to satisfy criterion 5 and can satisfy criterion 4 as long as the responsible regulatory agency has the power to direct the utility to make future payments to the fund if estimated decommissioning costs escalate faster than the fund's return on investment.

5.1.2 Internal Unfunded Decommissioning Reserve

An internal unfunded decommissioning reserve is the approach more prevalent in states with nuclear power plants. The most common procedure is to add the estimated cost of decommissioning as a negative salvage value to the original cost of the plant. Each year, the utility credits an unfunded reserve for decommissioning from operating revenues. At the end of the plant's operating life, the total accumulated negative salvage value depreciation is to equal the estimated cost of decommissioning (in year-of-startup dollars).

For investor-owned utilities, the recovery of future decommissioning expenses is complicated by federal tax regulations. Revenues collected for the decommissioning reserve are considered as taxable income.(3) However, the expense of decommissioning is presently not deductible until it is incurred (i.e., after plant shutdown).(4) Conceptually, the revenue requirements for this financing approach can be set so the sum of the after-tax revenues each year, compounded at the utility's after-tax cost of capital, provide the required after-tax decommissioning funds.

The chief disadvantage of the internal decommissioning reserve is the relative lack of decommissioning assurance as compared to the other two financing options, particularly with respect to premature decommissioning. From a cost and equity standpoint, it is difficult to generalize conclusions since the analysis is quite dependent both on taxing and accounting practices and on financial assumptions. A principal advantage of this approach is that it fits easily into existing rate-making practices and does not require a new entity to oversee or manage the decommissioning funds.

5.1.3 Sinking Fund Payment to an Outside Escrow Account

Under this financing option, the utility makes periodic payments to an outside escrow account, where the funds are invested in securities until they are needed for decommissioning. At least one state, Pennsylvania, has adopted this financing method.

If the escrow account is managed by a state agency, there is a good possibility that the income generated by the escrow account will not be subject to federal income taxes. It may also be possible to structure the account so an investor-owned utility's payments can be made from untaxed revenue.(1) If the escrow payment is not taxed, the utility's annual revenue requirement is simply equal to the annual payment.

This approach seems to satisfy all five evaluation criteria reasonably well. It provides the flexibility needed to meet criteria 4 and 5. It provides reasonable assurance of the availability of decommissioning funds, with the principal risk being that a plant may be shut down prematurely before adequate funds are collected. This approach is reasonably equitable, and payments to the fund can fluctuate with inflation so consumers are paying for decommissioning in dollars of constant purchasing power. The relative cost of this alternative is subject to assumptions on tax, accounting, and financial practices.

5.1.4 Payment from Revenue when Needed

Under this option, the utility takes no action until the funds are needed for decommissioning. At that time, the decommissioning costs are paid out of current revenues and decommissioning costs are treated as an allowable expense.

This option has the same disadvantage as the internal reserve option, a relative lack of assurance that the funds will be available. It has the additional disadvantage that the costs will be borne by people who do not benefit from the plant's operation.

5.2 FINANCIAL PROVISIONS FOR PREMATURE PLANT SHUTDOWN

Only the first alternative provides assurance that there will be adequate funds to pay for decommissioning if the nuclear power plant is shut down prematurely. Several options are available to reduce this risk of unavailability of funds in the event of premature shutdown. These include one or more of the options discussed below.

5.2.1 Large Initial Payment

The principal advantage of a large initial payment to a sinking fund prior to plant startup is the increased assurance it provides for meeting decommissioning costs. The principal disadvantage is the possibility of financial hardship on the utility, as under the prepayment funding alternative. A lesser disadvantage is the potential for inequitable distribution of decommissioning costs among the power consumers.

5.2.2 Higher Initial Sinking Fund Payments

The advantages and disadvantages of higher per-unit payments (in constant-value dollars) to a sinking fund during the early years of plant operation are comparable to those of the large-initial-payment option. This option's main advantage is the added assurance that adequate funds are available for decommissioning in the event of premature shutdown. A disadvantage is that power consumers during the early years will pay a disproportionate share of the decommissioning expenses.

5.2.3 Surety Bond

A surety bond posted by the utility has two advantages. First, it is potentially manageable (less burdensome) for a small company that is unable to make a large initial cash payment. Second, it distributes decommissioning costs to the power consumers more equitably than a large initial cash payment.

5.2.4 Decommissioning Insurance Pool

This option for ensuring adequate premature decommissioning funding requires utilities (and operators of other nuclear fuel-cycle facilities) to make payments into a decommissioning insurance pool. The pool is obligated to pay for the decommissioning of a facility if the operator defaults. One problem with this option is the setting of appropriate premiums. To establish premiums, the pool administrator is required to estimate the likelihood of non-performance or partial performance and the magnitude of the fund required to offset anticipated funding shortfalls. Another problem is the possibility that a decommissioning insurance pool might have to be established by the federal government, requiring congressional action.

5.3 DECOMMISSIONING FUNDING AT A MULTIPLE-REACTOR STATION

The problem of providing assurance that adequate funds will be available for decommissioning a nuclear power reactor after final shutdown is not significantly different for a reactor at a multiple-reactor station than it is for a reactor at a single-reactor station. The alternatives for accumulating funds for decommissioning, discussed above in Subsection 5.1, are equally applicable for a reactor at a single- or multiple-reactor station. This is particularly true for reactors that operate for the full design lifetime of about 40 years.

Assuring that adequate funds are available for decommissioning a reactor that is prematurely shut down has received increased attention in the last few years. Several options available for reducing the risk that there will be insufficient funds are discussed above in Subsection 5.2. If several, or all, of the reactors at a multiple-reactor station are owned by one utility, the funds accumulated for decommissioning the individual reactors can be pooled to provide a larger reserve to handle the premature decommissioning of one of the reactors. The pooling of decommissioning funds for a utility's reactors is not limited to reactors at a multiple-reactor station, though, since a utility operating several reactors at dispersed sites in one state could also elect to pool the funds accumulated for decommissioning the reactors.

The experience at Three Mile Island vividly illustrates the effect an accident at a reactor can have on an adjacent reactor. At a multiple-reactor station, where reactors probably would be located in groups of three or four reactors, a serious accident at one of the reactors could result in the extended shutdown of the other reactors in the group. However, even if the reactor at which the accident occurred were to be decommissioned prematurely, the probability is low that there would be technical justification for the premature decommissioning of the other reactors in the group. Startup of a reactor after an extended shutdown can be quite expensive. If the reactor that is forced to shut down during the recovery from an accident at an adjacent nuclear reactor is within a few years of planned shutdown, the utility may decide that it is more economical to decommission the reactor than to restart it.

If the likelihood of premature closure of a nuclear power station is increased by collocation, the degree of assurance of the availability of funds for decommissioning is somewhat decreased. This possibility suggests that more serious attention should be given to funding of decommissioning prior to plant startup and/or to the possibility of accruing funds for decommissioning at a faster rate than otherwise would be selected for an external sinking fund or internal decommissioning reserve. Alternatively, the reactor owner could be required to participate in an insurance pool to provide protection against premature plant closure. This concept is under review by the NRC and the nuclear liability insurance pools.[1]

REFERENCES

1. Robert S. Wood, Assuring the Availability of Funds for Decommissioning Nuclear Facilities, NUREG-0584, Rev. 2, draft report issued October 1980.

2. Internal Revenue Code, Section 115.

3. Ibid, Section 61(a).

4. Ibid, Section 162.

6.0 MULTIPLE-REACTOR STATION CONCEPTS

Multiple-reactor stations and studies of nuclear energy centers are described in this section. The management alternatives for a multiple-reactor station, including reactor types and standardization, site dedication, timing of construction, and reuse of structures and systems, are also discussed.

6.1 MULTIPLE-REACTOR STATIONS AND RELATED STUDIES

Most of the operating or planned nuclear power reactors in the United States are located at stations with two or more reactors. Thirteen 2-reactor stations are in operation and an additional thirty-five 2-reactor stations are being constructed or planned. Three 3-reactor stations are in operation and seven more are planned. Two 4-reactor stations are planned.

No nuclear energy centers containing more than four reactors are currently planned; however, several studies on the feasibility of operating nuclear energy centers with more than four reactors have been reported.[1-3] An Atomic Energy Commission study[1] published in 1974 examined nuclear energy centers with 10 to 40 reactors and related fuel-cycle and waste management facilities. A Nuclear Regulatory Commission study,[2] Nuclear Energy Center Site Survey - 1975, considered three basic types of nuclear energy centers:

1. Power plant centers, consisting of 10 to 40 nuclear electric-generating units of 1200 MWe capacity each.
2. Fuel-cycle centers, consisting of fuel reprocessing plants, mixed oxide fuel fabrication facilities, and radioactive waste management facilities.
3. Combined centers, containing both power plants and fuel-cycle facilities.

The Hanford Nuclear Energy Center study[3] assumed that 20 to 40 nuclear power plants would be located at the center, together with an interim spent fuel storage facility and waste management facilities.

The conclusions drawn in these studies are in reasonably good agreement. In general, these conclusions state that:

- Nuclear energy centers of up to 20 reactors are technically feasible.
- Nuclear energy centers would not unacceptably degrade the environment, decrease the reliability of the electrical power supply, or compromise safety.
- Nuclear energy centers of 10 to 20 reactors could show some economic advantages - up to 12% savings in construction costs compared to single- or dual-reactor sites.
- Extra transmission costs could reduce or eliminate the construction net savings.
- Nuclear energy centers could result in stable construction labor pools.
- There is no apparent change in public safety from nuclear energy centers compared to dispersed siting of the same number of reactors.
- Emergency response capabilities would be enhanced at nuclear energy centers.
- Nuclear energy centers should reduce concerns related to safeguarding fissionable material.
- Nuclear energy centers will probably evolve through normal utility growth by the year 2000.
- Nuclear energy centers could be more vulnerable to acts of war.

An article[(4)] by Burwell, Ohanian, and Weinberg argues for a nuclear facility siting policy that encourages locating new nuclear power reactors at sites of existing reactors. Such a policy, the article concludes, would lead to the development of nuclear energy centers as the demand for electricity increases. A recent GAO study[(5)] found that locating future nuclear powerplants at existing sites offers important advantages which warrant consideration by the NRC. The GAO study cited advantages for decommissioning of nuclear reactors at a multiple-reactor station as follows:

> "In view of the need to mothball or entomb a retired nuclear powerplant for 100 years or more, and the present regulatory uncertainty in the area of decommissioning and final powerplant disposition, placing future powerplants at existing nuclear sites would help the utilities to safely perform

the necessary surveillance of retired facilities. The cobalt-60 induced radioactivity would have time to decay allowing utilities to reduce the occupational hazards associated with dismantlement. The contaminated retired facilities would be located within the perimeter of the controlled nuclear sites, and the site operating staffs could routinely perform the necessary maintenance, radioactive monitoring, environmental monitoring, and inspections during the long protective storage periods. Also, continued use of sites for nuclear operations could reduce or eliminate public and political pressures on utilities to dismantle retired nuclear powerplants at a time when the levels of induced radioactivity in the plants are still high."

6.2 MANAGEMENT ALTERNATIVES FOR A MULTIPLE-REACTOR STATION

In the nuclear energy center studies discussed in Section 6.1, it is assumed that the reactors will be located in groups of three (triads) or four (quads), with the groups separated from each other by sufficient distance to avoid interactions that could adversely affect the environment. This same arrangement of the reactors at a multiple-reactor station is assumed in this decommissioning study.

In the following subsections, the various alternatives available to the organization(s) operating the reactors at a multiple-reactor station are discussed. These alternatives may influence the safety and cost of decommissioning the reactors.

6.2.1 Reactor Types and Standardization

At a multiple-reactor station with a small number of reactors, say four reactors (a quad), it is more likely that the reactors will be of the same type and design, either PWR or BWR, than it is for a station having a larger number of reactors. However, even at a multiple-reactor station with 10 to 20 reactors, it is expected that there will be several reactors of each type.

Standardization of the reactor type and design at a multiple-reactor station results in many advantages during construction, operation, and decommissioning. Standardization:

- Provides a major savings in engineering design, since it is carried out just once.
- Provides construction personnel with drawings for remaining units early, which gives flexibility to planning and manpower leveling, as well as improves productivity on the remaining units because of what was learned from the construction of the first unit; a similar improvement in productivity for decommissioning is anticipated after the first reactor is decommissioned.
- Simplifies operator training, since a group of identical reactors will have the same arrangement for controls, valves, and equipment.
- Minimizes the design input and safety review process for licensing the reactors.
- Provides fuel management flexibility during operation by fuel sharing between identical reactors.
- Reduces maintenance on identical units by correcting problems on subsequent units before the problems cause failure.

Some of these advantages may also be realized by a utility having reactors of a standardized design located at several single-reactor stations. The principal advantages of standardization during decommissioning of several identical reactors at a nuclear power station are:

- the minimization of the planning effort for decommissioning the second and later reactors of an identical design
- the improvement in productivity of the decommissioning workers due to the experience they gained on the first reactor
- the improvement of decommissioning techniques and the correction of mistakes.

A disadvantage of standardization is that both standardization of design and commonality of environment, management, equipment manufacturers, construction forces, and inspection tend to make common mode failure more likely at a nuclear energy center.

6.2.2 Site Dedication

When a nuclear power station is constructed, the site is committed for a period of up to 100 years or more, depending on whether the reactor is decommissioned by DECON, SAFSTOR, or ENTOMB. If the site is dedicated to nuclear power generation, replacement reactors will be constructed on a schedule that achieves startup of a replacement reactor just as an old reactor is retired. Site dedication of this type can foster a stable construction labor force for a much longer time than a multiple-reactor station at which the old reactors will not be replaced at retirement.

6.2.3 Timing of Construction

A nuclear energy center could be planned and scheduled so that construction and startup of its reactors occurs at regular intervals, say every 2 or 4 years, as indicated in the scenarios discussed in Section 3.4. It is more likely, however, that reactors will be added as the demand for electric energy increases the operating utility's service area. The five scenarios described in this study adequately illustrate the impact on safety and cost of decommissioning a reactor at a multiple-reactor station compared to decommissioning a reactor at a single-reactor station.

The lifetime schedules for construction, operation, and decommissioning of the reactors are shown in Figures 6.2-1 through 6.2-5 for the five scenarios described in Section 3.4. These figures illustrate how replacement reactors will be brought on-line as old reactors are retired at the end of their useful lives, 40 years after startup. Figures 6.2-1 through 6.2-4 show decommissioning by the DECON alternative and Figure 6.2-5 by the SAFSTOR alternative. A lifetime schedule for reactors decommissioned by ENTOMB would be essentially the same as the schedules shown for DECON in Figures 6.2-1 through 6.2-4.

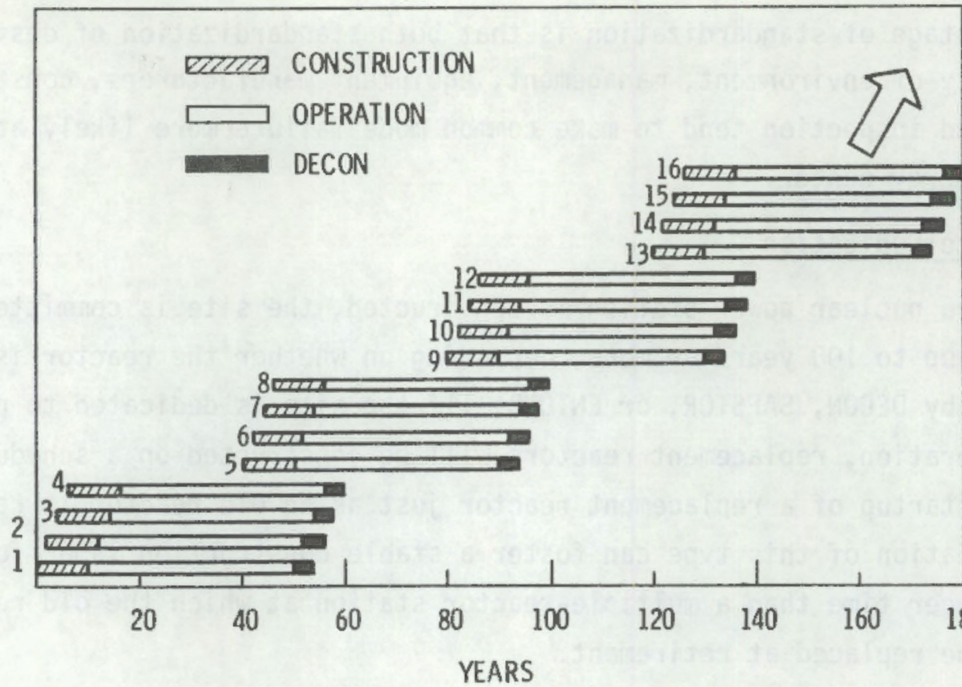

FIGURE 6.2-1. Lifetime Schedule for Construction, Operation, and DECON of a 4-Reactor Station - Scenario 1

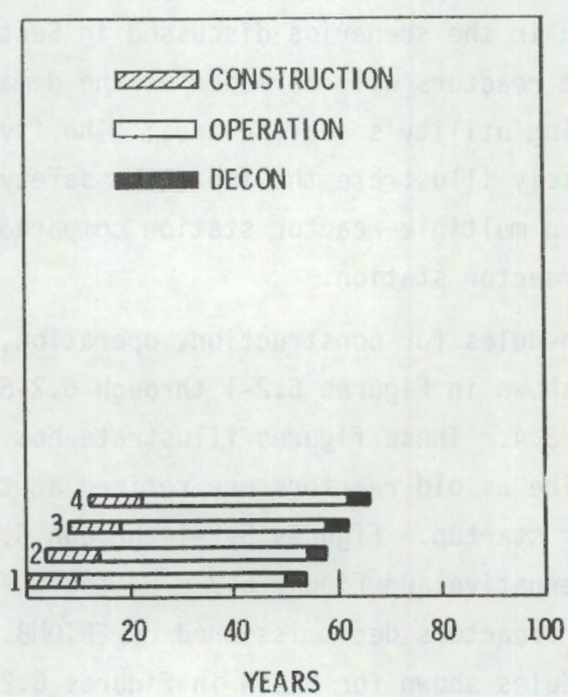

FIGURE 6.2-2. Lifetime Schedule for Construction, Operation, and DECON of a 4-Reactor Station - Scenario 2

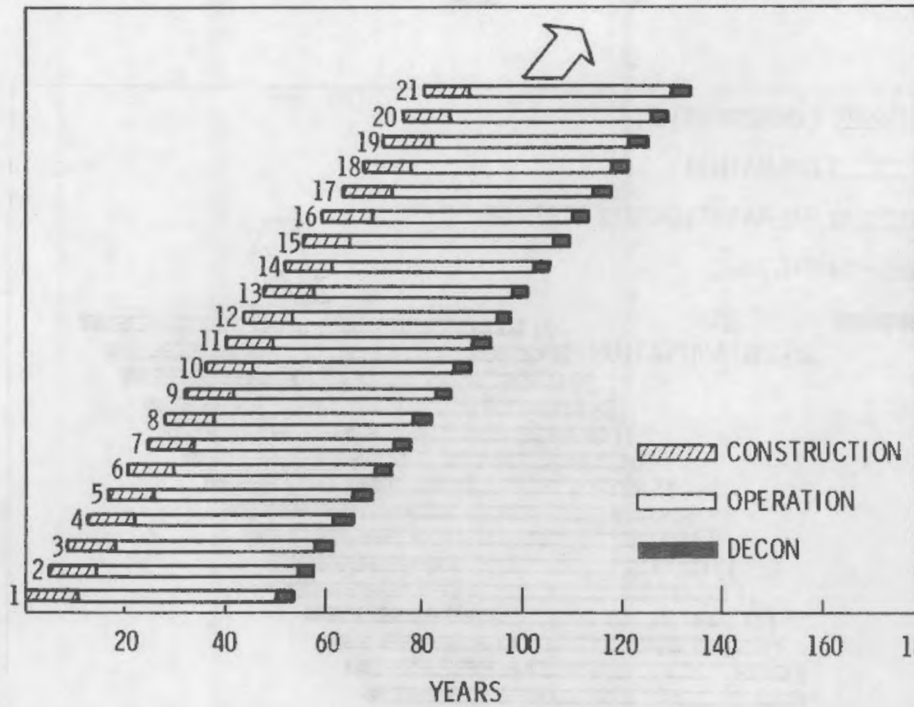

FIGURE 6.2-3. Lifetime Schedule for Construction, Operation, and DECON of a 10-Reactor Station - Scenarios 3 and 4

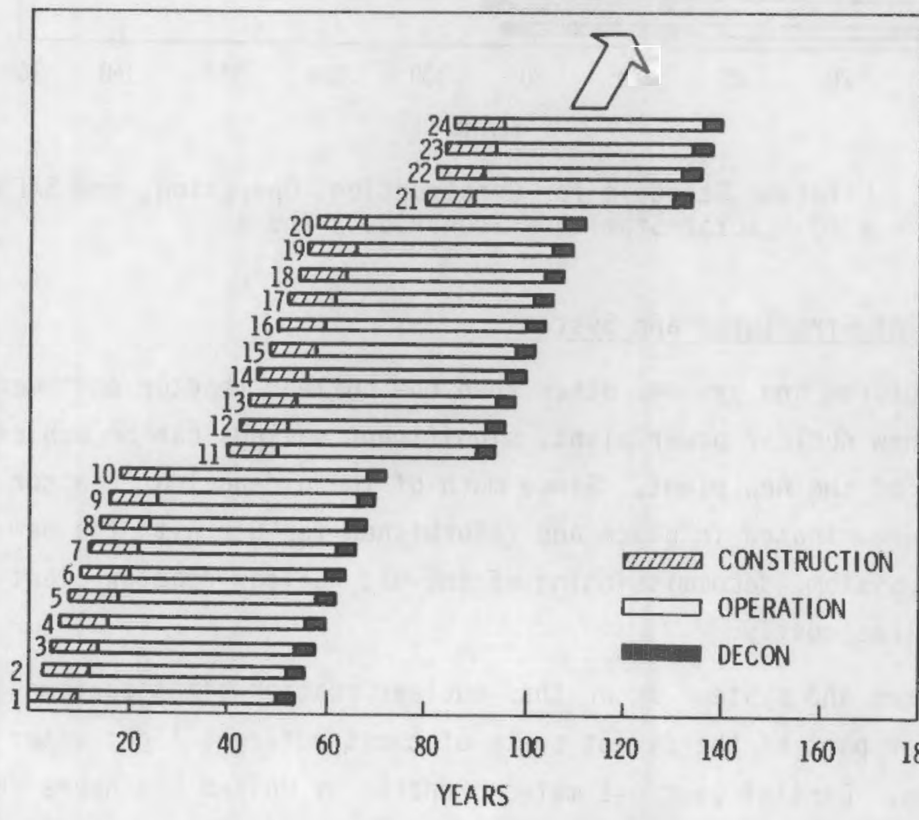

FIGURE 6.2-4. Lifetime Schedule for Construction, Operation, and DECON of a 10-Reactor Station - Scenario 5

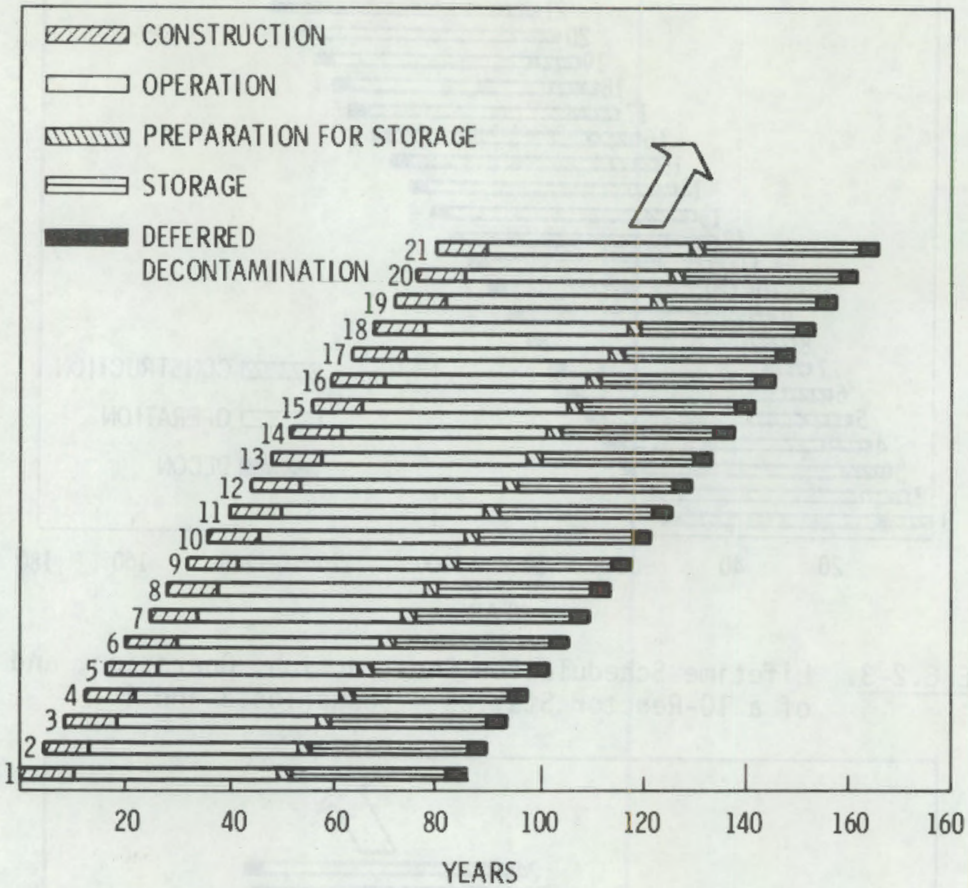

FIGURE 6.2-5. Lifetime Schedule for Construction, Operation, and SAFSTOR of a 10-Reactor Station - Scenarios 3 and 4

6.2.4 Reuse of Structures and Systems

If structures and systems other than the nuclear reactor equipment can be reused in a new nuclear power plant, significant savings can be achieved in the construction of the new plant. Since much of the old nuclear reactor plant would be decontaminated in place and refurbished for use with the new nuclear steam supply system, decommissioning of the old nuclear reactor plant would be simpler and less costly.

Structures and systems other than nuclear reactor plant equipment represent the major part of the direct costs of constructing a light-water reactor power station. Capital cost estimates prepared by United Engineers and Constructors[6,7] for a PWR and a BWR show the total direct construction costs, in 1978 dollars, to be $495 million for a PWR and $507 million for a BWR. The reactor plant equipment represents about 30% of the direct cost, 32% for the PWR and 29% for the BWR.

The estimated direct construction costs for a PWR and a BWR are given in Table 6.2-1. The direct construction costs for all of the plant other than the reactor plant equipment are estimated to be $335 million for the PWR and $357 million for the BWR. If refurbishment of these structures and systems costs as much as one-half of the original construction cost, there still would be a significant saving in the cost of the new plant. Possible means of facilitating removal and replacement of the nuclear reactor are discussed in Section 11.

TABLE 6.2-1. Cost Estimate Summary - Light Water Reactors

Construction Account	Estimated Cost ($ thousands) PWR(a)	BWR(b)
Structures and Improvements	119 126	133 167
Reactor Plant Equipment	156 857	147 750
Turbine Plant Equipment	130 766	137 102
Electric Plant Equipment	46 332	47 881
Miscellaneous Plant Equipment	13 870	13 014
Main Condenser Heat Reject System	25 368	25 839
Total Direct Costs	492 319	504 753

(a) From Table 1-1, Reference 6. Estimated costs escalated to 1978 dollars using the Handy-Whitman Utilities Cost Index.
(b) From Table 1-1, Reference 7. Estimated costs escalated to 1978 dollars using the Handy-Whitman Utilities Cost Index.

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2. Nuclear Energy Center Site Survey - 1975, U.S. Nuclear Regulatory Comission, NUREG-0001, January 1976.

3. H. Harty, The Hanford Nuclear Energy Center, A Conceptual Study, PNL-2640, Pacific Northwest Laboratory, Richland, Washington, September 1978.

4. C. C. Burwell, M. J. Ohanian and A. M. Weinberg, "A Siting Policy for an Acceptable Nuclear Future," Science 204: 1043 (June 8, 1979).

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6. Capital Cost: Pressurized Water Reactor Plant, NUREG-0241, United Engineers and Constructors, Inc., for the U.S. Nuclear Regulatory Commission, June 1977.

7. Capital Cost: Boiling Water Reactor Plant, NUREG-0242, United Engineers and Constructors, Inc., for the U.S. Nuclear Regulatory Commission, June 1977.

7.0 CHARACTERISTICS OF THE REFERENCE LIGHT WATER REACTORS

This section describes the characteristics of the reference PWR and BWR power reactors. The reference reactors are the same as those described in the PNL studies of decommissioning PWR and BWR reactors.[1,2] Summaries of detailed information developed in these studies are presented. Included are descriptions of the reference reactors and estimates of the radiation dose rates throughout the stations at shutdown.

The information presented is typical of present-generation large LWRs. While some details will vary from station to station, these differences are not expected to have major impacts on the results of this study.

7.1 THE REFERENCE PRESSURIZED WATER REACTOR

The reference PWR power station in this study is a 3500-MWt (1175-MWe) pressurized water reactor (PWR) of the Westinghouse design, specifically the Trojan Nuclear Plant at Rainier, Oregon, operated by the Portland General Electric Company.

The principal plant systems and structures of the reference PWR are described briefly in this subsection. More detailed information can be found in the PWR decommissioning study by Smith et al.[1]

7.1.1 Nuclear Power Generation System

The nuclear power generation system is illustrated in the functional schematic diagram in Figure 7.1-1. The principal components and systems of interest are the reactor vessel (containing the fuel and coolant) and the reactor coolant system (RCS), which transfers the heat from the fuel to the secondary coolant system via the steam generator heat exchangers where steam is produced for use in the turbine generator.

7.1.1.1 Reactor Vessel and Internals

The reactor vessel is a right circular cylinder with a welded hemispherical bottom and removable hemispherical top, as illustrated in Figure 7.1-2. The vessel is constructed of carbon steel about 0.216 m thick, with the inside

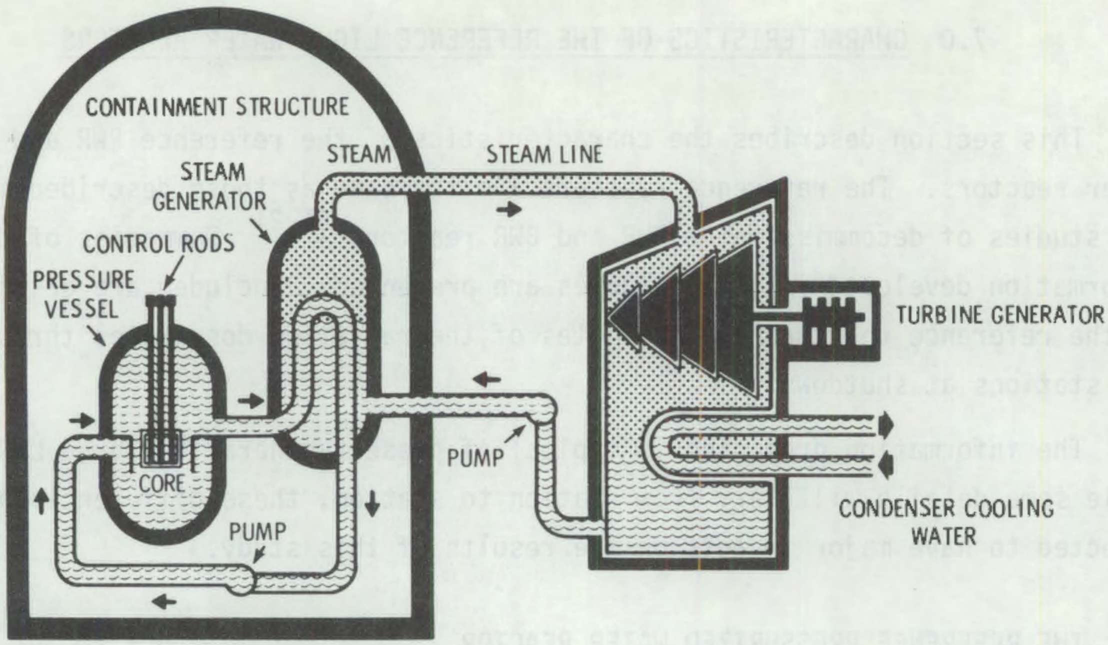


FIGURE 7.1-1. Pressurized Water Reactor

clad with stainless steel or Inconel about 4 mm thick. The approximate dimensions of the vessel are 12.6 m in height and 4.6 m in outer diameter. The vessel weighs nearly 400 Mg.

The vessel internal structures support and constrain the fuel assemblies, direct coolant flow, and guide in-core instrumentation, as well as provide some neutron shielding. The principal components are: the lower core support assembly (including the core barrel and shroud, with neutron shield pads and the lower core plate and supporting structure) and the upper core support and in-core instrumentation support assemblies. These structures are made of 304 stainless steel and have a total weight of about 190 Mg.

7.1.1.2 Reactor Coolant System

The reactor coolant system, schematically illustrated in Figure 7.1-3, consists of four loops for transferring heat from the reactor to the secondary coolant system. Each loop contains a U-tube steam generator, a reactor coolant pump, and connecting piping. Each steam generator, illustrated in Figure 7.1-4, is about 20.6 m in height, 3.4 m in diameter, weighs about 312 Mg, and contains nearly 3400 Inconel U-tubes.

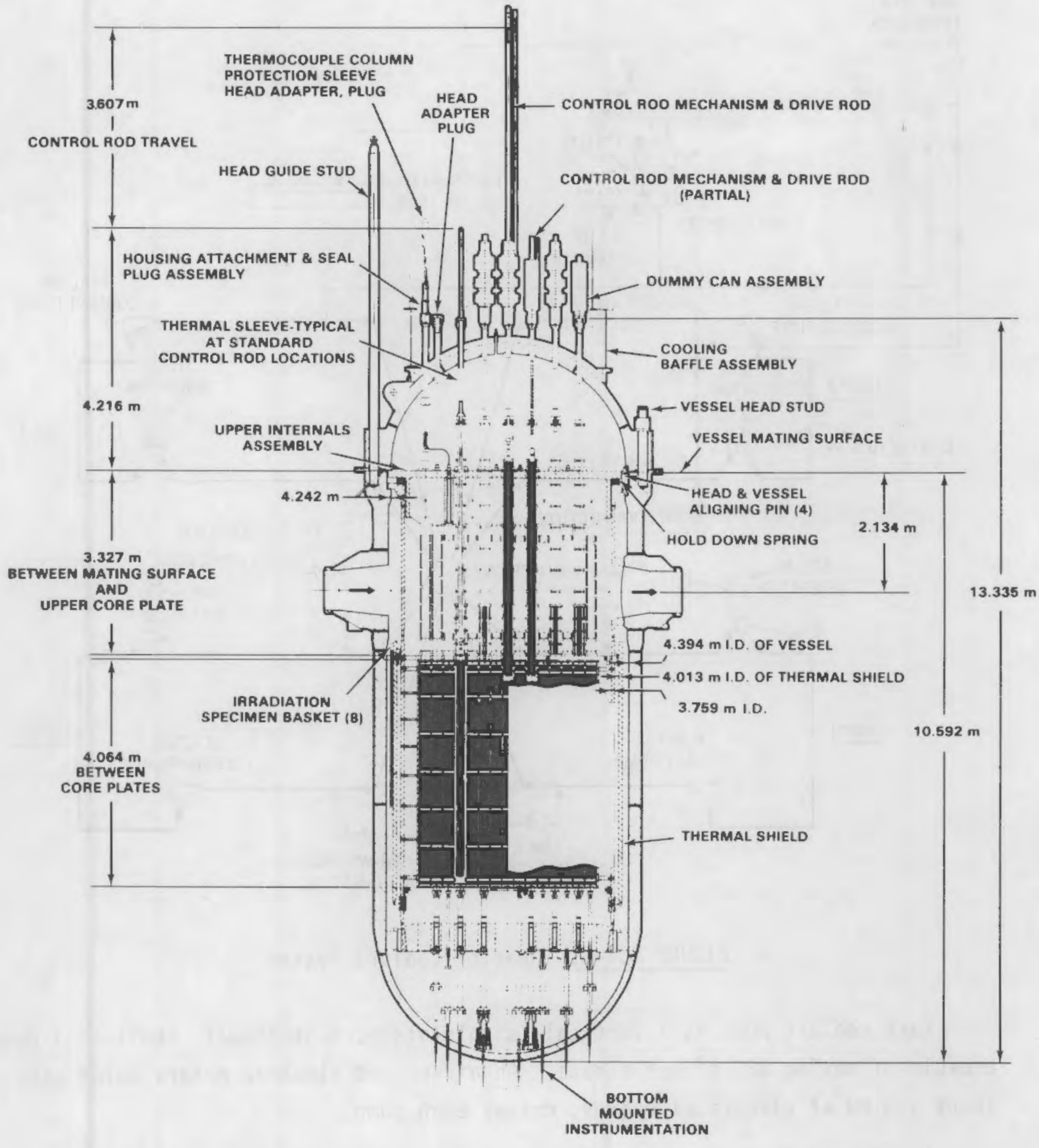


FIGURE 7.1-2. PWR Reactor Vessel Internals

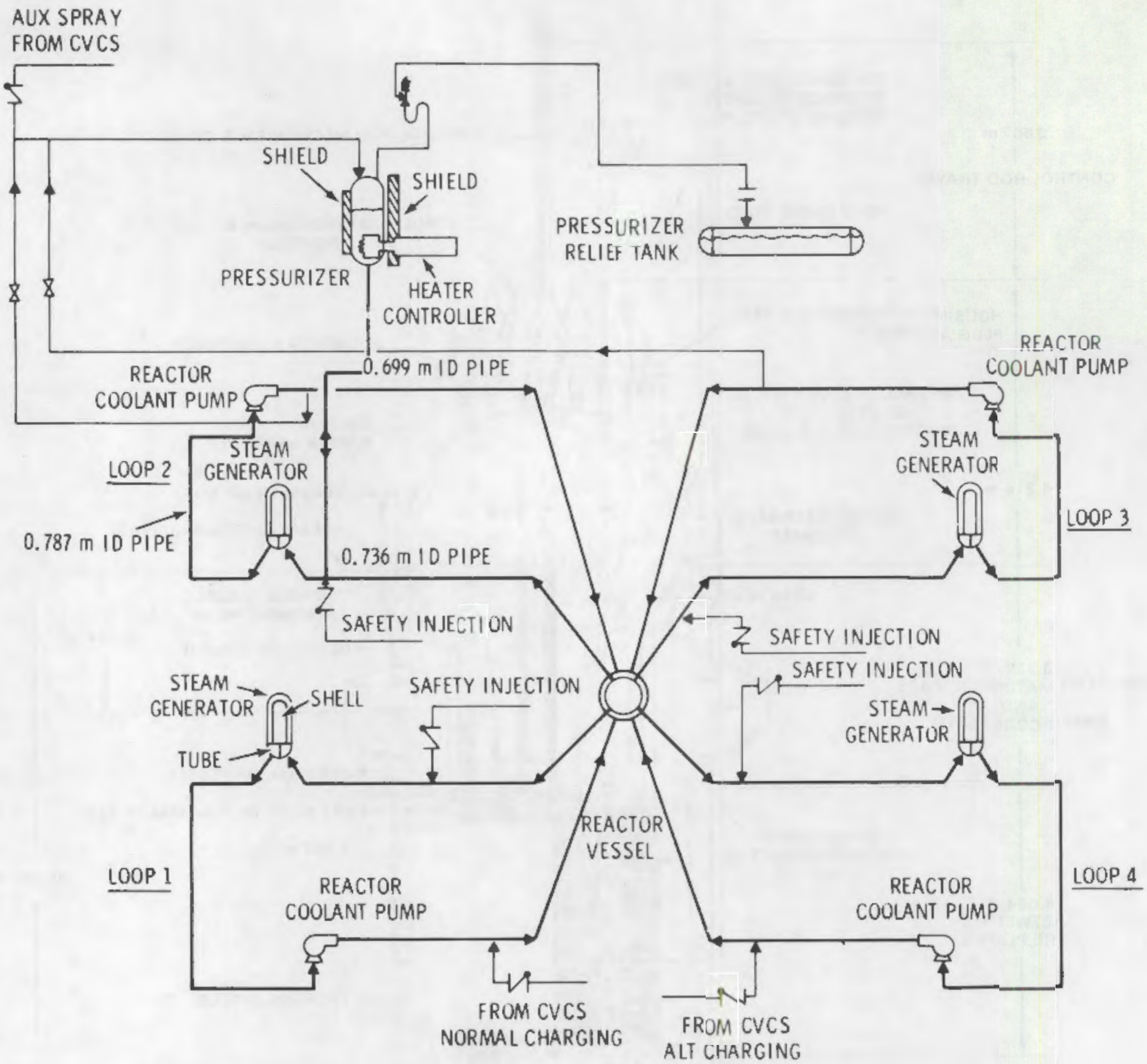


FIGURE 7.1-3. Reactor Coolant System

Each coolant pump is a vertical, single-stage, centrifugal, shaft-seal pump capable of moving 335 m^3 per minute. An air-cooled electric motor, which uses about 4.5 MW of electrical energy, drives each pump.

A total of 81 m of large-diameter (0.7 m I.D.) piping connects the four loops of the reactor coolant system to the reactor vessel. This piping has wall thicknesses in the 59 to 66 mm range, and weighs slightly over 100 Mg.

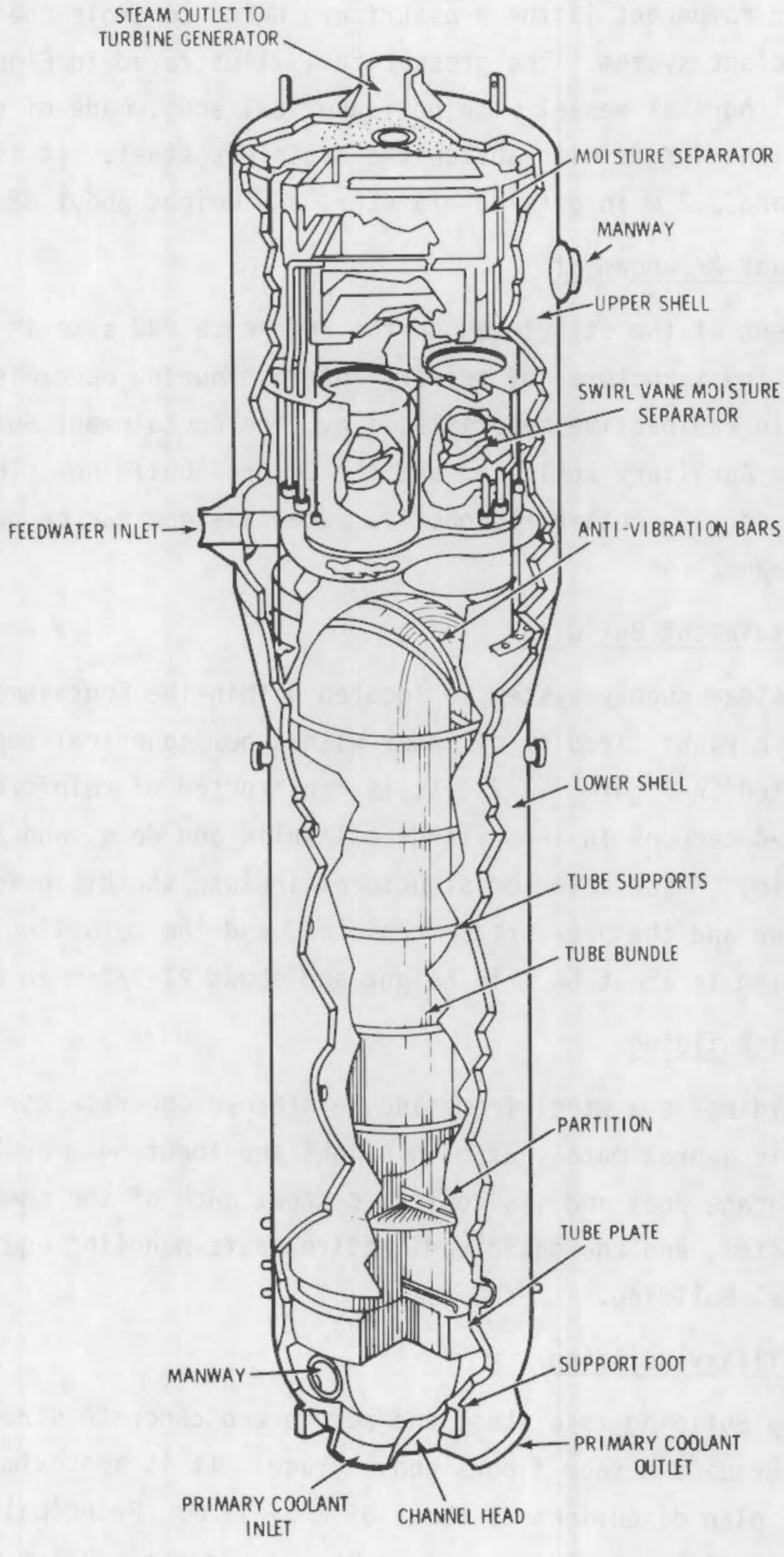


FIGURE 7.1-4. Steam Generator

Another major component is the pressurizer, which controls the pressure in the reactor coolant system. The pressurizer, illustrated in Figure 7.1-5, is a vertical, cylindrical vessel with hemispherical ends, made of carbon steel and clad on the inside with austenitic stainless steel. It is about 16.1 m in height and 2.3 m in outside diameter, and weighs about 88.7 Mg.

7.1.2 General Plant Arrangement

The arrangement of the structures on the reference PWR site is illustrated in Figure 7.1-6. The structures of primary interest during decommissioning are those which contain radioactive materials, i.e., the Containment Building, the Fuel Building, the Auxiliary Building, and the Control Building. The other onsite structures do not contain radioactive materials and can be demolished by conventional means.

7.1.2.1 Containment Building

The nuclear steam supply system is located within the Containment Building. This structure is a right circular cylinder with a hemispherical top and a flat base, as illustrated in Figure 7.1-7. It is constructed of reinforced concrete, with post-tensioned tendons in the cylindrical walls and dome, and lined with a welded steel skin. Major interior structures include the biological shield, the steam generator and the pressurizer cubicles, and the refueling cavity. The Containment Building is about 64 m in height and about 22-1/2 m in diameter.

7.1.2.2 Fuel Building

The Fuel Building is a steel frame and reinforced concrete structure with four floors. It is approximately 27 m in height and about 54 m by 19 m in plan. The spent fuel storage pool and its cooling system, much of the chemical and volume control system, and the solid radioactive waste handling equipment are located in the Fuel Building.

7.1.2.3 Auxiliary Building

The Auxiliary Building is a steel and reinforced concrete structure with two floors below grade and four floors above grade. It is approximately 30 m in height and has plan dimensions of about 35 m by 19 m. Principal systems contained in the Auxiliary Building include the liquid radioactive waste

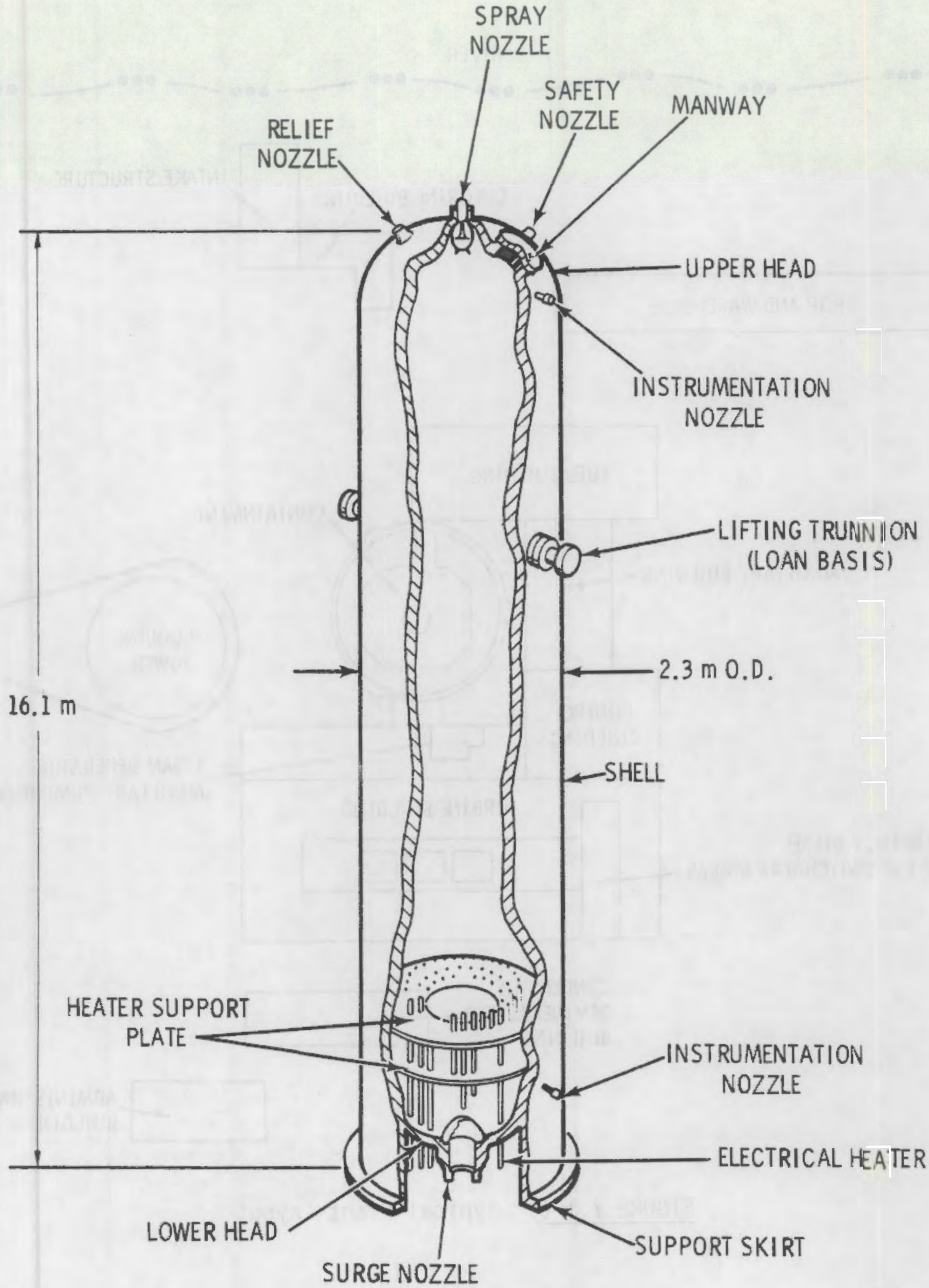


FIGURE 7.1-5. Cutaway of Pressurizer

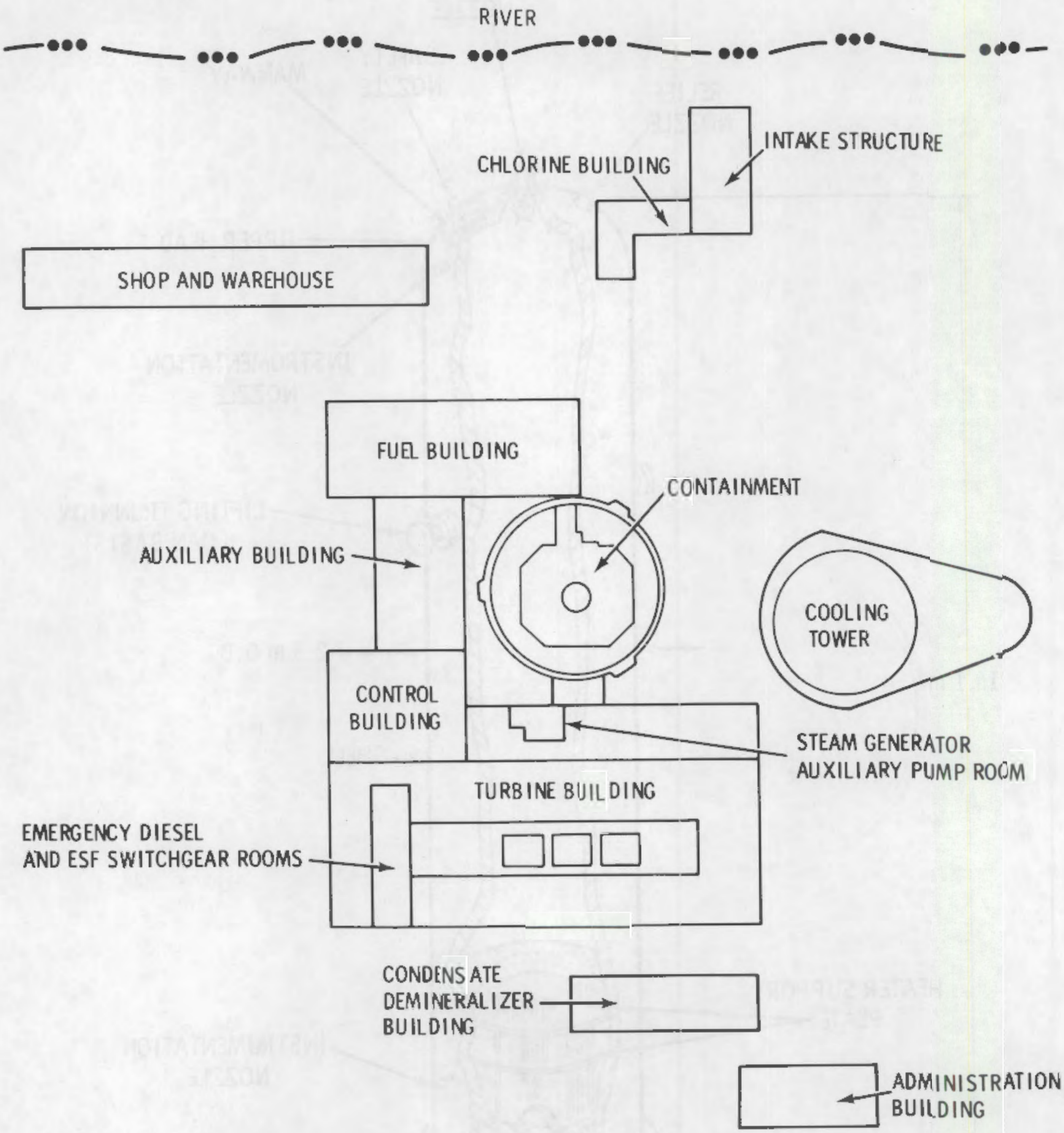
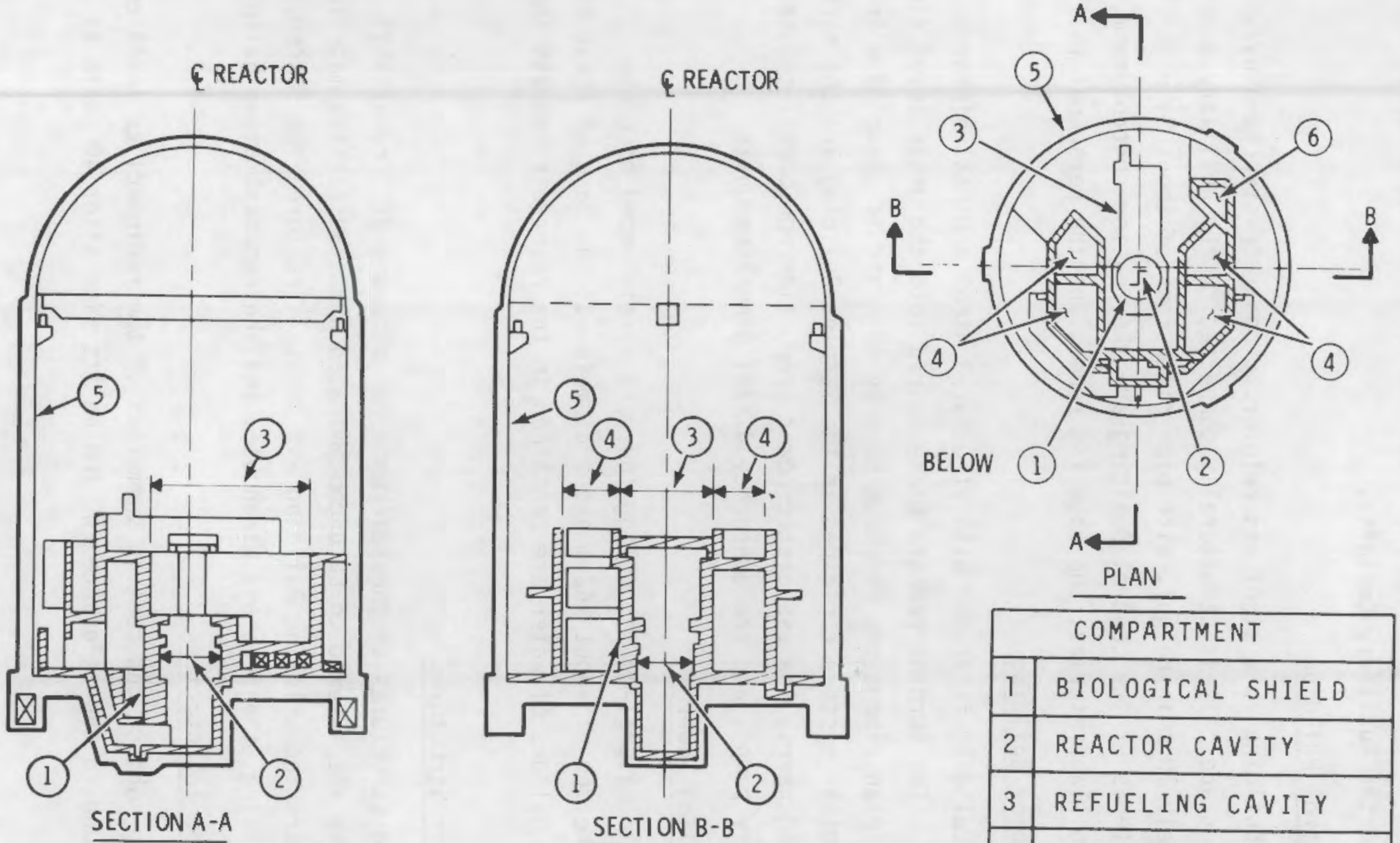


FIGURE 7.1-6. Typical Plant Layout



	COMPARTMENT
1	BIOLOGICAL SHIELD
2	REACTOR CAVITY
3	REFUELING CAVITY
4	STEAM GENERATOR
5	REACTOR CONTAINMENT
6	PRESSURIZER VESSEL

FIGURE 7.1-7. Containment Building

treatment systems, the filter and ion exchanger vaults, the waste gas treatment system, and the ventilation equipment for the Containement Building, the Fuel Building, and the Auxiliary Building.

7.1.2.4 Control Building

The Control Building is a steel and reinforced concrete structure having four floors above grade. It is structurally connected to the Auxiliary Building and is approximately 18 m in height, with plan dimensions of about 31 m by 24 m. The principal contents of the Control Building are the reactor control room, the process control laboratories, the counting rooms, and the personnel facilities.

7.1.2.5 Turbine Building

The Turbine Building is framed with structural steel and has reinforced concrete-slab floors. The turbine pedestals are poured into the grade-level floor. The structure has plan dimensions of about 95 m by 49 m and is about 33 m in height. The principal systems contained in the Turbine Building are the turbine generator, the condensers, the associated power production equipment, the steam generator auxiliary pumps, and the emergency diesel generator units.

7.1.2.6 Cooling Tower

The hyperbolic natural-draft cooling tower is a reinforced concrete structure with a height of about 142 m and a diameter at the base of about 119 m. About 5.2 million gallons of water are contained in the reservoir beneath the cooling fins.

7.1.2.7 Other Structures

The remaining structures on the reference PWR site are of conventional construction. They are assumed to be uncontaminated with radioactive materials. These structures are the Chlorine Building and Intake Structure, the Condensate Demineralizer Building, the Shop and Warehouse, and the Administration Building.

7.1.3 Radionuclide Inventories

The following subsections contain summaries of the radionuclide inventories expected to be found in the reference PWR and on its site after 40 years of normal operation. Annual atmospheric releases of radionuclides from the operating PWR are derived from calculated and reported releases and are used to calculate estimates of the accumulation of radionuclides on the site from 40 years of normal PWR operation.

7.1.3.1 Accumulated Radionuclides Within the Reference PWR

Significant quantities of radionuclides remain in a nuclear power station at the time of final reactor shutdown even after the irradiated fuel has been removed. Neutron-activated structural materials in and around the reactor pressure vessel contain large, relatively immobile quantities of radioactivity. Radioactive corrosion products and fission products from failed fuel, which are transported throughout the station by the reactor coolant streams, are the principal contributors to the more mobile radioactive contamination on piping, floors, and pool surfaces.

Neutron-Activated Reactor Components and Structural Materials. Production of radioactive reactor components and structural materials by neutron activation is a normal result of reactor operation. The concentration of a particular radionuclide in a given location in the reactor depends on the neutron flux level at that location, the duration of the exposure to the neutron flux, the concentration of the parent isotope, and the cross section of that isotope for the production of the radioactive species. Radionuclide concentrations present at shutdown in the reactor vessel, in its internal structures, and in its surrounding shielding enclosure are calculated for the reference PWR, assuming 30 effective full-power years (EFPY), equivalent to 40 calendar years at 75% of full-power operation.

Specific activities at the time of reactor shutdown of the principal radionuclides of interest in decommissioning are listed in Table 7.1-1 for each of the major reactor components. Radionuclides having half-lives shorter than 35 days are not included. The upper and lower values for ^{60}Co activity listed in Table 7.1-1 are based on assumed initial concentrations for ^{59}Co impurity of 0.05 to 0.15 wt% in the 304 stainless steel components and of 0.006 to 0.012 wt% in the SA533 carbon steel pressure vessel. The ^{93}Nb trace impurity, parent of the ^{94}Nb radionuclide, is assumed to have a concentration in the 304 stainless

TABLE 7.1-1. Radioactivity Levels in Major Activated Reactor Components at Time of Reactor Shutdown[a]

Radionuclide	Core Mid-Plane Radioactivities (Ci/m^3)						
	Shroud	Lower 4.72 m of Core Barrel	Thermal Shields	Vessel Inner Cladding	Lower 5.02 m of Vessel Wall	Upper Grid Plate[b]	Lower Grid Plate[b]
^{95}Nb	2.0×10^{3}	7.6×10^{0}	3.5×10^{0}	5.6×10^{-3}	1.7×10^{-3}		
^{59}Fe	4.6×10^{4}	4.4×10^{3}	2.0×10^{3}	1.0×10^{2}	2.7×10^{1}		
^{58}Co	1.5×10^{5}	1.0×10^{4}	4.6×10^{3}	3.3×10^{2}	6.6×10^{0}		
^{95}Zr	1.1×10^{-1}	6.2×10^{-3}	2.9×10^{-3}	2.0×10^{-4}	7.2×10^{-4}		
^{65}Zn	1.2×10^{2}	1.1×10^{0}	5.0×10^{-1}	6.7×10^{-4}	3.5×10^{-5}		
^{54}Mn	6.8×10^{4}	3.7×10^{3}	1.7×10^{3}	1.2×10^{2}	4.7×10^{1}		
^{55}Fe	1.3×10^{6}	1.5×10^{5}	6.7×10^{4}	3.5×10^{3}	7.2×10^{2}		
^{60}Co[c] upper	9.6×10^{5}	9.3×10^{4}	4.7×10^{4}	2.5×10^{3}	7.5×10^{1}		
lower	3.2×10^{5}	3.1×10^{4}	1.6×10^{4}	8.2×10^{2}	2.5×10^{1}		
^{63}Ni	1.2×10^{5}	1.5×10^{4}	6.8×10^{3}	3.6×10^{2}	3.8×10^{0}		
^{93}Mo	3.6×10^{-1}	5.2×10^{-2}	2.4×10^{-2}	1.2×10^{-3}	1.3×10^{-3}		
^{14}C	1.5×10^{2}	1.8×10^{1}	8.3×10^{0}	4.0×10^{-1}	1.9×10^{-2}		
^{94}Nb	5.4×10^{0}	2.6×10^{-1}	1.2×10^{-1}	9.5×10^{-3}	--		
^{59}Ni	7.4×10^{2}	1.3×10^{2}	5.0×10^{1}	3.0×10^{0}	3.2×10^{-2}		
Sum (Ci/m^3)	2.97×10^{6}	3.07×10^{5}	1.45×10^{5}	7.73×10^{3}	9.04×10^{2}	2.97×10^{6}	2.97×10^{6}
Average/Peak	0.755	0.637	0.778	0.637	0.637	0.003×4.74[d]	0.08×4.74[d]
Ci/kg[e]	2.787×10^{2}	2.433×10^{1}	1.403×10^{1}	7.621×10^{-1}	7.164×10^{-2}	5.254×10^{0}	1.403×10^{2}
Weight of Material (kg)	12 312	26 783	10 413	2 074	245 582	4 627	3.946
Sum (Ci)[f]	3.431×10^{6}	6.516×10^{5}	1.461×10^{5}	1.581×10^{3}	1.759×10^{4}	2.431×10^{4}	5.534×10^{5}
Total - Radioactivity				4.826×10^{6} Ci			
				1.786×10^{17} Bq			

(a) From Table 7.3-2, Reference 1.
(b) Normalized to shroud.
(c) Upper and lower bounds were computed using the maximum and minimum levels of ^{59}Co contaminant in the materials. All totals were computed using the upper bound values.
(d) $\frac{\text{Activity (Plate Average)}}{\text{Activity (Plate Edge)}} = 4.74$, $\frac{\text{Activity (Shroud at Plate Location)}}{\text{Activity (Shroud at Axial Midplane)}} = \begin{cases} 0.005, \text{ upper plate} \\ 0.08, \text{ lower plate} \end{cases}$
(e) Conversion factor assumes stainless steel density of $8.038 \times 10^3\ kg/m^3$.
(f) The number of significant figures carried is for computational accuracy and does not imply precision to four places.

steel of 0.016 percent by weight in the alloy. A total of over 4.8 million curies of radioactivity is calculated to be present in the activated reactor vessel and components at the time of final reactor shutdown.

The radioactivity inventory in the concrete biological shield is difficult to precisely define because the actual initial composition is not well known, particularly with regard to elements present in trace quantities. Calculations of activation products in the bioshield result in the listing given in Table 7.1-2. No rare earths are included in the calculation due to lack of quantitative data on their probable initial concentrations. The levels of radioactivity (Ci/m^3) are those calculated to be present at final reactor shutdown.

7.1.3.2 Surface Contamination

Numerous radioactive materials, activated corrosion products from structural materials in contact with coolant, and fission products from leaking fuel are present in the reactor coolant streams during reactor operation. Some of these coolant-transported radioactive materials are deposited on internal surfaces of equipment and piping, on external surfaces, and on the surrounding site. Summaries of the radioactive inventories deposited as both internal surface contamination in piping and equipment and external surface contamination inside the reference PWR buildings and on the surrounding site are presented below.

Internal Surface Contamination. The composition of these activated corrosion product sources is derived from information available in the literature.[3,4] Fractional activities of various corrosion products deposited on internal surfaces of equipment and piping are shown in Table 7.1-3. It can be seen that cobalt isotopes comprise 78% of the total activity at reactor shutdown.

External Surface Contamination. Contamination of surfaces external to the equipment and piping in the reference PWR occurs from leaks in the process systems. Contamination from leaks in areas normally accessible to operating personnel probably would be cleaned up according to operating procedures. Only in areas not accessible to operating personnel, such as ion exchanger vaults, would contamination build up throughout the lifetime of the plant. The fractional activities of the various corrosion and fission products that could be deposited on external surfaces in the PWR are shown in Table 7.1-3. It can be seen that cesium isotopes comprise 87% of the total activity at shutdown.

TABLE 7.1-2. Radioactivity Levels at the Inner Surface of the Activated Biological Shield at Reactor Shutdown[a]

Radionuclide	Principal Radiation Emitted	Radioactivity (Ci/m^3) Reference PWR (calculated)	Elk River Reactor (measured)
^{3}H	β	2.9×10^{-5}	
^{14}C	β	6.94×10^{-4}	
^{22}Na	γ	Not calculated	3.6×10^{-2}
^{33}P	β	3.24×10^{-1}	
^{35}S	β	3.17×10^{-2}	
^{36}Cl	γ	8.40×10^{-6}	
^{37}Ar	γ	2.15×10^{-1}	
^{39}Ar	β	3.96×10^{-2}	
^{40}K	γ	3.76×10^{-5}	
^{41}Ca	γ	7.00×10^{-3}	
^{45}Ca	β	3.66×10^{0}	
^{46}Sc	γ	1.86×10^{-4}	
^{51}Cr	γ	1.04×10^{-1}	
^{54}Mn	γ	1.68×10^{-1}	
^{55}Fe	γ	3.01×10^{1}	
^{59}Fe	γ	9.99×10^{-1}	
^{58}Co	γ	2.15×10^{-2}	
^{60}Co	γ	6.69×10^{-1}	1.01×10^{0}
^{59}Ni	γ	1.19×10^{-3}	
^{63}Ni	β	1.40×10^{-1}	
^{65}Zn	γ	4.47×10^{-7}	
^{93m}Nb	γ	2.77×10^{-5}	
^{95}Nb	γ	5.40×10^{-6}	
^{93}Mo	γ	6.69×10^{-5}	
^{99}Tc	β	4.93×10^{-5}	
^{152}Eu	γ	Not calculated	8.7×10^{-1}

(a) From Table 7.3-5, Reference 1.

TABLE 7.1-3. Radionuclide Inventory of PWR Surface Contamination at Reactor Shutdown

Radionuclide	Fractional Radioactivity at Shutdown: Internal Surface Contamination[(a)]	External Surface Contamination[(b)]	Site Surface Contamination[(c)]
^{51}Cr	2.4×10^{-2}	6.9×10^{-4}	4.7×10^{-3}
^{54}Mn	3.6×10^{-2}	1.4×10^{-3}	1.1×10^{-2}
^{55}Fe	--	2.2×10^{-2}	--
^{59}Fe	8.2×10^{-3}	8.7×10^{-4}	2.2×10^{-3}
^{57}Co	--	--	5.2×10^{-4}
^{58}Co	4.6×10^{-1}	7.5×10^{-3}	2.4×10^{-2}
^{60}Co	3.2×10^{-1}	7.5×10^{-2}	3.5×10^{-1}
^{89}Sr	--	1.2×10^{-3}	6.9×10^{-4}
^{90}Sr	--	6.9×10^{-4}	6.9×10^{-2}
^{90}Y	--	6.9×10^{-4}	6.9×10^{-2}
^{95}Zr	5.6×10^{-2}	2.5×10^{-4}	3.9×10^{-3}
^{95}Nb	5.6×10^{-2}	2.5×10^{-4}	3.9×10^{-3}
^{103}Ru	2.6×10^{-2}	--	3.9×10^{-4}
^{110m}Ag	--	--	8.6×10^{-4}
^{124}Sb	--	--	4.8×10^{-4}
^{125}Sb	--	--	6.9×10^{-4}
^{129m}Te	--	3.1×10^{-4}	--
^{131}I	--	1.2×10^{-2}	7.3×10^{-2}
^{134}Cs	--	1.2×10^{-1}	2.0×10^{-2}
^{136}Cs	--	1.1×10^{-3}	1.2×10^{-4}
^{137}Cs	1.2×10^{-3}	7.5×10^{-1}	3.7×10^{-1}
^{140}Ba	--	--	9.9×10^{-4}
^{140}La	--	--	9.9×10^{-4}
^{141}Ce	6.6×10^{-2}	--	1.2×10^{-5}
^{144}Ce	--	--	6.0×10^{-4}
Totals	1.0	1.0	1.0

(a) From Table 7.3-7, Reference 1.
(b) From Table 7.3-10, Reference 1.
(c) Based on Table 7.3-14, Reference 1.

Site Surface Contamination. Radioactive contamination is expected to be on the reference PWR site after 40 years of plant operation. An estimate of the radioactive contamination remaining onsite when the PWR is shut down after 40 years of operation is made, based on the 1975 reported releases from operating nuclear power stations.[5] The fractional activities of the various corrosion and fission products making up the site surface contamination are shown in Table 7.1-3.

7.1.4 Radiation Dose Rate Data

The measured radiation dose rate data used as the basis for this study came from six PWR reactor stations that had been operating from 3 to 6 years. The equilibrium levels of radiation dose rate from piping depositions have probably not yet been reached. However, the data presently available are not adequate to permit extrapolation to 30 years of full-power operation.[6] Therefore, composite radiation-level values created from data from six PWRs are used to estimate occupational radiation dose rates to decommissioning personnel without further upward adjustment. A representative sample of these estimated radiation dose rates is presented in Table 7.1-4. The wide range of dose rates shown in the table (from 0.001 to 30 R/hr) is postulated to be typical for the reference PWR after final shutdown and before any chemical decontamination efforts.

The reactor coolant system radiation levels are caused primarily by the activated corrosion products ^{58}Co and ^{60}Co. Measurements have shown that ^{60}Co increasingly dominates the radiation field after a few years of operation. Only ^{58}Co- and ^{60}Co-deposited activities need to be considered for any immediate decommissioning approach, since these two radionuclides contribute more than 90% of the out-of-core radiation dose rates, with 70% of these attributed solely to ^{60}Co.[7] The relative decay rates of the principal activated corrosion products as a function of time are plotted in Figure 7.1-8, while the time dependence of radioactivity and the radiation dose rates in activated reactor components are shown in Figure 7.1-9. The curves in the figure roughly indicate the relative contribution to the dose rate by the different corrosion-product isotopes and the total activity as a function of time after reactor shutdown. The relative fraction of ^{60}Co activity shown may be lower than that encountered in a plant that has operated 30 to 40 years, but these values represent presently available information.

TABLE 7.1-4. Estimated Radiation Dose Rates in the Reference PWR at Shutdown[a]

Location	Type of Measurement[b]	Dose Rate (R/hr)
Reactor Containment Building		
Reactor Coolant Pump Bowl	Contact	12-30[c]
RCS Piping, Cold Leg	Contact	0.5-0.6
Steam Generators	General Area	0.05.-0.4
Emergency Personnel Lock	Inside Lock Area	0.001-0.012
Floor Drains	Contact	0.1-0.6
Pressurizer Area	General Area	≤0.2
Regenerative Heat Exchanger (Hx)	Contact	1-15
Between Steam Generator (SG) Enclosure and Containment Vessel (CV) Wall	General Area	≤0.025
Between RCS Pumps and SG's	General Area	0.1-0.9
Between Upper Internals Storage and CV Wall	General Area	0.02-0.1
Near CV Wall	General Area	0.005-0.02
Reactor Cavity, Inside Edge	General Area	0.1-1
Steam Generators	General Area	≤0.2
Auxiliary Building		
Component Cooling Water Pumps	General Area	≤0.15
Waste Tank Room	General Area	0.2-0.4
Treated Waste Monitor Tanks	Contact	0.01-0.3
Pipeway	General Area	0.05-0.15
Resin Storage Tank	General Area	≥0.4
Volume Control Tank	General Area	1-3
Radwaste Evaporator Room	General Area	0.25-0.5
Waste Evaporator Panel	General Area	0.001-0.01
Demineralizers	General Area	0.01-0.2
HEPA Exhaust Filters	Contact	≥0.005
Fuel Building		
Waste Holdup Tank Rooms	General Area	2-5
Water Heat Exchangers	General Area	0.07-0.14
Gas Stripper Feed Pumps	General Area	≥0.025
Drumming Room	General Area	0.2-1.5
Drumming Room Entrance	General Area	0.2
CVCS Monitor Tanks	Contact	≤0.3
Boric Acid Evaporator Room	General Area	0.3-0.5
Spent Fuel Pool Pump	General Area	≥0.05
Spent Fuel Pool Skimmer Filters	General Area	≥0.1
Controlled Access Machine Shop	General Area	0.02-0.1
Spent Fuel Pit	General Area	≥0.025

(a) From Table 7.4-2, Reference 1.
(b) Contact means the closest approach to a surface (a surface dose rate) including the necessary geometry and source size corrections done in the field by the health physicist. General Area refers to the radiation field in a room or area; not specifically from one discrete source or direction, although a specific source or object may be the sole contributor to the General Area radiation level measurement.
(c) Example: 12-30 means in the range of from 12 to 30 R/hr.

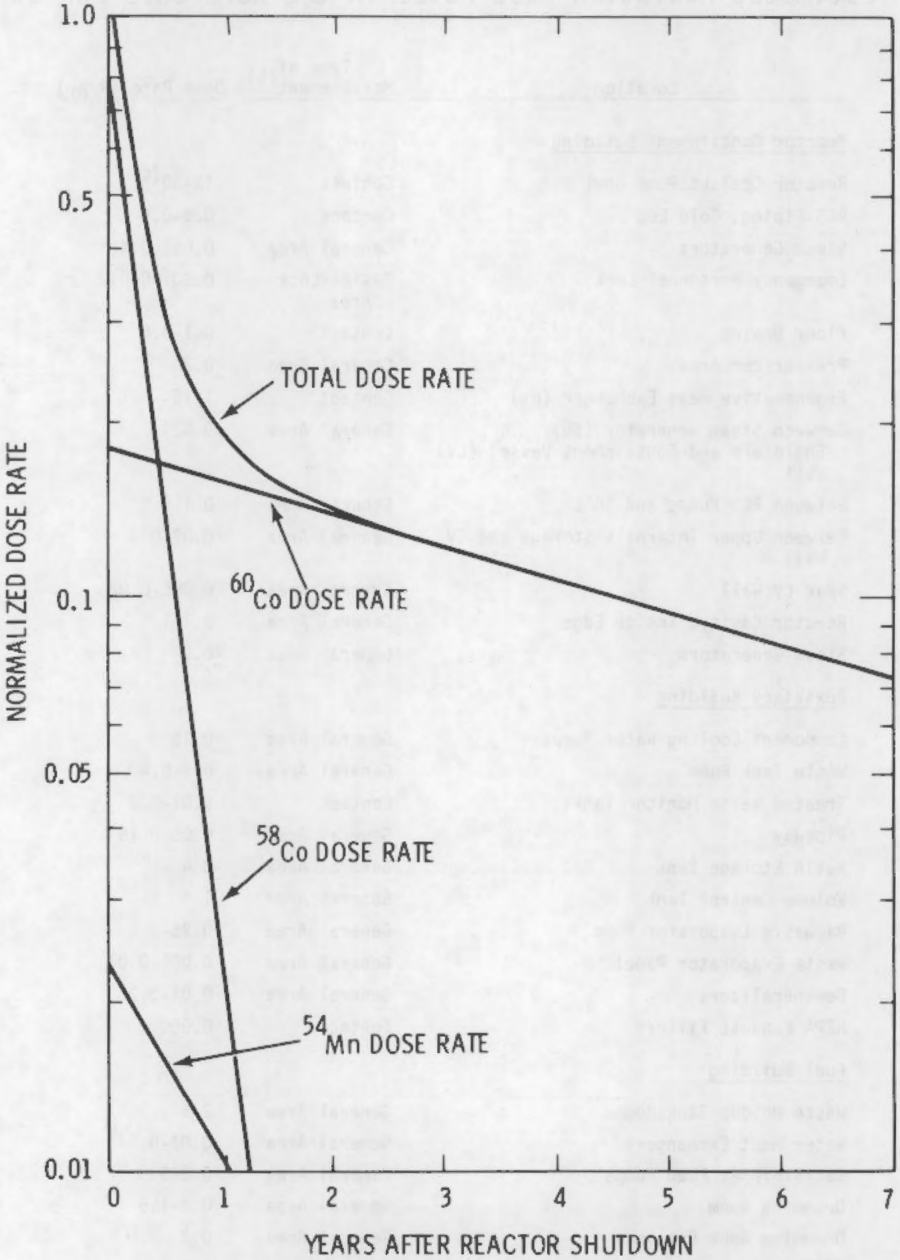


FIGURE 7.1-8. Radioactive Decay of Activated Corrosion Products

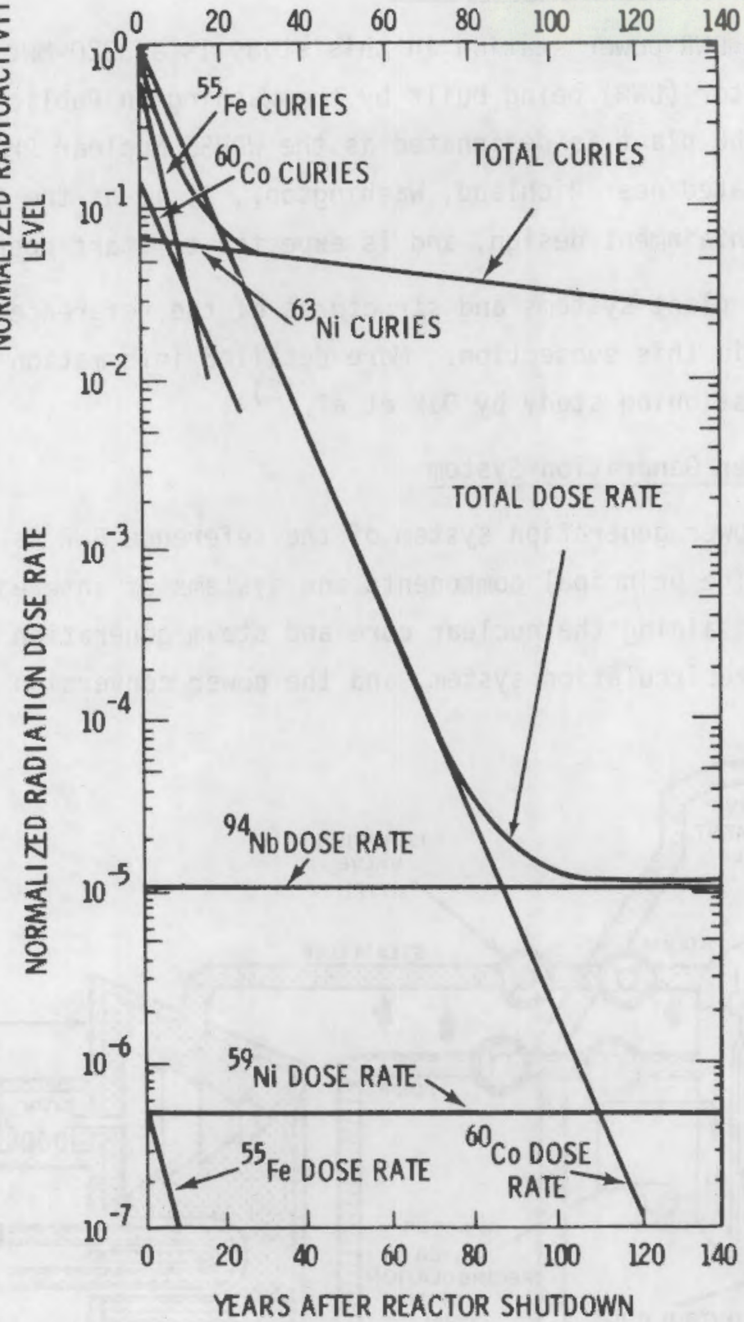


FIGURE 7.1-9. Time Dependence of Radioactivity Levels and Radiation Dose Rates in the Activated Reactor Components

7.2 THE REFERENCE BOILING WATER REACTOR

The reference BWR power station in this study is a 3320-MWt (1155-MWe) boiling water reactor (BWR) being built by the Washington Public Power Supply System (WPPSS). The plant is designated as the WPPSS Nuclear Project No. 2 (WNP-2) and is located near Richland, Washington. It is of the BWR/5 class and the Mark-II containment design, and is expected to start operation in 1983.

The principal plant systems and structures of the reference BWR are described briefly in this subsection. More detailed information can be found in the BWR decommissioning study by Oak et al.[2]

7.2.1 Nuclear Power Generation System

The nuclear power generation system of the reference BWR is illustrated in Figure 7.2-1. The principal components and systems of interest are the reactor vessel (containing the nuclear core and steam generation equipment), the reactor water recirculation system, and the power conversion system.

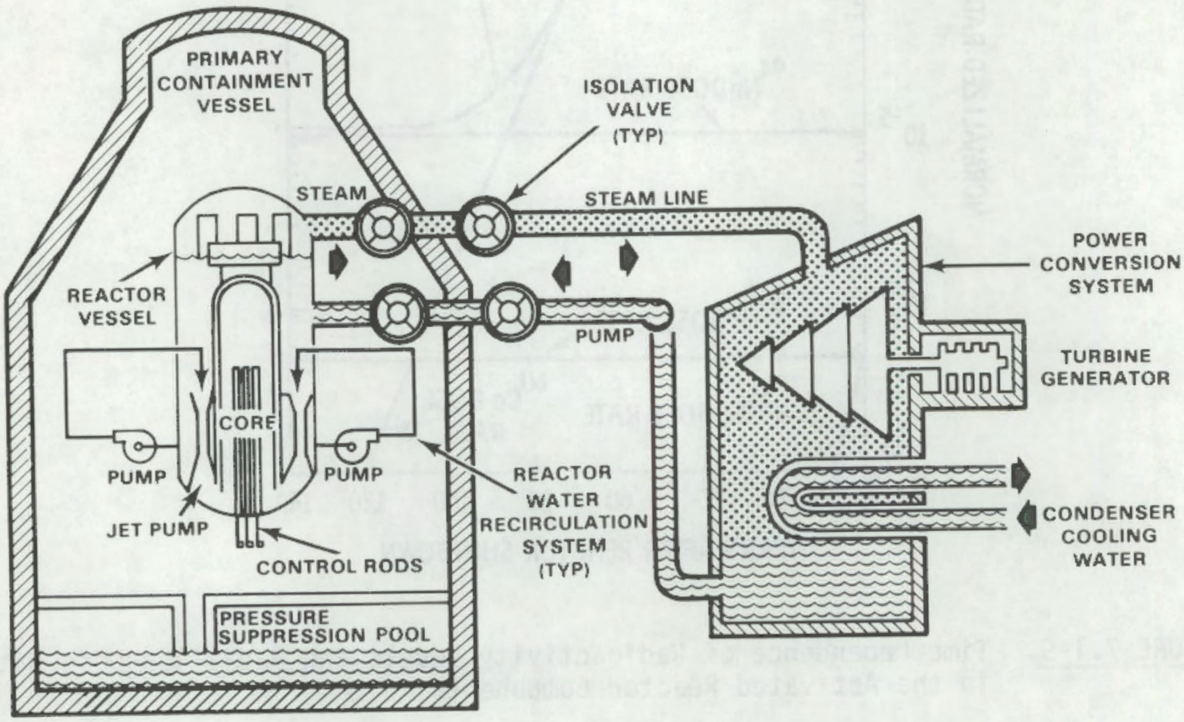


FIGURE 7.2-1. Boiling Water Reactor

7.2.1.1 Reactor Vessel and Internals

The reactor vessel is a right circular cylinder with a permanently attached hemispherical bottom and a removable hemispherical top, as illustrated in Figure 7.2-2. The vessel is made of carbon steel about 0.171 m thick, with the inside clad with stainless steel about 3 mm thick. The approximate dimensions of the vessel are 22.2 m in height and 6.7 m in outer diameter. The mass of the vessel is nearly 750 Mg empty.

The major reactor internal components are the core (fuel, flow channels, control rods, and instrumentation), the core support structure (including the core shroud, top fuel guide, and core support plate), the shroud head and steam separator assembly, the steam dryer assembly, the jet pumps, the feedwater spargers, and the core spray lines.

7.2.1.2 Reactor Water Recirculation System

The reactor water recirculation system, shown in Figure 7.2-3, has two loops external to the reactor vessel but inside the primary containment vessel. Each loop contains a pump, two motor-operated isolation valves, and one hydraulically operated flow-control valve. Each loop supplies reactor water to 10 jet pumps located inside the reactor vessel in the annular region between the core shroud and the vessel wall (refer to Figure 7.2-2).

7.2.1.3 Power Conversion System

The power conversion system converts the usable energy from the steam produced in the reactor vessel to electricity, condenses the steam, and heats the condensate and pumps it back to the reactor as feedwater. The system, shown in Figure 7.2-4, consists of a large steam turbine and generator, moisture separator-reheaters, a single-pass condenser, motor-driven condensate and condensate booster pumps, a full-flow condensate demineralizer system, turbine-driven feedwater pumps, and six stages of feedwater heating.

7.2.2 General Plant Arrangement

The arrangement of the structures on the reference BWR plant site is illustrated in Figure 7.2-5. The structures of primary interest during decommissioning are the Reactor Building, the Turbine Generator Building, and the

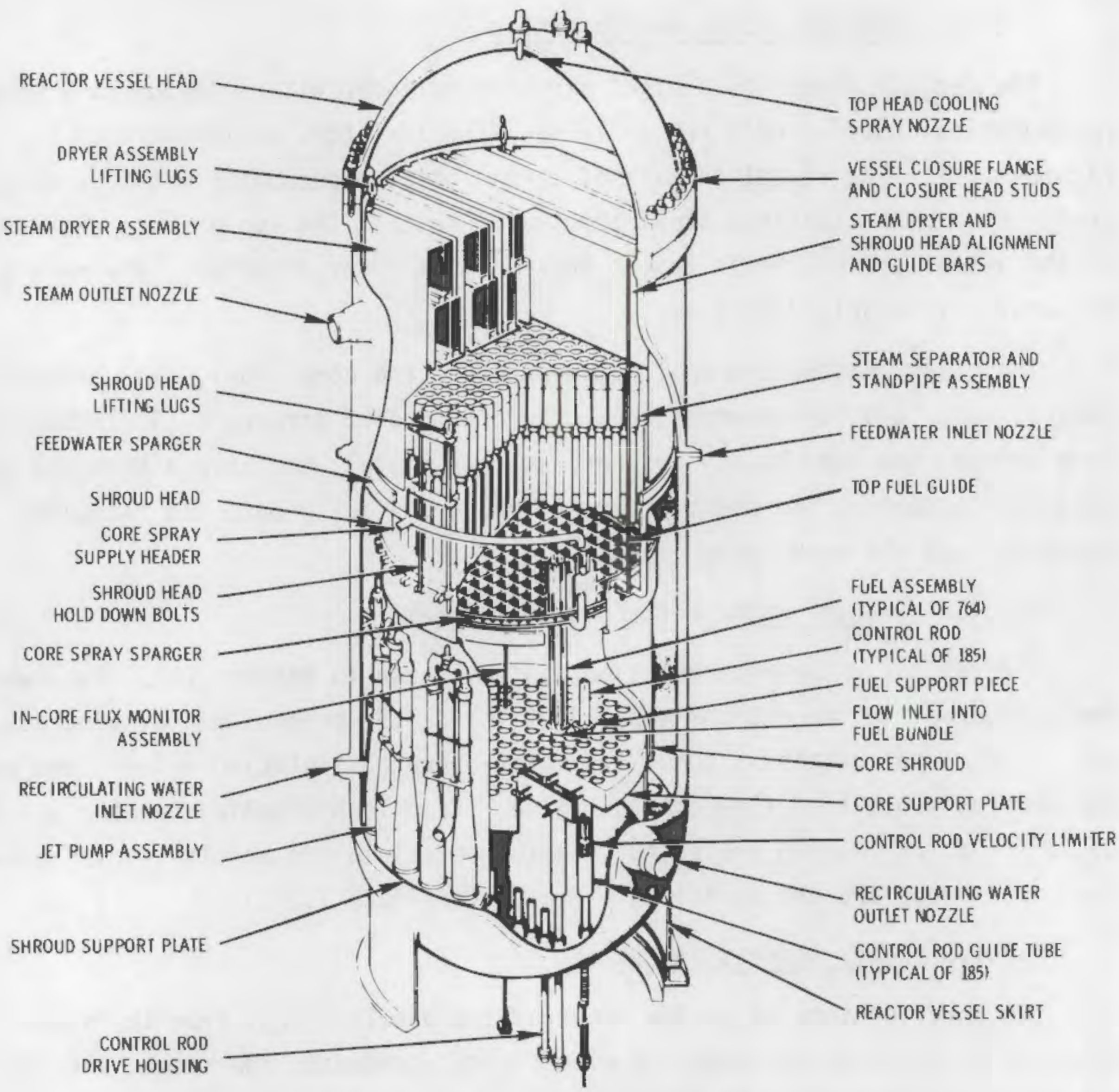


FIGURE 7.2-2. Reactor Vessel and Internals

Radwaste and Control Building. These buildings contain radioactive materials that require special handling during decommissioning. The other structures, if removed, are conventionally demolished.

The buildings in the main complex are in close proximity to each other but are physically separate from one another both above and below grade.

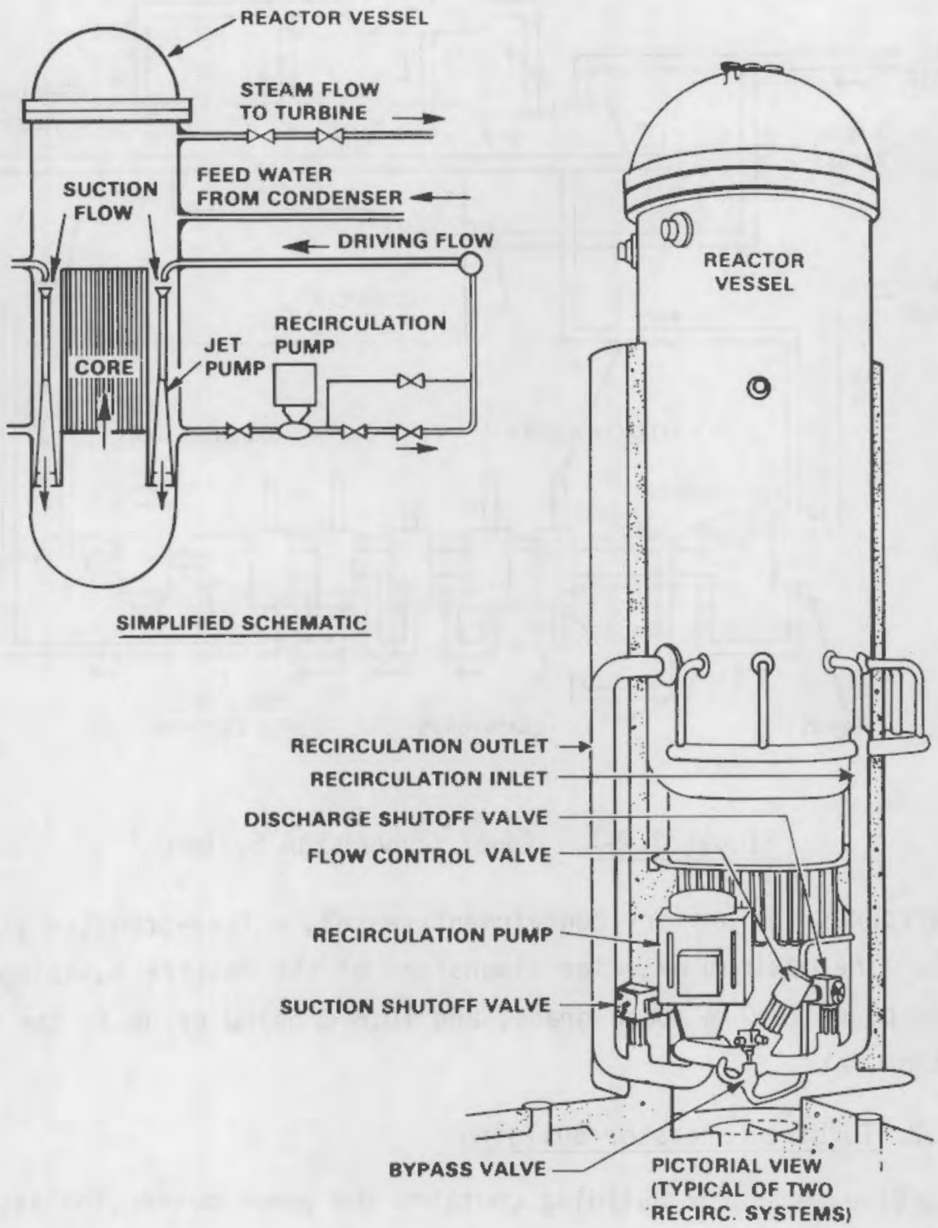


FIGURE 7.2-3. Reactor Water Recirculation System

7.2.2.1 Reactor Building

The Reactor Building, containing the nuclear steam supply system and its auxiliaries, is constructed of reinforced concrete capped by metal siding and roofing supported by structural steel. As shown in Figure 7.2-6, the

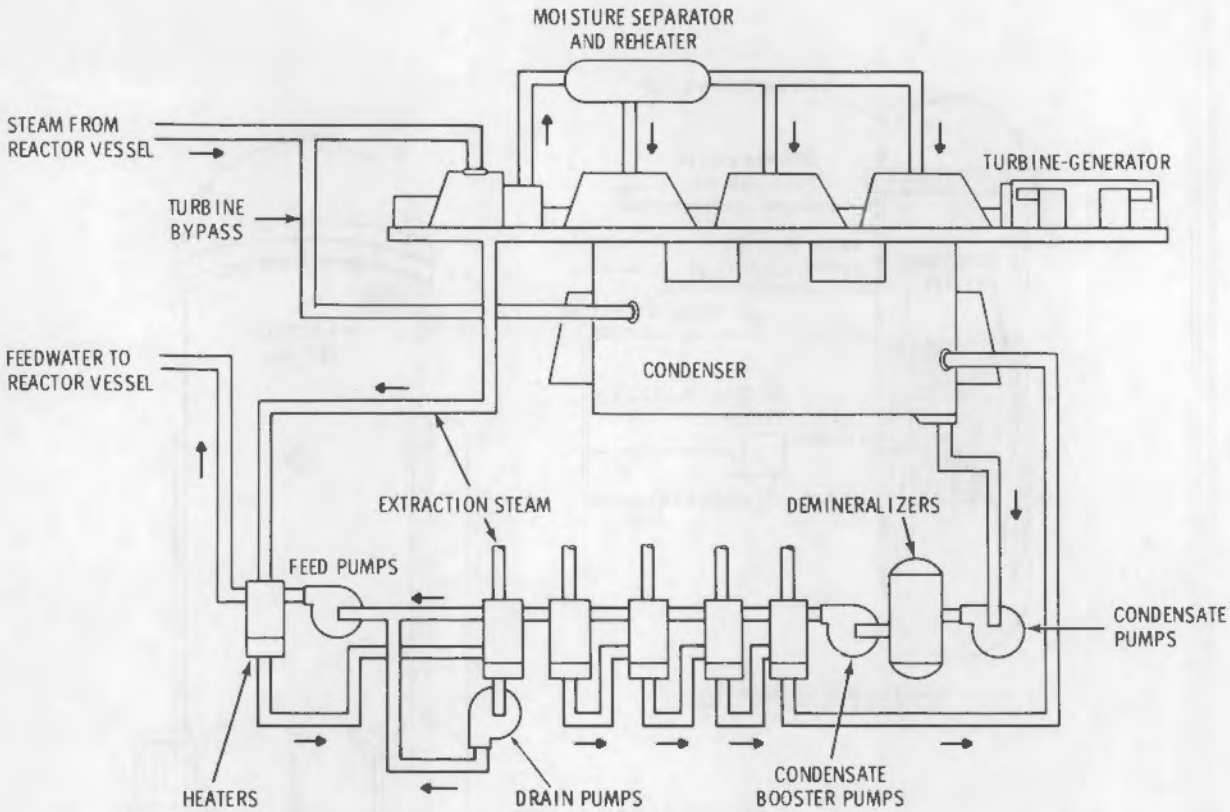


FIGURE 7.2-4. Power Conversion System

building surrounds the primary containment vessel, a free-standing steel pressure vessel. The maximum exterior dimensions of the Reactor Building are 41.9 m by 52.9 m in plan, 70.1 m above grade, and 10.6 m below grade to the bottom of the foundation mat.

7.2.2.2 Turbine Generator Building

The Turbine Generator Building contains the power conversion system equipment and auxiliaries. It is constructed of reinforced concrete capped by steel-supported metal siding and roofing, and is approximately 58.8 m by 91.4 m in plan and 42.5 m high. There are two floors above the ground floor. Two steel tanks for condensate storage are located within a reinforced concrete dike just outside the building.

7.2.2.3 Radwaste and Control Building

The Radwaste and Control Building houses, among other systems, the condenser off gas treatment system, the radioactive liquid and solid waste systems,

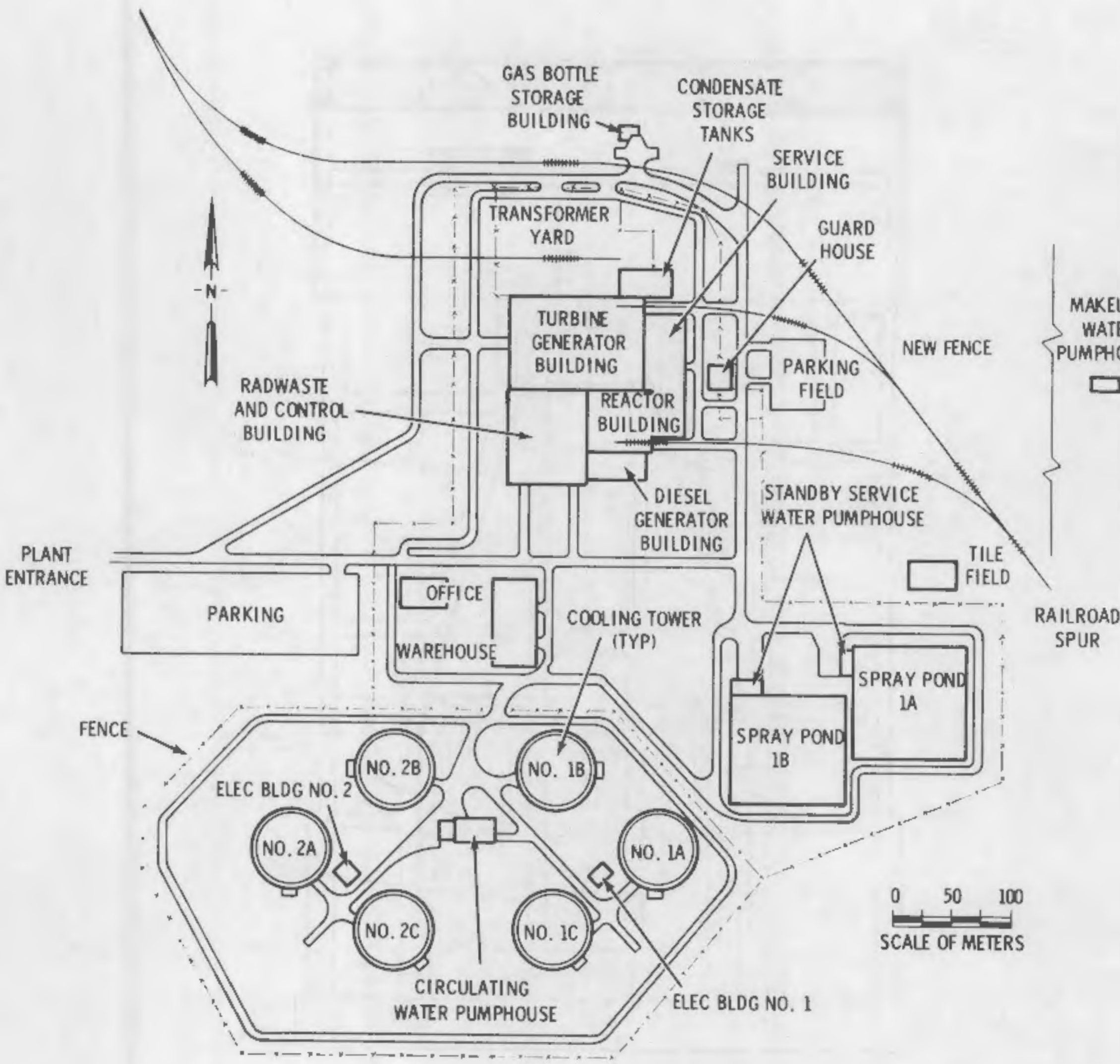


FIGURE 7.2-5. Site Layout of the Reference BWR Power Plant

the condensate demineralizer system, the reactor water cleanup demineralizer system, and the fuel pool cooling and cleanup demineralizer system. The building is constructed of reinforced concrete and metal-sided and -roofed structural steel, with two full floors and one partial floor above the ground floor. It is approximately 63.7 m by 48.8 m in plan and 32 m in overall height.

7.2.2.4 Other Structures

The remaining buildings of the reference BWR site complex, which, in this study, are assumed to be uncontaminated with radioactive material, are the Diesel Generator Building, the Service Building, the Cooling Tower Complex, the Spray

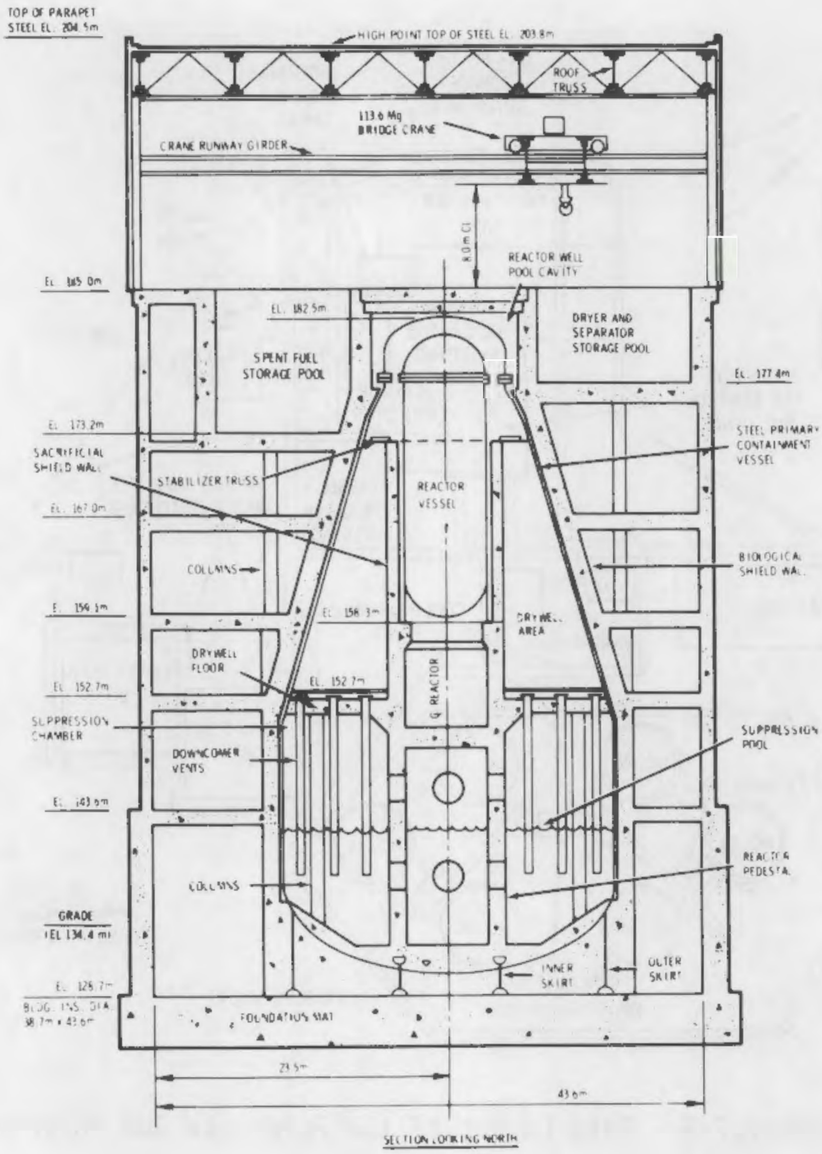


FIGURE 7.2-6. BWR Reactor Building

Pond Complex, the Makeup Water Pumphouse, the Office Building, the Warehouse, the Guardhouse, and the Gas Bottle Storage Building.

7.2.3 Radionuclide Inventories

The radionuclide inventories at the time of final reactor shutdown (excluding the irradiated spent fuel) are of two types: 1) neutron-activated components in and surrounding the reactor core and 2) surface contamination from fission products and activated corrosion products deposited inside certain piping and equipment systems, on some structural surfaces, and on the site. Details of the calculational methods used for estimating the radionuclide inventories at the reference BWR are presented in the BWR decommissioning study.[2]

7.2.3.1 Neutron-Activated Components

Radioactive material is produced in the structural components in and around the reactor vessel because of interactions with neutrons produced in the reactor fuel during operation. Three basic types of materials are used in and around the reactor vessel: stainless steel (Type 304), carbon steel (Type SA533), and reinforced concrete. This subsection contains summaries of the radionuclide inventories for, the total radioactivity in, and selected dose rates for the neutron-activated components.

Radionuclide Inventories in Neutron-Activated Materials. The radionuclide inventories calculated for the neutron-activated materials at final reactor shutdown are presented in Table 7.2-1. These inventories are calculated using the thermal neutron flux distribution at the axial midplane of the fuel zone for 30 EFPY of operation. They are designed to represent maximum values of the neutron-induced radioactivity present in the reference BWR at final shutdown. Thus, the radioactivity concentrations listed in Table 7.2-1 are the maximum concentrations used in this study.

Total Radioactivity in Neutron-Activated Components. The total radioactivity in neutron-activated components is summarized in Table 7.2-2. Radioactivity totals in the reactor vessel and its internal components range from about 0.5 Ci in a single control rod guide tube to about 6.3 million Ci in the core shroud. The sacrificial shield is calculated to contain about 166 Ci, and the total radionuclide inventory in all neutron-activated components of the reference BWR is about 6.6 million Ci. The activated portion of the core shroud contains about 96% of the total radioactivity in the neutron-activated components.

TABLE 7.2-1. Radionuclide Inventory in Neutron-Activated BWR Components

Radionuclide	Stainless Steel[(a)] Radioactivity Concentration at Shutdown (Ci/m^3)	Stainless Steel[(a)] Fractional Radioactivity at Shutdown	Carbon Steel[(b)] Radioactivity Concentration at Shutdown (Ci/m^3)	Carbon Steel[(b)] Fractional Radioactivity at Shutdown	Concrete[(c)] Radioactivity Concentration at Shutdown (Ci/m^3)	Concrete[(c)] Fractional Radioactivity at Shutdown
^{3}H	4.65×10^{-4}	1.63×10^{-10}	(d)	(d)	2.58×10^{-6}	6.72×10^{-7}
^{10}Be	2.63×10^{-6}	--(e)			(d)	(d)
^{14}C	1.05×10^{2}	3.68×10^{-5}	6.77×10^{-3}	1.84×10^{-5}	1.36×10^{-4}	3.54×10^{-5}
^{32}P	1.11×10^{2}	3.89×10^{-5}	9.20×10^{-1}	2.51×10^{-3}	4.35×10^{-2}	1.13×10^{-2}
^{33}P	6.65×10^{2}	2.33×10^{-4}				
^{35}S	5.52×10^{1}	1.94×10^{-5}	1.76×10^{-2}	4.80×10^{-5}	3.25×10^{-3}	8.46×10^{-4}
^{36}Cl	2.69×10^{-4}	--(e)			1.21×10^{-6}	3.15×10^{-7}
^{37}Ar	(d)	(d)			3.08×10^{-2}	8.02×10^{-3}
^{39}Ar					5.69×10^{-3}	1.48×10^{-3}
^{40}K					3.67×10^{-5}	9.55×10^{-6}
^{41}Ca					7.90×10^{-4}	2.06×10^{-4}
^{45}Ca					3.91×10^{-1}	1.02×10^{-1}
^{46}Sc					2.10×10^{-6}	5.47×10^{-7}
^{51}Cr	1.45×10^{6}	5.09×10^{-1}	1.75×10^{0}	4.77×10^{-3}	1.11×10^{-2}(f)	2.89×10^{-3}
^{54}Mn	8.50×10^{3}	2.98×10^{-3}	1.06×10^{1}	2.89×10^{-2}	9.60×10^{-3}(f)	2.50×10^{-3}
^{55}Fe	9.22×10^{5}	3.24×10^{-1}	3.35×10^{2}	9.13×10^{-1}	3.15×10^{0}(f)	8.20×10^{-1}
^{59}Fe	2.74×10^{4}	9.61×10^{-3}	9.44×10^{0}	2.57×10^{-2}	1.01×10^{-1}(f)	2.63×10^{-2}
^{58}Co	2.10×10^{4}	7.37×10^{-3}	1.49×10^{0}	4.06×10^{-3}	3.00×10^{-3}(f)	7.81×10^{-4}
^{60}Co	3.36×10^{5}	1.18×10^{-1}	6.49×10^{0}	1.77×10^{-2}	6.45×10^{-2}(f)	1.68×10^{-2}
^{59}Ni	6.36×10^{2}	2.23×10^{-4}	1.46×10^{-2}	3.98×10^{-5}	1.24×10^{-4}	3.23×10^{-5}
^{63}Ni	8.75×10^{4}	3.07×10^{-2}	1.73×10^{0}	4.71×10^{-3}	1.47×10^{-2}(f)	3.83×10^{-3}
^{65}Zn	3.23×10^{1}	1.13×10^{-5}	1.88×10^{-6}	5.12×10^{-9}		
^{93}Zr	8.15×10^{-6}	--(e)				
^{95}Zr	1.41×10^{-2}	4.21×10^{-5}	1.62×10^{-4}	4.41×10^{-7}		
^{93m}Nb	1.35×10^{-1}	4.74×10^{-8}	3.90×10^{-4}	1.06×10^{-6}	3.05×10^{-6}	7.94×10^{-6}
^{94}Nb	1.50×10^{0}	5.26×10^{-7}	8.30×10^{-7}	2.26×10^{-9}		
^{95}Nb	1.20×10^{2}	4.21×10^{-5}	3.76×10^{-4}	1.02×10^{-6}		
^{93}Mo	3.26×10^{-1}	1.14×10^{-7}	9.39×10^{-4}	2.56×10^{-6}	7.36×10^{-6}	1.92×10^{-6}
^{99}Tc	3.18×10^{-2}	1.12×10^{-8}	2.64×10^{-4}	7.19×10^{-7}	4.08×10^{-6}	1.06×10^{-6}
^{108m}Ag	7.36×10^{-2}	2.58×10^{-8}			9.73×10^{-8}	2.53×10^{-8}
^{108}Ag	8.67×10^{1}	3.04×10^{-5}			1.24×10^{-4}	3.23×10^{-5}
^{109m}Ag	3.51×10^{0}	1.27×10^{-6}			2.56×10^{-10}	--(e)
^{109}Cd	3.42×10^{0}	1.20×10^{-6}			2.17×10^{-10}	--(e)
^{110m}Ag	8.04×10^{0}	2.82×10^{-6}			6.83×10^{-5}	1.78×10^{-5}
^{110}Ag	2.02×10^{2}	7.09×10^{-5}			1.74×10^{-3}	4.53×10^{-4}
^{151}Sm	2.12×10^{-2}	7.44×10^{-9}			1.30×10^{-3}	3.39×10^{-4}
^{152}Eu	1.12×10^{-3}	3.93×10^{-10}			1.00×10^{-2}	2.60×10^{-3}
^{154}Eu	3.12×10^{0}	1.09×10^{-6}			1.31×10^{-3}	3.41×10^{-4}
^{160}Tb	9.48×10^{-4}	3.33×10^{-10}				
^{166m}Ho	7.84×10^{-4}	2.75×10^{-10}			3.91×10^{-6}	1.02×10^{-6}
Totals	2.85×10^{5}	1.00	3.67×10^{2}	1.00	3.84×10^{0}	1.00

(a) Calculated at the inner surface of the 304 stainless steel core shroud, at the axial midplane of the fuel zone, for 30 EFPY of operation. From Table 7.4-1, Reference 2.
(b) Calculated at the inner surface of the SA533 carbon steel reactor vessel, at the axial midplane of the fuel zone, for 30 EFPY of operation. From Table 7.4-2, Reference 2.
(c) Calculated at the inner surface of the concrete portion of the sacrificial shield, at the axial midplane of the fuel zone, for 30 EFPY of operation. From Table 7.4-3, Reference 2.
(d) A blank indicates that the radionuclide is not present.
(e) Indicates a value of less than 1.00×10^{-10}.
(f) Due largely to structural steel in the sacrificial shield.

TABLE 7.2-2. Estimated Total Radioactivity in Neutron-Activated Components[(a)]

Component (quantity)	Estimated Activated Volume (m^3)	Radioactivity per Component (Ci)	Estimated Total Radioactivity (Ci)
Core Shroud (1)	3.75	6.30×10^6	6.30×10^6
Jet Pump Assembly (10)	0.076	2.00×10^3	2.00×10^4
Reactor Vessel (1)			
Cladding	0.428	4.58×10^2	2.16×10^3
Shell Wall	15.26	1.70×10^3	
Sacrificial Shield (1)			
Inner Shell	2.19	1.03×10^2	
Reinforced Concrete Region	73.30	3.47×10^0	1.60×10^2
Outer Shell	6.22	5.39×10^1	
Steam Separator Assembly (1)			
Shroud Head Plate	0.841	8.65×10^3	9.60×10^3
Steam Separator Risers	0.376	9.52×10^2	
Top Fuel Guide (1)	0.310	3.01×10^4	3.01×10^4
Orificed Fuel Support (193)	0.0036	3.63×10^0	7.01×10^2
Core Support Plate (1)	2.54	6.50×10^2	6.50×10^2
Incore Instrument Strings (55)	0.00026	1.99×10^2	1.10×10^4
Control Rod (185)	0.0019	9.61×10^2	1.78×10^5
Control Rod Guide Tube (185)	0.0024	5.12×10^{-1}	9.47×10^1
Total			6.55×10^6

(a) These data are summarized from Table E.1-6 in Appendix E of Reference 2.

7.2.3.2 Surface Contamination

Both activated corrosion products (from structural materials in contact with the reactor water) and fission products (from leaking fuel) contribute to the radionuclide mixtures and levels of surface contamination. This subsection contains summaries of the radionuclide inventories and depositions of both internal surface contamination in piping and equipment and external surface contamination inside the reference BWR and on the surrounding site.

Internal Surface Contamination. Specific alloys used in the structural components of the reactor coolant system play a major role in the composition of the internal surface contamination. The activated corrosion product ^{60}Co is dominant in a BWR because of the abundance of its parent in structural materials, its large-formation cross section, its energetic decay, and its relatively long decay half-life. Cobalt-58 is only a minor source of radiation in a BWR, while in a PWR it is a significant contributor to the shutdown radiation levels.[8] Depending on the type of condenser tubes and condensate polishing system used, ^{65}Zn could be an isotope of concern.

Mobile fission products from leaking reactor fuel also contribute to the internal surface contamination. Their concentrations are directly related to the number of leaking fuel elements in the reactor core and thus will change during plant operation. The composition of internal surface contamination assumed in this study is summarized in Table 7.2-3.

External Surface Contamination in the Reference BWR. The mixtures of radionuclides found on external structural surfaces in the reference BWR are calculated based on an accumulation of the radionuclides present in the reactor water on a surface over the 30 EFPY plant life.[6] The resulting mixture accounts for both continuous accumulation and radioactive decay. External surface radioactive contamination at shutdown is shown in Table 7.2-3.

External Surface Contamination on the Site. Radionuclides are assumed to be deposited on the reference site as a result of normal BWR operation over 30 EFPY of service. Accidental releases are not expected to significantly increase the radioactivity present on the reference site, and are not considered in this analysis. Annual airborne radionuclide releases from operating BWRs vary widely and are dependent on such plant factors as size, operating conditions, and gaseous radwaste systems. For this study, the airborne releases are based on releases reported from 23 operating BWRs for 1975.[5] Because fuel failures were higher during this period than at present, these values may produce an overestimate of normal releases expected over a plant's operating life. The radionuclide depositions on the reference BWR site at shutdown following normal BWR operation for 30 EFPY are listed in Table 7.2-3.

Surface Contamination Deposition in the Reference BWR. The estimated radioactivity depositions, both on internal piping and equipment surfaces and on external structural surfaces in the reference BWR, are summarized in Table 7.2-4. A total of 8.5×10^3 Ci is estimated to be present on internal piping and equipment surfaces and on external surfaces in the reference BWR.

TABLE 7.2-3. Radionuclide Inventory of BWR Surface Contamination

	Fractional Radioactivity at Shutdown		
Radionuclides	Internal Surface Contamination[(a)]	External Surface Contamination[(b)]	Site Surface Contamination[(c)]
^{32}P	(d)	1.1×10^{-3}	
^{51}Cr	2.1×10^{-2}	5.3×10^{-2}	2.9×10^{-5}
^{54}Mn	3.9×10^{-1}	7.2×10^{-4}	3.7×10^{-3}
^{55}Fe		3.7×10^{-1}	
^{59}Fe	2.5×10^{-2}	5.3×10^{-4}	1.8×10^{-5}
^{58}Co	9.3×10^{-3}	5.6×10^{-3}	3.2×10^{-4}
^{60}Co	4.7×10^{-1}	2.9×10^{-1}	5.0×10^{-2}
^{63}Ni		3.4×10^{-3}	
^{65}Zn	6.1×10^{-3}	1.8×10^{-2}	1.1×10^{-5}
^{89}Sr		2.0×10^{-3}	1.1×10^{-2}
^{90}Sr		1.5×10^{-2}	2.7×10^{-1}
^{90}Y		1.5×10^{-2}	2.7×10^{-1}
^{91}Y		8.1×10^{-4}	
^{95}Zr	4.0×10^{-3}	1.6×10^{-4}	6.9×10^{-5}
^{95}Nb	4.0×10^{-3}	1.6×10^{-4}	6.9×10^{-5}
^{103}Ru	2.3×10^{-3}	2.9×10^{-4}	
^{106}Ru	2.8×10^{-3}	3.9×10^{-4}	7.2×10^{-4}
^{110m}Ag		8.8×10^{-6}	4.0×10^{-5}
^{124}Sb			2.9×10^{-7}
^{125}Sb			3.0×10^{-6}
^{129m}Te		4.9×10^{-4}	
^{131}I		1.5×10^{-2}	4.8×10^{-4}
^{134}Cs	1.9×10^{-2}	8.8×10^{-3}	2.3×10^{-2}
^{136}Cs		1.0×10^{-4}	2.0×10^{-6}
^{137}Cs	3.4×10^{-2}	1.8×10^{-1}	3.7×10^{-1}
^{140}Ba		2.0×10^{-3}	3.2×10^{-3}
^{140}La		2.0×10^{-3}	3.2×10^{-3}
^{141}Ce	3.0×10^{-3}	2.9×10^{-4}	8.0×10^{-5}
^{144}Ce	8.1×10^{-3}	2.9×10^{-4}	2.3×10^{-4}
^{143}Pr		2.0×10^{-4}	
^{147}Nd		1.2×10^{-5}	
Totals	1.0	1.0	1.0

(a) Based on a BWR sludge sample analysis given in EPRI 404-2.[(6)] From Table 7.4-6, Reference 2.
(b) From Table 7.4-7, Reference 2.
(c) From Table 7.4-8, Reference 2.
(d) A blank indicates that the radionuclide is not present.

TABLE 7.2-4. Summary of Surface Contamination in the Reference BWR[a]

Category / Building	Estimated Total Surface Area (m^2)	Deposited Radioactivity (Ci)
Internal Surfaces		
Piping	3.4×10^4	2.2×10^3
Equipment		
Reactor Building	8.6×10^3	1.9×10^3
Turbine Generator Building	2.0×10^5	1.2×10^3
Radwaste and Control Building	1.4×10^3	3.2×10^3
Subtotal, Internal Surfaces		8.5×10^3
External Surfaces		
Reactor Building	5.2×10^3	7.4×10^1
Turbine Generator Building	1.9×10^3	4.4×10^0
Radwaste and Control Building	2.0×10^3	3.6×10^1
Subtotal, External Surfaces		1.1×10^2
Total		8.6×10^3

(a) From Table 7.4-10, Reference 2.

7.2.4 Radiation Dose Rate Data

The radiation dose rate in any specific area affects the planning of decommissioning work with respect to temporary shielding, work sequences, decontamination, and radiation exposure. Once these factors have been studied to determine the most efficient work sequence, it is possible to estimate the radiation exposure time and the resultant occupational dose for each task.

The degree to which concrete surfaces are contaminated determines how much surface requires removal and how much contaminated concrete rubble requires disposal.

This subsection presents summaries of data concerning radiation dose rates and concrete surface contamination for the reference BWR at final shutdown.

7.2.4.1 Estimated Radiation Dose Rates at Shutdown

Measured shutdown radiation dose rate data were obtained from seven operational BWRs, Dresden Units 2 and 3 and Quad Cities Units 1 and 2 operated by Commonwealth Edison Company, Peachbottom Units 2 and 3 operated by Philadelphia Electric Company, and Monticello operated by Northern States Power Company. At the time of measurements, the reactors had operated commercially for from 3 to 8 years. Composites created from these data are used as radiation dose rates in the reference BWR at final shutdown. Typical samples of the composite radiation dose rates are shown in Table 7.2-5. Detailed lists of these radiation dose rates are contained in Figures D.1-1 through D.1-7 in Appendix D of Reference 2.

7.2.4.2 Estimated Concrete Surface Contamination Levels at Shutdown

Measured concrete surface contamination level data were obtained from the same four operational BWR sites as were the dose rate data. Typical samples of composites of these data are listed in Table 7.2-6. More detailed lists of measured concrete surface contamination data are provided in Figures D.2-1 through D.2-7 in Appendix D of Reference 2.

7.2.4.3 Contaminated Concrete Rubble Volumes Removed During DECON

The volumes of contaminated concrete rubble estimated removed during DECON of the reference BWR are summarized in Table 7.2-7 for the Reactor Building (outside Primary Containment), the Primary Containment, the Turbine Generator Building, and the Radwaste and Control Building. The maximum measured contamination level in each location is also displayed.

TABLE 7.2-5. Estimated Radiation Dose Rates in the Reference BWR at Shutdown[a]

Location	Type of Measurement[b]	Measured Dose Rate (R/hr)
Reactor Bldg., Elev. 128.7 m through 152.7 m		
Low-Pressure Core Spray Pump	Contact	.005 - .015
High-Pressure Core Spray Pump	Contact	.002 - .008
Residual Heat Removal Pump	General Area	.020 - .050
Reactor Water Recirculation Pump	Contact	.100 - .370
Drywell Equipment Hatch	General Area	.100
Main Steam Tunnel	General Area	.090 - .210
Reactor Bldg., Elev. 159.1 m through 185.0 m		
Reactor Vessel (near the feedwater nozzles)	Contact	.700 - 3.0
Reactor Water Cleanup Pumps	Contact	.100 - 12.0
Residual Heat Removal Heat Exchanger Piping	Contact	.800
Regenerative Heat Exchanger	Contact	.300 - 10.0
Regenerative Heat Exchanger	General Area	.020 - .750
Reactor Well Pool Cavity	Contact	.015 - .060
Turbine Generator Bldg., Elev. 134.4 m (grade)		
Main Condenser	Contact	.002
Steam Jet Air Ejector Condenser	Contact	.002 - .030
Condensate Storage Tanks	General Area	.001
Turbine Generator Bldg., Elev. 143.6 m		
Turbine	General Area	.001 - .002
High-Pressure Feedwater Heaters and Piping	Contact	.002 - .025
Moisture Separator Drain Tank	General Area	.002
Turbine Generator Bldg., Elev. 152.7 m		
Main Steam and Feedwater Pipe Chase	General Area	.002
Low-Pressure Feedwater Heaters	Contact	.002 - .015
Moisture Separator Reheater	General Area	.002
Radwaste and Control Bldg., Elev. 133.2 m through 142.3 m		
Floor Drain Collector Tank	Contact	.150 - 5.000
Floor Drain Collector Tank	General Area	.050 - 1.600
Spent Resin Tank	General Area	.005 - .150
Waste Sludge Phase Separator Tank	General Area	.005 - .450
Decontamination Solution Concentrator Waste Tank	General Area	.500 - .620
Radwaste Centrifuge Room	General Area	.010 - .060
Radwaste and Control Bldg., Elev. 148.4 m through 160.0 m		
Waste Demineralizer Pumps	Contact	.016 - .040
Waste Demineralizer Piping	Contact	.020 - 6.000
Decontamination Solution Concentrator	Contact	.200 - .300

(a) From Table 7.3-1, Reference 2.
(b) General Area refers to the radiation field in a room or area, not specifically from one discrete source or direction, although a specific source may be the sole contributor to the radiation measurement.
Contact means the closest approach to a surface (a surface dose rate) including the necessary geometry and source size corrections done in the field by the health physicist.

TABLE 7.2-6. Typical Measured Concrete Surface Contamination Levels in the Reference BWR at Shutdown[(a)]

Location	Measured Contamination Level[(b)] (cpm/100 cm^2)
Reactor Bldg., Elev. 128.7 m through 152.7 m	
Suppression Chamber	0.3-2.5k[(c)]
Reactor Water Recirculation Pump Area (Drywell Floor)	2-2000k
Drywell Personnel Lock Room	0.2-30k
Drywell Equipment Hatch Room	0.4-2k
Main Steam Tunnel	0.1-12.5k
CRD Repair Room, Elev. 152.7 m	0.6-35k
Reactor Bldg., Elev. 159.1 m through 185.0 m	
Control Rod Drive Module Areas	0.2-20k
Reactor Water Cleanup Pump Rooms	1->500k
Reactor Water Cleanup Regenerative and Non-Regenerative HX Room	Floor - 7-77k Walls - 4-8k
Turbine Generator Bldg., Elev. 134.4 (grade)	
Main Condenser Area	0.2-2.5k
Reactor Feedwater Pump Rooms	0.5-9
Catalytic Recombiner Room	0.2-20k
Turbine Generator Bldg., Elev. 143.6 m	
High-Pressure Feedwater Heater Area	0.2 k
Low-Pressure Feedwater Heater Area	0.2-2.1k
Turbine By-Pass Valve Assembly Area	30-100k
Turbine Generator Bldg., Elev. 152.7 m	
Turbine Area	0.1-0.4k
Moisture Separator Reheater Area	0.1-1.0k
Radwaste and Control Bldg., Elev. 133.2 m through 142.3 m	
Condensate Phase Separator Tank Area	4-250k
Solid Radwaste Storage Area	0.5-150k
Solid Radwaste Hopper Mixer Room	0.6-90k
Equipment Removal Plugs and Filter Demineralizer Removal Room (Elev. 154.5 m)	0.2-6.2k
Concentrator Waste Measuring Tank Room	80k
Cleanup Hold Pump Areas, Valve and Pump Rooms	2.8-10k
Fuel Pool Hold Pump Rooms	2.5-200k
Hot Machine Shop (Elev. 148.4 m)	<0.1k

(a) From Table 7.3-2, Reference 2.
(b) Composite of measurements taken during maintenance outages at operating BWRs.
(c) 0.3-2.5k stands for 300 to 2,500 cpm/100 cm^2 (typical).

TABLE 7.2-7. Contaminated Concrete Rubble Volumes Removed During DECON of the Reference BWR[a]

Building[b]	Maximum Measured Contamination Levels[c] ($cpm/100\ cm^2$)	Estimated Total Rubble Volumes[d] (m^3)
Reactor Building[e]	>500k[f]	204.5
Primary Containment	2 000k	155.8
Turbine Generator Building	100k	105.8
Radwaste and Control Building	300k	203.4
Total Rubble Volume		699.5

(a) From Table 7.3-3, Reference 2.
(b) Other buildings and facilities on the reference BWR site are assumed to have no contamination.
(c) Measurements taken during maintenance outages at operating BWRs.
(d) Based on a contamination thickness of 0.051 m.
(e) Includes all areas of the Reactor Building except inside Primary Containment.
(f) 500k stands for 500,000 $cpm/100\ cm^2$ (typical).

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8.0 IMPACT OF MULTIPLE REACTORS ON DECOMMISSIONING COST

In this section the impact of having more than one reactor at a nuclear power station on the cost of decommissioning one of those reactors is developed by comparison with costs previously estimated for decommissioning reactors at power stations with only one reactor. Factors examined in this analysis include several different approaches to disposal of nuclear waste, the dedication of the site to nuclear power generation, the availability of centralized services, and the type and number of reactors present at the station.

The changes in the estimated decommissioning costs for DECON, SAFSTOR, and ENTOMB, relative to the base case single-reactor studies for the factors given above, are summarized in Table 8.0-1.[a] This information forms the basis for evaluating the decommissioning costs for the five different scenarios developed in Section 10.

TABLE 8.0-1. Summary of Decommissioning Cost Differences

Factor	Cost Differences ($ thousands)					
	DECON		SAFSTOR(a)		ENTOMB	
	PWR	BWR	PWR	BWR	PWR	BWR
Waste Disposal						
Onsite Interim Storage For:						
30 Years	+1640	+410	-2005	-2984	-949	-908
50 Years	-1770	-3100	-2080	-3611	-1395	-2502
100 Years	-1780	-3160	-2105	-3656	-1407	-2562
Onsite Disposal	-2969	-4485	-3098	-4341	-2077	-3548
Central Services						
Radiation Monitoring	-462	-618	-718	-1054	-462	-654
Security	-459	-522	-808	-1066	-459	-605
Solid Waste Processing	-133	-221	-144	-253	-133	-221
Equipment Decontamination	-1138	-1402	-1141	-1437	-1138	-1402

(a) For deferred decontamination after 30 years of safe storage.

(a) All costs in this study are estimated in 1978 dollars.

8.1 DISPOSAL OF NUCLEAR WASTE

Several options for disposal of the nuclear waste generated by decommissioning a reactor at a multiple-reactor station are:

- burial offsite at a licensed disposal facility
- interim onsite storage with transfer to an offsite licensed disposal facility at a later date
- burial onsite at a permanent nuclear waste disposal facility.

The impact of each of these options on the cost of disposal of nuclear waste from reactor decommissioning is discussed in the following subsections.

8.1.1 Offsite Nuclear Waste Disposal

In the studies of decommissioning a reference PWR[1] and a reference BWR[2] the nuclear waste was assumed to be sent offsite to a licensed nuclear waste facility. Decommissioning a single reactor at a multiple-reactor station will result in the same nuclear waste quantity, packaging cost, transportation cost, and disposal-site handling and burial charges as will decommissioning an identical reactor at a single-reactor station. Therefore, the cost for disposal of the nuclear waste from decommissioning a single reactor at a licensed disposal facility offsite is the same whether the reactor is alone on the site or is one of a number of reactors at a multiple-reactor station.

8.1.2 Onsite Interim Nuclear Waste Storage

At a site where several nuclear reactors are located there is a good chance that the site will be large enough to accommodate an onsite interim nuclear waste storage facility. Storing onsite the nuclear decommissioning waste for a period of 30 to 100 years before transferring the waste to a permanent offsite disposal facility could result in cost savings, as discussed below.

Interim onsite storage of nuclear waste with later permanent disposal offsite involves the following tasks:

- packaging
- transporting to interim onsite storage
- placing in interim storage

- retrieving from interim storage
- transporting to a permanent disposal facility
- placing in a permanent disposal facility.

Several assumptions made in estimating the impact of interim onsite storage of nuclear waste are:

1. The quantity of nuclear waste placed in onsite interim waste storage is the same as would be sent immediately to an offsite waste disposal facility.

2. The packaging used for disposal of radioactive material is able to withstand interim storage, retrieval from storage, and relocation to an offsite permanent disposal facility without requiring repackaging.

3. Since transport to interim onsite waste storage is over private roads within a privately owned and controlled area, it is not necessary to meet the DOT surface radiation dose rate requirement. Shielding is provided for the truck cab to limit the dose rate to 2 mR/hr. The radiation dose of workers is controlled to assure that it does not exceed the 10 CFR 20 limits. This assumption should result in fewer cask loads and the use of fewer shielded cask liners.

4. The cost of placing and maintaining nuclear waste in interim storage is equal to the disposal charge at a licensed waste disposal site ($93.57/m^3$).[a]

5. There are no liner or curie surcharges at the onsite storage facility.

6. The cost of retrieving the waste from interim storage is the same as the disposal charge at a licensed waste disposal site ($93.57/m^3$).[a]

7. After interim storage for 30 to 100 years some of the contaminated material will have decayed to levels permitting unrestricted release. Therefore, the quantity of nuclear waste that eventually must be sent to offsite disposal will decrease with increasing storage time.

(a) It is estimated that these placement and retrieval charges are greater than the cost of construction, operation, depreciation, and decommissioning of the interim waste storage facility.

8. The liner and curie surcharges at the commercial waste disposal facility are lower after interim onsite storage because of the radioactive decay that has occurred.

9. For neutron-activated material the radioactive decay during interim storage of even 100 years is insufficient to permit unrestricted release of the material. Therefore, all of the neutron-activated material must be relocated to a licensed nuclear waste disposal facility after interim onsite storage.

10. All costs are expressed in 1978 dollars.

An onsite interim nuclear waste storage facility would be designed to remotely place the containers of waste in storage cells and remotely remove the containers at the end of the storage period. Design features and operating practices would minimize the radiation exposure of the workers. Since the nuclear waste could be in interim storage for as long as 100 years, the facilities would have to be designed for long life and require a minimum of maintenance.

The concept for the onsite interim nuclear waste storage facility is shown schematically in Figure 8.1-1. Basically, the facility consists of a row of concrete cells, 10 m square by 7 m deep, with concrete cover blocks that are thick enough to provide the necessary radiation shielding. A mobile gantry crane enclosed in a lightweight sheet-metal building is used to place the radioactive waste in and retrieve the waste from the cells. Both the bridge crane and the building are mounted on a chassis, 13 m wide by 16 m long, with a tracked carriage at each corner. The enclosure is provided primarily for weather protection, since the external surfaces of the waste containers will be free of smearable contamination when they are placed in the storage cells. A trap door in the roof of the crane building permits movement of containers and casks into and out of the structure.

The nuclear waste from decommissioning an LWR by DECON will fill about 30 of the cells. For a multiple-reactor station with 10 reactors, 300 cells will be needed for interim storage of the decommissioning waste.

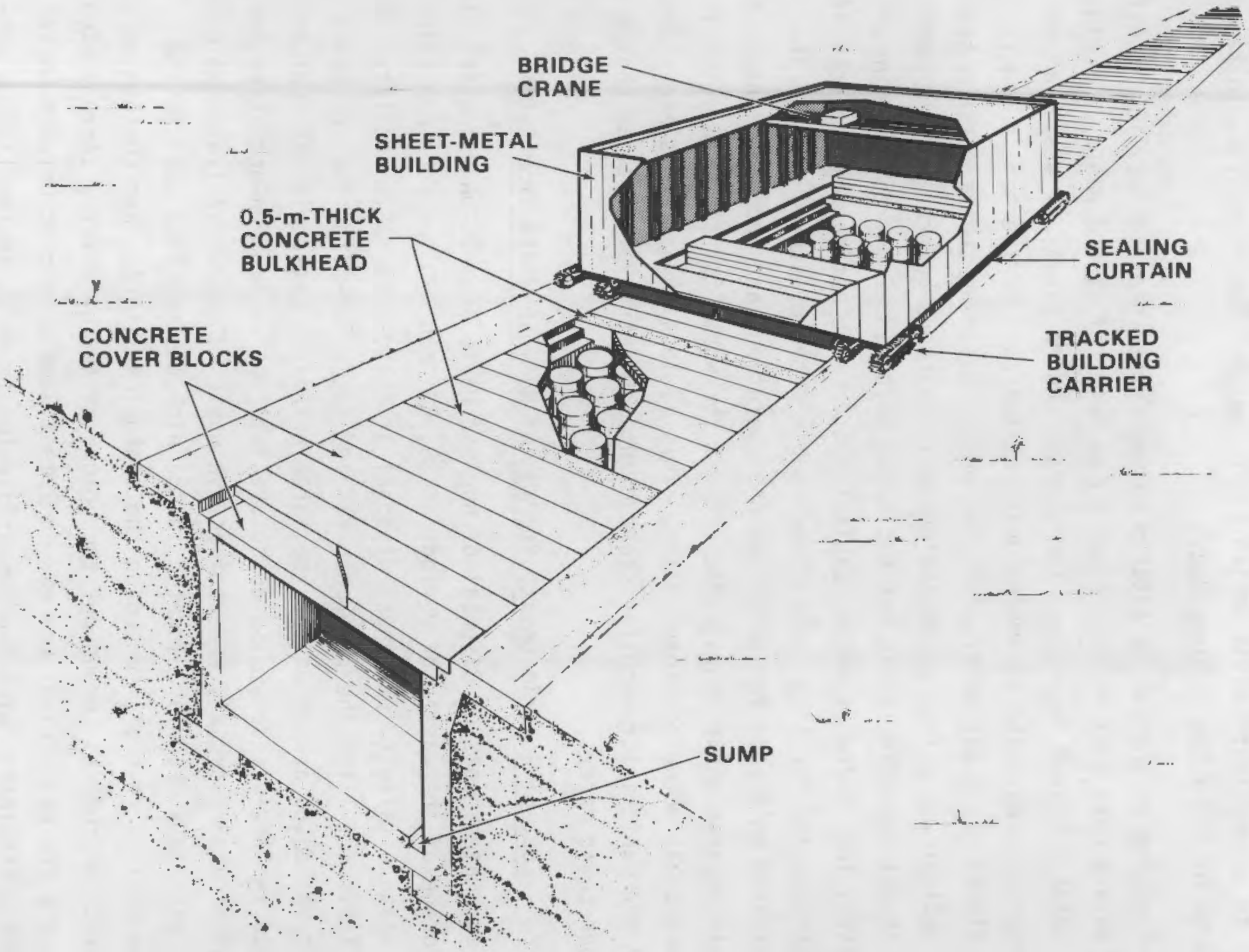


FIGURE 8.1-1. Onsite Interim Nuclear Waste-Storage Facility

After a cell is filled with waste containers the cover blocks are installed and a waterproof seal is applied to the coverblocks. The floor of each cell is sloped to a sump that can be monitored for water. The capability to sample the contents of the sumps is provided.

Construction of the onsite interim nuclear waste storage facility is estimated to have a unit cost of $38.75 per cubic meter of stored waste, assuming that the cells are used four times for storage and retrieval of waste before being decommissioned. The estimated unit capital cost of the mobile gantry crane is $16.67 per cubic meter of stored waste, assuming that the crane handles the nuclear waste from decommissioning 10 reactors before it is decommissioned. Annual operating costs are estimated to be $3.22 per cubic meter of stored waste, 10% of the estimated capital costs. The estimated unit cost of decommissioning the facility is $3.22 per cubic meter of stored waste. The total estimated unit cost for construction, operation, and decommissioning of the interim nuclear waste storage facility if the waste is stored 30 years is $155.24 per cubic meter of stored waste. This is less than the assumed charge of $93.57 per cubic meter each for storage and for retrieval, a total charge of $187.14 per cubic meter.

8.1.2.1 Cost of Interim Onsite Storage of Nuclear Waste from DECON

The estimated costs of disposal of nuclear waste from DECON using interim onsite storage of the waste for periods of 30, 50, and 100 years before shipping the waste offsite to permanent disposal at a licensed waste facility are given in Table 8.1-1 for the reference PWR and Table 8.1-2 for the reference BWR. Disposal costs are shown for the three principal categories of nuclear waste (used in previous decommissioning studies)[1,2]: neutron-activated material, contaminated material, and radioactive waste. Neutron-activated materials are those materials which are located in the high neutron flux zone in and around the nuclear reactor, including the biological shield, and contain neutron activation products throughout the volume of the material. Contaminated materials are process piping, process equipment, tools, and structures whose surface are contaminated with neutron activation products and/or fission products. Radioactive wastes include ion exchange resins, filter cartridges, evaporator bottoms liquids, and miscellaneous combustible wastes contaminated

TABLE 8.1-1. Estimated Cost of Disposal of Nuclear Waste from DECON of a PWR Using Interim Onsite Waste Storage

Storage Location	Years After Shutdown	Cost of Waste Disposal ($ thousands) Type of Waste: Neutron-Activated	Contaminated	Radwaste	Option Total
Offsite, Immediate[a]	0	2 734[b]	5 183[c]	693[d]	8 610
Onsite, Interim	0	1 933	3 467	240	5 640
Offsite, Permanent	30	708	3 636	259	10 245[e]
	50	687	332	181	6 840[e]
	100	684	322	171	6 827[e]

(a) Base case. Cost of immediate offsite disposal of the nuclear waste.
(b) From Table G.4-3 of Reference 1.
(c) From Table G.4-4 and G.4-5 of Reference 1.
(d) From Table G.4-6 of Reference 1.
(e) Total includes cost of placing waste in interim storage.

TABLE 8.1-2. Estimated Cost of Disposal of Nuclear Waste from DECON of a BWR Using Interim Onsite Waste Storage

Storage Location	Years After Shutdown	Cost of Waste Disposal ($ thousands) Type of Waste: Neutron-Activated	Contaminated	Radwaste	Option Total
Offsite, Immediate[a]	0	2300[b]	4909[c]	1469[d]	8678
Onsite, Interim	0	409	3337	447	4193
Offsite, Permanent	30	870	3452	572	9086[e]
	50	742	313	328	5576[e]
	100	702	313	308	5516[e]

(a) Base case. Cost of immediate offsite disposal of nuclear waste.
(b) From Table I.3-3 of Reference 2.
(c) From Table I.3-4 of Reference 2.
(d) From Tables H.5-10 and I.3-5 of Reference 2.
(e) Total includes cost of placing waste in interim storage.

with radionuclides, such as plastic sheeting, rags, disposable protective clothing, etc. Also shown are the costs of initially placing the nuclear waste in interim storage onsite. Differences in the estimated cost of onsite interim storage of waste followed by offsite disposal are given in Table 8.1-3 for storage periods of 30, 50, and 100 years. Interim onsite storage of the nuclear waste for 30 years results in a higher total cost of waste disposal for both the reference reactors, \$1.6 million for the PWR and \$0.4 million for the BWR, because the 30-year storage period is too short for the radioactivity on the contaminated material to decay to the level at which significant quantities of the contaminated material can be released. With temporary onsite storage for 50 or 100 years, waste disposal cost reductions of about \$2 million for the reference PWR and about \$3 million for the reference BWR are estimated.

TABLE 8.1-3. Estimated Total Cost Differences - Interim Onsite Nuclear Waste Storage vs. Immediate Offsite Nuclear Waste Disposal for DECON

Interim Onsite Storage Period (yr)	Cost Differences (\$ thousands)[a,b] PWR	BWR
30	+1640	+410
50	-1770	-3100
100	-1780	-3160

(a) The cost differences are based on the cost of placing the nuclear waste in interim onsite storage plus the cost of later removal and disposal offsite in a licensed waste disposal facility.

(b) A + sign indicates an increase in cost over the cost of immediate offsite waste disposal, and a - sign indicates a decrease in cost.

8.1.2.2 Cost of Interim Onsite Storage of Nuclear Waste from SAFSTOR

The schedule for disposal of the nuclear waste from SAFSTOR of the reference PWR with interim onsite storage of the waste is shown in Figure 8.1-2 for the case of a 30-year period of safe storage of the reactor and interim onsite storage of the nuclear waste for 50 years. The nuclear waste from

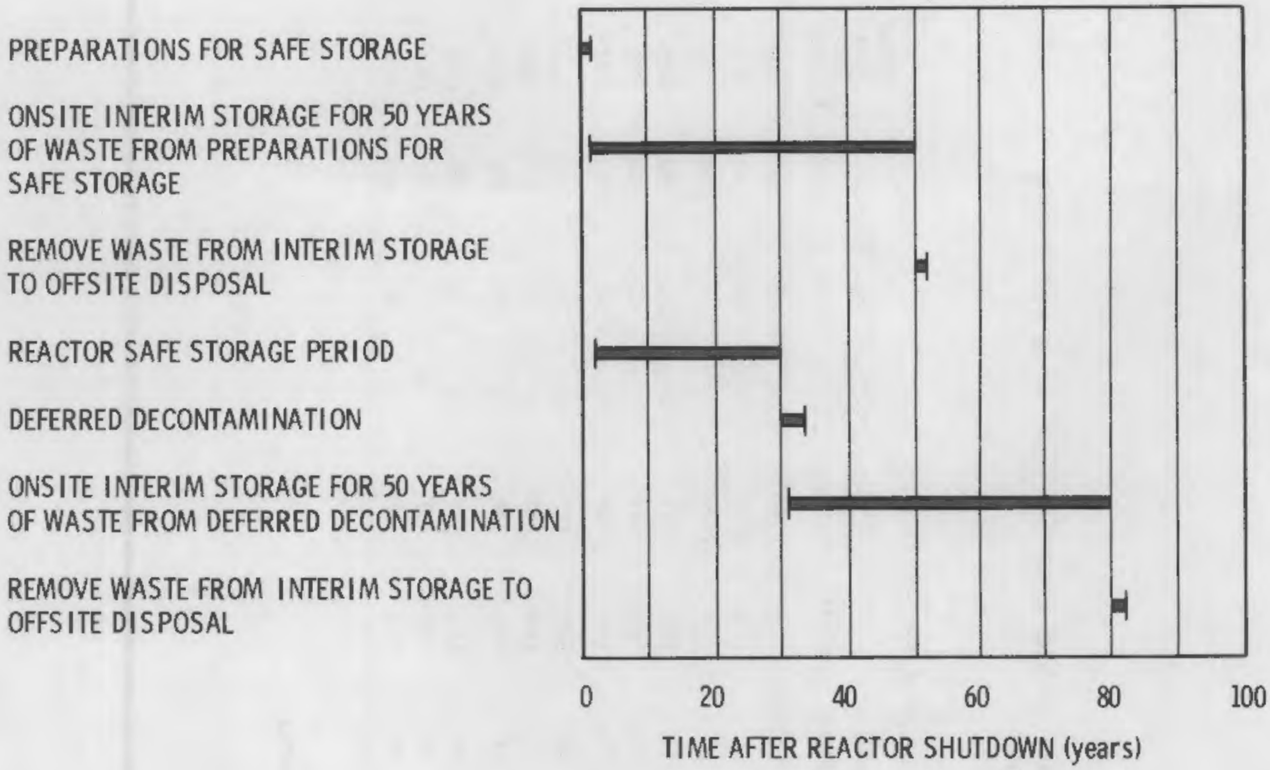


FIGURE 8.1-2. Schedule for Interim Onsite Storage of the Nuclear Waste from SAFSTOR (for a 30-year safe storage period of the reactor and interim onsite storage of the waste for 50 years)

preparations for safe storage is removed to an offsite waste disposal facility after 50 years of interim onsite storage; this would be 50 years after reactor shutdown. Nuclear waste from deferred decontamination is placed in interim onsite storage (30 years after reactor shutdown) and removed to an offsite waste disposal facility after 50 years of interim onsite storage (80 years after reactor shutdown).

The estimated costs of disposal of nuclear waste from SAFSTOR using interim onsite waste storage for 30, 50, and 100 years before removal to permanent disposal offsite at a licensed waste disposal facility are given in Tables 8.1-4 and 8.1-5 for the reference PWR and the reference BWR, respectively. Estimated costs for waste disposal are shown for preparations for safe storage and for deferred decontamination after 30, 50, and 100 years of safe storage. Disposal costs are presented for the three categories of nuclear waste, neutron-activated material, contaminated material, and radwaste. Tables 8.1-5 and 8.1-6 give the estimated cost of removing the nuclear waste generated during preparations

TABLE 8.1-4. Estimated Cost of Disposal of Nuclear Waste from SAFSTOR of a PWR Using Interim Onsite Nuclear Waste Storage

Preparations for Safe Storage				Deferred Decontamination									
					Onsite Interim Storage Cost ($ thousands)				Offsite Disposal Cost ($ thousands)				
Onsite Interim Waste Storage Period (years)	Onsite Interim Storage Cost ($ thousands)	Offsite Disposal Cost ($ thousands)	Subtotal	Safe Storage Period (years)	Neutron-Activated	Contami-nated	Radwaste	Subtotal	Neutron-Activated	Contami-nated	Radwaste	Subtotal	Option Total Cost ($ thousands)
0[(a)]	0	544[(b)]	544	30	0	0	0	0	2734[(c)]	5183[(c)]	166[(c)]	8084	8628
				50	0	0	0	0	2734[(c)]	32[(c)]	108[(c)]	2874	3418
				100	0	0	0	0	2734[(c)]	32[(c)]	72[(c)]	2838	3382
30	196	121	317	30	1910	3467	45	5422	443	330	111	884	6623
				50	1858	21	29	1908	441	21	72	534	2759
				100	1858	21	19	1898	438	13	50	501	2716
50	196	59	255	30	1910	3467	45	5422	441	330	100	871	6548
				50	1858	21	29	1908	440	21	72	533	2696
				100	1858	21	19	1898	438	13	47	498	2651
100	196	51	247	30	1910	3467	45	5422	438	321	96	855	6524
				50	1858	21	29	1908	438	13	65	516	2671
				100	1858	21	19	1898	436	9	46	491	2636

(a) Base case. Cost of immediate offsite disposal of nuclear waste.
(b) From Table H.3-2 of Reference 1.
(c) Based on Table H.5-2 of Reference 1. Numbers reduced to remove the 25% contingency.

TABLE 8.1-5. Estimated Cost of Disposal of Nuclear Waste from SAFSTOR of a BWR Using Interim Onsite Nuclear Waste Storage

Preparations for Safe Storage				Deferred Decontamination									
					Onsite Interim Storage Cost ($ thousands)				Offsite Disposal Cost ($ thousands)				
Onsite Interim Waste Storage Period (years)	Onsite Interim Storage Cost ($ thousands)	Offsite Disposal Cost ($ thousands)	Subtotal	Safe Storage Period (years)	Neutron-Activated	Contaminated	Radwaste	Subtotal	Neutron-Activated	Contaminated	Radwaste	Subtotal	Option Total Cost ($ thousands)
0[a]	0	1216[b]	1216	30	0	0	0	0	2300[c]	4909[c]	255[c]	7464	8680
				50	0	0	0	0	2300[c]	43[c]	204[c]	2547	3763
				100	0	0	0	0	2300[c]	43[c]	140[c]	2483	3699
30	361	291	652	30	394	3337	84	3815	688	320	221	1229	5696
				50	368	31	67	466	195	26	179	400	1518
				100	284	31	46	361	162	19	124	305	1318
50	361	172	533	30	394	3337	84	3815	195	316	210	721	5069
				50	368	31	67	466	162	22	170	354	1353
				100	284	31	46	361	162	18	121	301	1195
100	361	152	513	30	394	3337	84	3815	193	309	194	696	5024
				50	368	31	67	466	162	18	160	340	1319
				100	284	31	46	361	162	15	116	293	1167

(a) Base case. Cost of immediate offsite disposal of nuclear waste.
(b) From Tables H.5-10 and J.5-3 of Reference 2.
(c) From Table J.7-2 of Reference 2.

TABLE 8.1-6. Estimated Total Cost Differences - Interim Onsite Nuclear Waste Storage vs. Immediate Offsite Nuclear Waste Disposal for SAFSTOR

Interim Onsite Storage Period (yr)[c]	Cost Differences ($ thousands)[a,b] Deferred Decontamination After 30 Year[d]		50 Year[d]		100 Year[d]	
	PWR	BWR	PWR	BWR	PWR	BWR
30	-2005	-2984	-660	-2244	-670	-2381
50	-2080	-3611	-720	-2408	-730	-2504
100	-2105	-3656	-750	-2443	-750	-2532

(a) The cost differences are based on the cost of placing the nuclear waste from both preparations for safe storage and deferred decontamination in interim onsite storage plus the cost of later removal and disposal in an offsite licensed waste disposal facility.
(b) A - sign indicates a decrease in cost under the cost of immediate offsite waste disposal.
(c) Time after waste is placed in onsite interim storage.
(d) Time after reactor shutdown.

for safe storage from interim storage to permanent disposal after interim storage periods of 30, 50, or 100 years. For the three deferred decontamination cases, the cost is given for removal of the nuclear wastes to offsite disposal at times of 30, 50, or 100 years after the waste was placed in onsite interim storage. This means that if deferred decontamination took place 30 years after reactor shutdown, removal to offsite disposal would be at 60, 8D, or 130 years after reactor shutdown; with deferred decontamination 50 years after reactor shutdown, offsite disposal would be at 80, 100, or 150 years after shutdown; and with deferred decontamination 100 years after reactor shutdown, offsite disposal would be at 130, 150, or 200 years after shutdown.

Differences in the estimated cost of immediate offsite nuclear waste disposal and the estimated cost of onsite storage of nuclear waste followed by removal to an offsite disposal facility are given in Table 8.1-6 for interim storage periods of 30, 50, and 100 years. The lowest waste disposal costs for SAFSTOR with interim onsite waste storage are given by the case with 100 years of safe storage and 100 years of onsite interim waste storage, $2.6 million for the reference PWR and $1.1 million for the reference BWR. However, the greatest reductions in the total waste disposal costs for both the PWR and the BWR are achieved by 100 years of interim onsite storage of the waste from deferred decontamination that takes place after 30 years of safe storage.

8.1.2.3 Cost of Interim Onsite Storage of Nuclear Waste from ENTOMB

The estimated costs of disposal of nuclear waste from ENTOMB with interim onsite storage of the waste before removal offsite to permanent disposal are given in Table 8.1-7 for the reference PWR and in Table 8.1-8 for the reference BWR. Disposal costs are shown for each of the three categories of nuclear waste: neutron-activated material, contaminated material, and radwaste. The differences between the cost of waste disposal with interim onsite storage for 30, 50, and 100 years and the cost of immediate offsite waste disposal are presented in Table 8.1-9. The greatest cost reductions are estimated to be achieved by interim onsite storage for 100 years, $1.4 million for the PWR and $2.6 million for the BWR. However, the incremental savings achieved by extending the storage period from 50 years to 100 years are estimated to be quite small.

TABLE 8.1-7. Estimated Cost of Disposal of Nuclear Waste from ENTOMB of a PWR Using Interim Onsite Nuclear Waste Storage

Storage Location	Years After Shutdown	Cost of Waste Disposal ($ thousands)			
		Type of Waste			
		Neutron-Activated	Contaminated	Radwaste	Option Total
Onsite, Interim	0	945	401	240	1586
Offsite, Permanent	0	2498[a]	472[a]	693[a]	3663
	30	331	538	259	2714[b]
	50	316	185	181	2268[b]
	100	314	185	171	2256[b]

(a) From Table 4.5-1 of Reference 3.
(b) Includes cost of placement of waste in interim onsite storage external to the entombment structure.

TABLE 8.1-8. Estimated Cost of Disposal of Nuclear Waste from ENTOMB of a BWR Using Interim Onsite Nuclear Waste Storage

Storage Location	Years After Shutdown	Cost of Waste Disposal ($ thousands): Type of Waste: Neutron-Activated	Contaminated	Radwaste	Option Total
Onsite, Interim	0	484	1230	447	2161
Offsite, Permanent	0	2394[a]	1846[b]	1469[c]	5709
	30	741	1327	572	4801[d]
	50	614	104	328	3207[d]
	100	574	104	308	3147[d]

(a) From Table K.3-3 of Reference 2.
(b) From Table K.3-4 of Reference 2.
(c) From Tables H.5-10 and I.3-5 of Reference 2. See Section K.3.1.3 of Appendix K of Reference 2.
(d) Includes cost of placement of waste in interim onsite storage external to the entombment structure.

TABLE 8.1-9. Estimated Total Cost Differences - Interim Onsite Nuclear Waste Storage vs. Immediate Offsite Nuclear Waste Disposal for ENTOMB

Temporary Onsite Storage Period (yr)	Cost Differences ($ thousands)[a,b]: PWR	BWR
30	-949	-908
50	-1395	-2502
100	-1407	-2562

(a) The cost differences are based on the cost of placing the nuclear waste in interim onsite storage plus the cost of later removal and disposal in an offsite licensed waste disposal facility.
(b) A - sign indicates a decrease in cost compared with cost of immediate offsite waste disposal.

8.1.3 Onsite Nuclear Waste Disposal

Sites where large numbers of nuclear power reactors are located conceivably will be large enough to include a permanent onsite low-level nuclear waste disposal facility. Permanent onsite low-level nuclear waste disposal facilities will be operated only at those multiple-reactor stations where the hydrology of the site will not cause flooding of the disposal facility. Any nuclear waste that must be disposed of in a deep geologic disposal facility will be sent off-site to a government-operated facility. Several factors that contribute to lower costs for onsite nuclear waste disposal are:

- lower transportation costs because of the short haul to the disposal site
- no overweight charges, since all travel is over private roads
- no relief driver charges, since only one driver is needed
- shielded cask liners may not be used for some of the activated materials, since travel is over private roads and the DOT maximum surface dose rate may be exceeded.

The following assumptions are made in estimating the effect of onsite nuclear waste disposal on decommissioning costs:

1. The quantity of nuclear waste sent to onsite waste disposal is the same as would be sent to an offsite waste disposal facility.
2. Since transport to the onsite waste disposal facility is over private roads in a privately owned and controlled area, it is not necessary to limit the container or cask surface dose rate to 0.2 R/hr as required by DOT for transport on public highways. Shielding is provided for the truck cab to limit the dose rate to 2 mR/hr. The radiation dose to workers is controlled procedurally to assure that it does not exceed the 10 CFR 20 limits.
3. There are no curie or liner surcharges for onsite waste disposal.
4. When heavy loads such as casks are involved, the handling charge is equal to the handling charge for such a load at an offsite licensed waste disposal facility.
5. The disposal charge is the same as that at an offsite licensed waste disposal facility ($93.57/m^3) and covers the costs of construction, operation, and decommissioning of the facility.

6. The onsite disposal facility is located 24 km from the reactor.

7. One-day cask rental is charged for each shipment.

8.1.3.1 Cost of Onsite Disposal of Nuclear Waste from DECON

The estimated costs of onsite disposal of the nuclear waste from DECON of the reference PWR and reference BWR are presented in Table 8.1-10. The costs of offsite disposal of the waste are also given for comparison. The savings achieved by onsite waste disposal are about $3 million for the PWR and about $4.5 million for the BWR.

TABLE 8.1-10. Estimated Cost of Onsite Disposal of Nuclear Waste from DECON

Disposal Location	Cost of Waste Disposal ($ thousands) — Type of Waste: Neutron-Activated	Contaminated	Radwaste	Total
Reference PWR				
Offsite	2733[a]	5183[b]	693[c]	8609
Onsite	1933	3467	240	5640
			Saving	2969
Reference BWR				
Offsite	2300[d]	4909[e]	1469[f]	8678
Onsite	409	3337	447	4193
			Saving	4485

(a) From Table G.4-3 of Reference 1.
(b) From Tables G-4-4 and G.4-5 of Reference 1.
(c) From Table G.4-6 of Reference 1.
(d) From Table I.3-3 of Reference 2.
(e) From Table I.3-4 of Reference 2.
(f) From Tables H.5-10 and I.3-5 of Reference 2.

8.1.3.2 Cost of Onsite Disposal of Nuclear Waste from SAFSTOR

The estimated costs of onsite disposal of the nuclear waste from SAFSTOR of the reference PWR and reference BWR are given in Table 8.1-11. These costs are for disposal of the waste from preparations for safe storage plus the waste from deferred decontamination after 30, 50, or 100 years of safe storage. The costs of offsite disposal of the nuclear waste from SAFSTOR, developed in the PWR and BWR decommissioning studies,[1,2] are given for comparison. Costs for onsite disposal of nuclear waste are shown to be lower than for offsite disposal. The estimated savings for both the PWR and the BWR are greatest if deferred decontamination is started 30 years after reactor shutdown, $3.1 million for the PWR and $4.3 million for the BWR.

TABLE 8.1-11. Estimated Cost of Onsite Disposal of Nuclear Waste from SAFSTOR

Years of Storage Before Deferred Decontamination	Cost of Waste Disposal ($ thousands)[a] Type of Waste: Neutron-Activated	Contaminated	Radwaste	Totals: Onsite Disposal	Offsite Disposal	Savings
Reference PWR						
30	1910	3467	317	5694	8792[b]	3098
50	1858	21	255	2134	3566[b]	1432
100	1858	21	246	2125	3520[b]	1395
Reference BWR						
30	394	3337	608	4339	8680[c]	4341
50	368	31	453	852	3763[c]	2911
100	284	31	433	748	3699[c]	2951

(a) Costs include cost of waste disposal from preparations for safe storage and from deferred decontamination.
(b) Based on Tables H.3-2 and H.5-2 of Reference 1. Numbers reduced to remove 25% contingency.
(c) Based on Tables H.5-10, J.5-3, and J.7-2 of Reference 2.

8.1.3.3 Cost of Onsite Disposal of Nuclear Waste from ENTOMB

In Table 8.1-12, the estimated costs of disposal of the nuclear waste from ENTOMB are given for onsite and offsite disposal. Onsite disposal of the nuclear waste from ENTOMB is estimated to save $2.1 million for the PWR and $3.5 million for the BWR.

TABLE 8.1-12. Estimated Cost of Onsite Disposal of Nuclear Waste from ENTOMB

	Cost of Waste Disposal ($ thousands)			
	Type of Waste			
Disposal Location	Neutron-Activated	Contaminated	Radwaste	Total
		Reference PWR		
Offsite	2498[a]	472[a]	693[a]	3663
Onsite	945	401	240	1586
			Saving	2077
		Reference BWR		
Offsite	2394[b]	1846[c]	1469[d]	5709
Onsite	484	1230	447	2161
			Saving	3548

(a) From Table 4.5-1 of Reference 3.
(b) From Table I.3-3 of Reference 2.
(c) From Table I.3-4 of Reference 2.
(d) From Tables H.5-10 and I.3-5 of Reference 2.

8.2 SITE DEDICATION

Dedication of a site to nuclear power generation results in replacement reactors being constructed on a schedule to achieve startup of a replacement reactor as an old reactor is shut down. At such dedicated sites, either relatively long periods of construction activity will occur periodically or there will be continuous construction activity at the site if the startup of the reactors is spaced to occur over a 30-year period.

Dedication of a multiple-reactor site to nuclear power generation:

- fosters stable operating and construction labor forces
- favors the establishment of onsite interim nuclear waste storage or onsite nuclear waste disposal
- results in improved efficiency of construction and decommissioning as management and the labor force accumulate onsite experience
- encourages the provision of centralized services.

It is expected that the efficiency of decommissioning the reactors at a multiple-reactor station will improve after the first reactor is decommissioned due to the learning process. Reductions in manpower requirements for decommissioning subsequent reactors of the same type at a multiple-reactor station result from the following factors:

- the minimization of the planning effort for decommissioning the second or later reactors of the same type
- the standardization and improvement of decommissioning techniques
- the stabilization of the work force, resulting in less time spent in learning or rehearsing decommissioning procedures
- the improvement of the productivity of decommissioning workers as a result of the learning experience on the first reactor.

The reduction in decommissioning manpower costs at multiple-reactor stations results principally from a reduction in the time required to perform a given operation, rather than from a reduction in the number of workers. Therefore, the total time to decommission a plant is reduced, and the cost reduction factors are applied to support staff labor as well as to decommissioning worker labor.

Assumptions used to estimate the cost reduction factors are:

1. The cost reduction factor for planning and preparation for the second and each succeeding reactor of a particular type (PWR or BWR) is 0.50.
2. The cost reduction factor for decommissioning operations for the second reactor of a particular type is 0.95.
3. The cost reduction factor for decommissioning operations for the third and each succeeding reactor of a particular type is 0.90.

Cost reduction factors for decommissioning several reactors of the same type at a multiple-reactor station are shown in Table 8.2-1. These factors are also applicable for estimation of occupational radiation dose reduction.

TABLE 8.2-1. Cost and Dose Reduction Factors

Number of Reactors of One Type	Average Cost Reduction Factor	
	Planning & Preparation	Decommissioning Operations
1	1.0	1.0
4	0.62[a]	0.94[a]
5	0.60	0.93
10	0.55	0.92
20	0.53	0.91

(a) $\frac{1.0 + .5 + .5 + .5}{4} = 0.62$;

$\frac{1.0 + .95 + .9 + .9}{4} = 0.94$

The factors given in Table 8.2-1 are used to estimate the decommissioning staff labor costs at multiple-reactor stations having four or five reactors of the same type. Table 8.2-2 gives the estimated staff labor costs for decommissioning several PWRs and BWRs by DECON, SAFSTOR, and ENTOMB; estimated staff labor costs for decommissioning a single reactor are given for comparison. These costs are used to estimate the savings in staff labor for the five scenarios studied in Section 10.

8.3 AVAILABILITY OF CENTRALIZED SERVICES

A number of centralized site services may be available at a multiple-reactor station. The centralized services considered in this study are:

- health physics services
- security forces
- solid waste processing
- equipment decontamination services
- maintenance shops and services
- laundry services
- transportation services
- central stores.

TABLE 8.2-2. Decommissioning Staff Labor Costs

No. of Reactors Decommissioned	Staff Labor Costs/Reactor ($ thousands)[a]				
		SAFSTOR[b]			
	DECON	30 Yr	50 Yr	100 Yr	ENTOMB
		PWRs			
1	7 981[c]	11 179[d]	11 179[d]	11 179[d]	7 607[e]
4	7 345	10 138	10 138	10 138	7 001
5	7 237	9 950	9 950	9 950	6 898
		BWRs			
1	15 066[f]	24 272[g]	21 937[g]	21 937[g]	15 424[h]
4	13 704	21 050	18 926	18 926	14 046
5	13 528	20 734	18 647	18 647	13 854

(a) Security force labor costs deleted.
(b) Includes cost of preparations for safe storage and cost of deferred decontamination. No improvement in labor efficiency is anticipated for continuing care.
(c) Based on Table 10.1-2 of Reference 1.
(d) Based on Tables 10.1-2 and 10.2-2 of Reference 1.
(e) Based on Table 4.5-1 of Reference 3.
(f) Based on Table I.3-6 of Reference 2.
(g) Based on Tables J.5-4 and J.7-2 of Reference 2.
(h) Based on Table K.3-5 of Reference 2.

The impact of providing each of these centralized services on the cost of reactor decommissioning is discussed in the following subsections. Centralized services are considered in this study for 10-reactor stations.

8.3.1 Health Physics Services

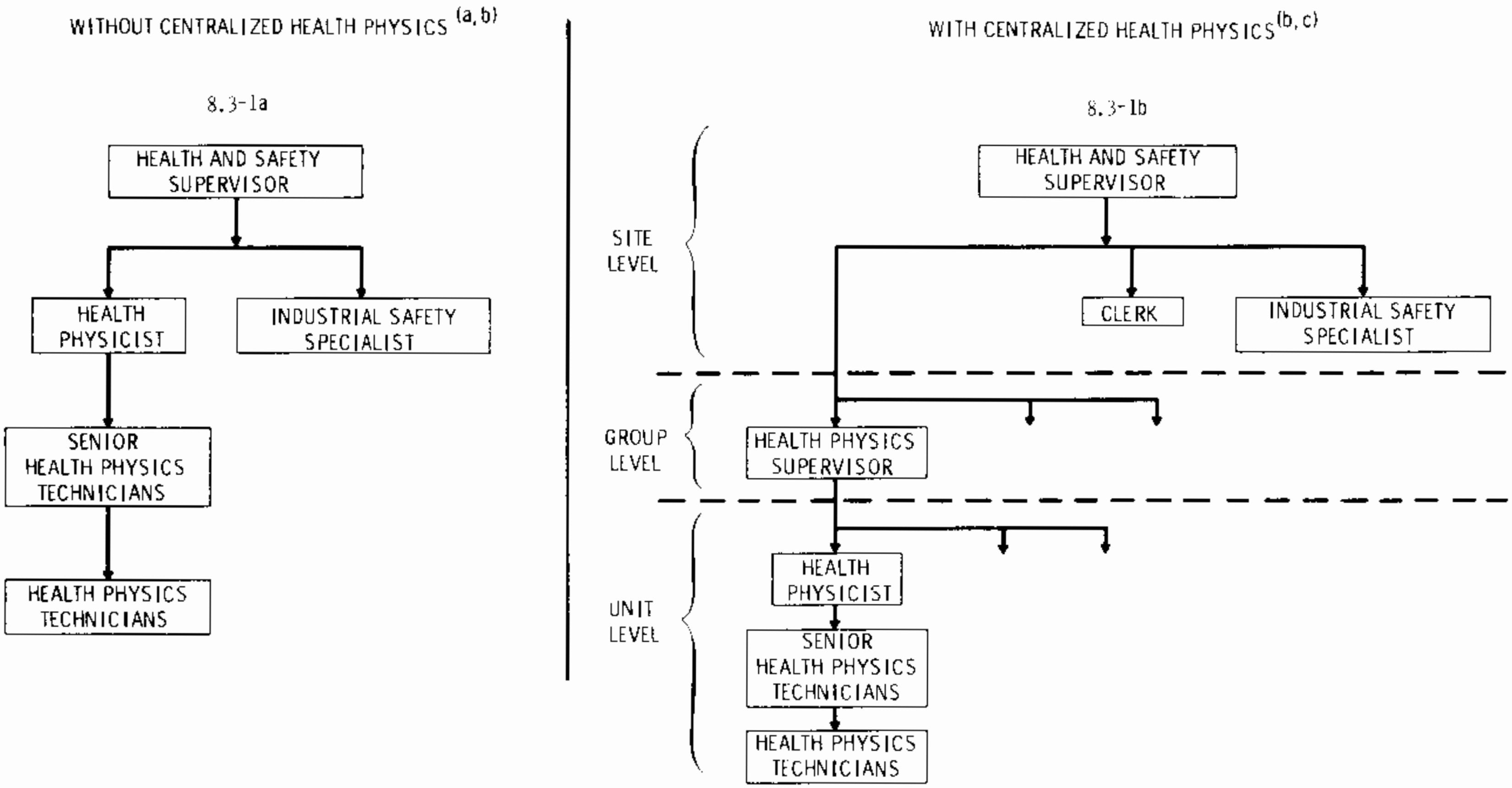
Centralized health physics services at a multiple-reactor station could significantly reduce the costs of health physics activities at each reactor, during both the reactor operating life and the decommissioning period following operation. The two major factors postulated to contribute to this cost reduction are:

- the reduced health physics staff overhead at each reactor, resulting from the sharing of certain staff members between several reactors at the site
- the reduced peak-load staffing requirements per reactor, because the large pool of health physics technicians at the site can be shared between reactors as needed.

The health physics staff organizations considered for decommissioning in this analysis are shown in Figure 8.3-1. The staff organization without centralized services (Figure 8.3-1a) is essentially the same as that postulated for the PWR and BWR decommissioning studies[1,2] of single-reactor stations. In Figure 8.3-1b, the postulated organization with centralized health physics services is shown as a three-tiered organization to reduce overhead manpower. At the multiple-reactor station level the health and safety supervisor is responsible for all health physics activities at the station. He is aided by a clerk and the industrial safety specialist on the station level and by health physics supervisors at the group (or quad) level. (For administrative purposes the reactors are assumed to be located on the station in groups of four, or quads). At each reactor a health physicist, who reports to the group health physics supervisor, is in charge of the health physics activities.

In addition to the modified staff organization with centralized health physics services, a more efficient use of the health physics technicians is assumed. Manpower requirements and costs for these staff members are assumed to be reduced 10% from those required without centralized health physics services.

To calculate the decommissioning cost savings resulting from centralized health physics services, the costs for radiation monitoring with and without centralized health physics services in the PWR and the BWR decommissioning studies[1,2] are used here as the base costs, because the costs would be the same whether a single reactor is alone on a site or operates independently (without centralized services) on a multiple-reactor site. The detailed calculations of the costs for the centralized health physics services are presented in Section B.1 of Appendix B of this study and the results are summarized here. To develop the costs for the centralized services, it is assumed that:



(a) BASED ON FIGURES 9.1-3 AND 9.2-6 OF REFERENCE 1 AND ON FIGURE H.1-1 OF REFERENCE 2.
(b) PROTECTIVE EQUIPMENT ATTENDANTS UNAFFECTED BY ORGANIZATION CHANGE AND, THEREFORE, NOT INCLUDED HERE.
(c) ASSUMES SITE DIVIDED INTO THREE GROUPS OF REACTORS WITH THREE OR FOUR UNITS IN EACH GROUP.

FIGURE 8.3-1. Health Physics Staff Organization for Decommissioning

- a site-wide overhead structure exists, reducing the overhead burden on each individual reactor
- labor requirements for senior health physics technicians and health physics technicians are reduced by 10% because sharing of technicians between reactors reduces the need to hire extra personnel for high dose-rate activities.

Health physics staff labor costs for decommissioning an LWR at a multiple-reactor station, both with and without centralized health physics services, are summarized in Table 8.3-1 for the three decommissioning alternatives. Estimated net savings achieved by using centralized health physics services are also presented. These net savings are in the range of 30 to 40% of the base cost (without centralized services) for the PWR and in the range of 25 to 30% for the BWR. Overall savings are greater for the BWR than for the PWR because of the greater requirement for health physics personnel at the BWR, as estimated in References 1 through 3.

8.3.2 Security Forces

A station-wide central security force at a multiple-reactor station could provide security services more efficiently for each reactor than such services could be provided at a single-reactor station. Two factors that account for this cost reduction are:

- the overhead structure for each reactor can be reduced by sharing certain staff members between reactors
- the off-shift coverage at a reactor being decommissioned can be reduced or eliminated after the spent fuel has been shipped (no special nuclear material at reactor) if provision is made for routine spot-checks by roving security patrolmen, reducing the overall personnel requirement.

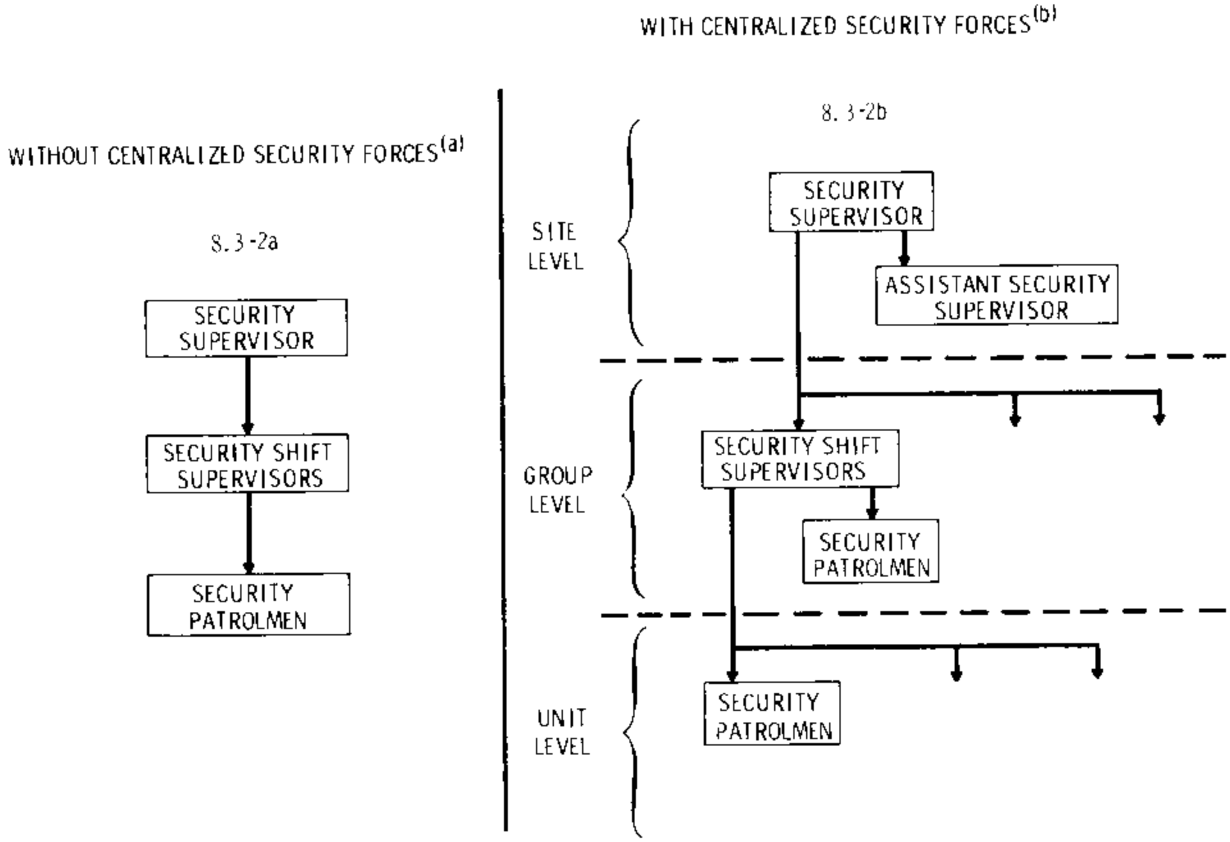
The organization structures for the security force considered in this study are shown in Figure 8.3-2. The security organization without centralized services, Figure 8.3-2a, is the same as that shown in Reference 2 for decommissioning the reference BWR. The organization of the security force with centralized services, shown in Figure 8.3-2b, assumes a three-level approach as

TABLE B.3-1. Summary of Health Physics Staff Labor Costs for Decommissioning of an LWR at a Multiple-Reactor Station[a]

Decommissioning Alternative	Total Health Physics Staff Labor Costs ($ thousands): w/o Centralized Health Physics	w/Centralized Health Physics	Net Savings w/Centralized Health Physics ($ thousands)
PWR			
DECON[b]	1424	962	462
SAFSTOR:[c]			
Preparations for Safe Storage[d]	668	412	256
Deferred Decontamination[e]	1424	962	462
Totals	2092	1374	718
ENTOMB[e]	1424	962	462
BWR			
DECON[f]	2349	1731	618
SAFSTOR:[c]			
Preparations for Safe Storage[g]	1530	1094	436
Deferred Decontamination[e]	2349	1731	618
Totals	3879	2825	1054
ENTOMB[h]	2406	1752	654

(a) Assumed to be a 10-reactor station.
(b) From Table B.1-1.
(c) Centralized health physics services are assumed to have no significant impact on costs for continuing care.
(d) From Table B.1-2.
(e) Assumed to be the same as for DECON.
(f) From Table B.1-3.
(g) From Table B.1-4.
(h) Reactor vessel internals removed; from Table B.1-5.

described in Subsection 8.3.1 for centralized health physics services. At the station level the security supervisor and assistant security supervisor have overall responsibility for station security matters. Each of the reactor groups (quads) has a security shift supervisor assisted by security patrolmen at both the group and reactor levels.



(a) BASED ON FIGURE H.1-1 OF REFERENCE 2.
(b) ASSUMES SITE DIVIDED INTO THREE GROUPS OF REACTORS WITH THREE OR FOUR UNITS IN EACH GROUP.

FIGURE 8.3-2. Security Force Organization for Decommissioning

Estimated costs of providing security forces for decommissioning the reference PWR and the reference BWR at a multiple-reactor station, both with and without centralized security forces, are summarized in Table 8.3-2. The net savings possible by using a centralized security force are also presented. For the different alternatives, overall net savings with a central security force during the decommissioning of a reactor range from 21 to 32% of the cost of providing security with a separate security force at the reactor. The net savings percentages are not significantly influenced by the reactor type.

8.3.3 Solid Waste Processing

In the decommissioning studies of the reference PWR[1] and the reference BWR[2] at single-reactor stations, it was assumed that the dry solid radioactive

TABLE 8.3-2. Summary of Security Force Labor Costs for LWR Decommissioning at a Multiple-Reactor Station[a]

Decommissioning Alternative	Total Security Force Labor Costs ($ thousands)		Net Savings w/Centralized Security Forces ($ thousands)
	w/o Centralized Security Forces	w/Centralized Security Forces	
PWR			
DECON[b]	2129	1670	459
SAFSTOR:[c]			
Preparations for Safe Storage[d]	1155	1005	150
Deferred Decontamination[e]	1390	732	658
Totals	2545	1737	808
ENTOMB[f]	2129	1670	459
BWR			
DECON[g]	2495	1973	522
SAFSTOR:[c]			
Preparations for Safe Storage[h]	2032	1729	303
Deferred Decontamination[i]	1622	859	763
Totals	3654	2588	1066
ENTOMB[j]	2671	2066	605

(a) Assumed to be a 10-reactor station.
(b) From Table B.2-1.
(c) Centralized security forces are assumed to have no significant impact on costs for continuing care.
(d) From Table B.2-2.
(e) From Table B.2-3.
(f) Assumed to be the same as for DECON.
(g) From Table B.2-4.
(h) From Table B.2-5.
(i) From Table B.2-6.
(j) From Table B.2-7.

waste was compacted to achieve a five-fold reduction in volume. At a multiple-reactor station, a central waste incinerator to serve the whole station can further reduce the volume of combustible radioactive waste by at least a factor of five, giving an overall volume reduction factor of 25. A central waste incinerator can provide significant savings in waste disposal costs for both the operating and decommissioning phases of reactor life.

It is assumed in this study that a central waste incinerator is provided at the multiple-reactor station to process the combustible solid waste from the 10 operating reactors in five, two-shift days per week. In Section B.3 of Appendix B, the capital cost of the central waste incinerator is estimated to be $3.9 million, or $390,000 per reactor at the site. It is assumed that the annual operating and maintenance cost is 5% of the capital cost of the incinerator. Since this yields an annual savings when compared to disposal of compacted combustible waste of $36,000 per operating reactor (see Table B.3-1 of Appendix B) and the decommissioning of a reactor generates only about 10% of the combustible radioactive waste over the reactor 40-year lifetime, it is assumed that the capital cost of the incinerator is borne by reactor operation.

The cost of using the incinerator for reducing the volume of the combustible radioactive waste from decommissioning a reactor is only the additional incremental cost of operating and maintaining the facility during incineration of the waste. The net cost savings resulting from incineration of combustible radioactive waste during decommissioning a reactor at a multiple-reactor station are presented in Table 8.3-3. Savings for both types of reactors for each of the three decommissioning alternatives are given. The savings are small compared to the total cost of radioactive waste disposal for decommissioning a reactor but represent a significant fraction of the disposal costs of compacted radioactive waste without incineration, 65 to 70% for the PWR and 55 to 70% for the BWR.

8.3.4 Equipment Decontamination Services

Equipment decontamination services can be more fully utilized at a multiple-reactor station than at a single-reactor station, thereby increasing the economy of these services and the economic incentive to provide improved services and

TABLE 8.3-3. Summary of Net Savings from Incineration of Combustible Radioactive Waste from Reactor Decommissioning

Decommissioning Alternative	Total Disposal Costs[a] ($ thousands): Compacted Combustible Wastes	Total Disposal Costs[a] ($ thousands): Incinerated Wastes	Net Savings with Incineration ($ thousands)
PWR			
DECON/ENTOMB	207	74	133
SAFSTOR:			
Preparations for Safe Storage	59	19	40
Deferred Decontamination After 30 yr	148	44	104
Deferred Decontamination After 50 yr	96	28	68
Deferred Decontamination after 100 yr	65	20	45
Totals, w/30-yr Deferred Decontamination	207	63	144
Totals, w/50-yr Deferred Decontamination	155	47	108
Totals, w/100-yr Deferred Decontamination	124	39	85
BWR			
DECON/ENTOMB	396	175	221
SAFSTOR:			
Preparations for Safe Storage	143	63	80
Deferred Decontamination after 30 yr	255	82	173
Deferred Decontamination after 50 yr	204	65	139
Deferred Decontamination after 100 yr	140	46	94
Totals, w/30-yr Deferred Decontamination	398	145	253
Totals, w/50-yr Deferred Decontamination	347	128	219
Totals, w/100-yr Deferred Decontamination	283	109	174

(a) From Table B.3-2 of Appendix B.

facilities at a multiple-reactor station. Several types of equipment decontamination services are considered here for inclusion in the centralized services:

- decontamination of special tools and equipment used for decommissioning, allowing maintenance and reuse of these items
- mobile decontamination systems for in-situ chemical decontamination of piping and components
- central electropolishing and chemical decontamination facilities for improved decontamination of pipe sections and components.

These services would provide significant benefits during both operation and decommissioning of a reactor. The resulting benefits during decommissioning are analyzed here.

8.3.4.1 Decontamination of Special Tools and Equipment

The special tools and equipment required to decommission an LWR represent a sizable cost investment. In the reference studies,[1-3] these items are not assumed to be salvaged after decommissioning and, thus, their full cost is assumed to be borne by a single decommissioning. However, most of these items could be reused if proper decontamination and maintenance were performed on them, reducing the net cost of decommissioning a reactor.

For the following analysis, it is assumed that the special decommissioning tools and equipment are decontaminated, maintained, or refurbished in the central maintenance shops, and reused where possible. An estimated useful lifetime (in terms of the number of decommissioning cycles) is assigned to each item, and the capital costs for the item are assumed to be shared equally by that number of cycles. The annual decontamination and maintenance costs are assumed to be 10% of the total capital cost of the item. However, each item is assumed to be used for only half of the total decommissioning period and, thus, the effective cost of decontamination and maintenance is assumed to be 5% per year over the total length of only one decommissioning schedule. Items with a useful lifetime of only one decommissioning cycle are not assumed to require any substantial decontamination or maintenance. The total costs with reuse (the costs for capital and for decontamination and maintenance) are compared to those costs without reuse to calculate the net savings resulting from decontamination, maintenance, and reuse of the special tools and equipment.

Details of the estimated costs of providing special tools and equipment for the decommissioning of PWRs with the tools and equipment being decontaminated and reconditioned for reuse where possible are given in Tables B.4-1 and B.4-2 of Appendix B. Similar estimated cost details for the decommissioning of BWRs are given in Tables B.4-3 and B.4-4.

Costs of special tools and equipment for decommissioning a reactor at a multiple-reactor station and the savings achievable with reuse of these tools and equipment are summarized in Table 8.3-4. The costs are shown both with and without decontamination and reuse of the items, and net savings for each reactor decommissioning with reuse of the items are also presented. Costs and savings with reuse of the tools and equipment are based on the assumption that no significant capital investment is required to provide space for decontamination and interim storage of these items, because there is judged to be adequate available space onsite.

Net savings per reactor decommissioned by decontamination and reconditioning of special tools and equipment for reuse are estimated to be between 40 and 60% of the total capital cost of the items, $\sim$\$300 thousand for a PWR and $\sim$\$1.2 million for a BWR. The potential overall savings are higher for the BWR than for the PWR because of the estimated greater need for special tools and equipment in the BWR study[2] than in the PWR study.[1]

8.3.4.2 Mobile Chemical Decontamination Equipment

Mobile chemical decontamination equipment is assumed in the BWR study[2] to be used for in-situ decontamination of piping and components during decommissioning by any of the three alternatives. However, such equipment is not discussed in the PWR study.[1] The costs of using such equipment for PWR decommissioning are estimated here 1) to provide a common basis between PWR and BWR decontamination activities and 2) because such equipment is judged to provide additional benefits in terms of ease of decontamination, better control of the process, and more consistent conditions and, consequently, more consistent results.

TABLE 8.3-4. Summary of Special Tools and Equipment Costs for LWR Decommissioning at a Multiple-Reactor Station[a]

Decommissioning Alternative	Total Costs/Decommissioning for Special Tools and Equipment ($ thousands) Without Reuse	With Reuse	Net Savings/ Decommissioning with Reuse ($ thousands)
PWR			
DECON[b]	822	495	327
SAFSTOR:			
Preparations for Safe Storage[c]	28[d]	13[e]	15[e]
Deferred Decontamination	762	457	305
Totals	790	470	320
ENTOMB[f]	822	495	327
BWR			
DECON[g]	2016	851	1165
SAFSTOR:			
Preparations for Safe Storage[h]	351[i]	153[e]	198[e]
Deferred Decontamination	1728	726	1002
Totals	2079	879	1200
ENTOMB[j]	2016	851	1165

(a) Assumed to be a 10-reactor station.
(b) From Table B.4-1.
(c) From Table B.4-2.
(d) Calculated from Table H.5-2 of Reference 1.
(e) Calculated from value for DECON by multiplying by the ratio of the costs (without reuse) for deferred decontamination and DECON.
(f) Assumed to be the same as for DECON.
(g) From Table B.4-3.
(h) From Table B.4-4.
(i) From Table J.7-2 of Reference 2.
(j) Reactor vessel internals removed; assumed to be the same as for DECON.

In the BWR study, five mobile chemical decontamination units, estimated to cost $20,000 each, and four mobile chemical mixing and heating units, costing $2,500 each, are assumed to be used (see Tables I.3-9 and J.5-6 of Reference 2). Assuming proper maintenance and decontamination of the units, the cost of the units would not be charged to the decommissioning of a single reactor. In Tables B.4-3 and B.4-4 of Appendix B the estimated useful lifetime of such units is five reactor decommissionings. The savings for each reactor decommissioning achieved by using this portable chemical decontamination equipment for decommissioning five instead of one BWR is $68,700 for DECON and ENTOMB and $74,200 for SAFSTOR.

It is assumed in this study that the same number of portable units are required in the decommissioning of the PWR as were assumed to be needed for the BWR. The estimated costs of these units for decommissioning a PWR are presented in Table 8.3-5, using the same rationale and assumptions as were used for the BWR. The savings per reactor shown for using the portable chemical decontamination equipment during the decommissioning of five PWRs are given as $72,000 for DECON or ENTOMB and $81,000 for SAFSTOR. The savings are greater for the PWR because equipment maintenance is costed as a function of the time schedule, 3 years for the PWR and 3-1/2 years for the BWR for DECON.

TABLE 8.3-5. Estimated Costs for Mobile Chemical Decontamination Equipment for PWR Decommissioning

Decommissioning Alternative	Estimated Total Capital Cost ($ thousands)[a]	Estimated Useful Lifetime (No. of Decommissionings)[b]	Cost/Decommissioning with Reuse ($ thousands)[c]			Savings/ Decommissioning ($ thousands)
			Capital	Maintenance[d]	Total	
DECON/ENTOMB	110	5	22	17	39	71
SAFSTOR[e]	110	5	22	7	29	81

(a) From Table I.3-9 and Table J.5-6 of Reference 2.
(b) Assumes adequate maintenance.
(c) Rounded to the nearest $1000.
(d) Based on assumed average rate of 5% of capital cost per year; assumes a 3-year decommissioning schedule for DECON or entombment and a 16-month schedule for preparations for safe storage.
(e) Chemical decontamination equipment used only during preparations for safe storage.

8.3.4.3 Central Electropolishing and Chemical Decontamination Facility

A central electropolishing and chemical decontamination facility could be used to reclaim piping, valves, and other plant components for reuse or salvage, reducing both the net cost of decommissioning and the volume of waste requiring disposal. Electropolishing could also be used during construction to polish component surfaces before installation to reduce the subsequent rate of contamination buildup, thus reducing occupational radiation doses and costs for both operations and decommissioning.[4]

An electropolishing facility sized to provide adequate capacity to handle construction, operation, and decommissioning of a single-unit reactor station is described in Section 11 of Reference 5. The information in the reference is used as a basis for the analysis presented in this study; major differences are:

- The facility size is increased somewhat in this analysis to allow for occasional increased demands for the facility services from the 10 reactors onsite, and allow the processing of larger equipment items, with a lower overall cost per reactor than with individual units at each reactor.
- Chemical decontamination facilities are included here to provide more complete capability.
- Portable electropolishing equipment is also postulated to be included here for in-situ decontamination of plant components.

The estimated cost of a central electropolishing and chemical decontamination facility that can serve a multiple-reactor station with 10 operating reactors is $1.88 million. In Appendix B the total of the capital and operating costs charged to the decommissioning of a reactor is $235,000.

Significant savings are achievable by cleaning contaminated stainless steel components to unrestricted release levels for either salvage as scrap or refurbishment and reuse of components. Savings resulting from electropolishing and salvage of stainless steel are two-fold. The material does not require disposal as radioactive waste and the metal can be sold as scrap.

The estimated costs and potential savings resulting from use of a central electropolishing facility during decommissioning a reactor are summarized in Table 8.3-6. The estimates do not include savings that would result from decontamination and refurbishment of components for eventual reuse. However, such reuse is desirable where possible and, with the appropriate capabilities onsite, is judged to occur in some cases. As an example, recovery of even a small fraction of the stainless steel valves in the reactor plant being decommissioned would yield considerable additional savings, even assuming that refurbishment of these valves would cost an average of 50% of their replacement costs. (Valve reconditioning typically costs less than 50% of new-valve cost.)[6]

8.3.4.4 Equipment Decontamination Services Summary

The net savings associated with the central decontamination services considered in this study are summarized in Table 8.3-7. The total net savings for

TABLE 8.3-6. Estimated Costs and Potential Cost Savings Associated with Use of a Central Electropolishing Facility During Decommissioning

Type of Reactor	Facility Costs/Decommissioning ($ thousands)[a] Capital[b]	Operation and Maintenance[c]	Total	Net Recovery Value of Stainless Steel ($ thousands)[a,d]	Net Cost Savings/ Decommissioning ($ thousands)[a]
PWR	47	188	235	975[e]	740
BWR	47	188	235	472[f]	237

(a) Rounded to the nearest $1000.
(b) Based on a facility cost of $1,880,000, 25% of which is assumed to be charged to decommissioning, with 10 reactors at the site.
(c) Assumed to be 10% of total capital cost/year; electropolishing associated with decommissioning estimated to be completed in 1 year.
(d) Based on $0.60/kg salvage value and $0.74/kg disposal cost, for a net recovery value of $1.34/kg (see p. 10-3 of Reference 1).
(e) Based on 80% recovery of 910,000 kg potentially recoverable.
(f) Based on 80% recovery of 179,000 kg potentially recoverable stainless steel and 435,000 kg of potentially recoverable carbon steel.

TABLE 8.3-7. Summary of Net Cost Savings Associated with Central Decontamination Services During LWR Decommissioning

Decommissioning Alternative	Net Cost Savings Associated with Decontamination Options ($ thousands)[a] Reuse of Special Tools and Equipment[b]	Mobile Decontamination Equipment[c]	Central Electropolishing Facility with SS Recovery[d]	Total
PWR				
DECON	327	71	740	1138
SAFSTOR[e]	320	81	740	1141
ENTOMB	327	71	740	1138
BWR				
DECON	1165	--[f]	237	1402
SAFSTOR[e]	1200	--	237	1437
ENTOMB[g]	1165	--	237	1402

(a) Rounded to the nearest $1000.
(b) From Table B.4-5.
(c) From Table B.4-6.
(d) From Table B.4-8.
(e) For deferred decontamination after 30 years of safe storage.
(f) Implicitly included in Reference 3; net savings associated with decontamination and reuse included in reuse of special tools and equipment.
(g) Reactor vessel internals removed.

decommissioning a BWR are about 40% greater than the savings for decommissioning a PWR. This is attributable to the significantly greater estimated cost of special tools and equipment given in the BWR decommissioning study.[2]

8.3.5 Maintenance Shops and Services

Central maintenance shops at a multiple-reactor station could have substantially greater capability than the maintenance shop at a single-reactor station. During the reactor operation phase, the more normal and routine maintenance tasks would be accomplished in the maintenance shop at the reactors. The more difficult, special, and overload tasks would be performed at the central shops. Central maintenance shops would be of much greater value to reactor operation than to decommissioning.

During reactor decommissioning the central maintenance shops could:

- provide maintenance and refurbishment of the special tools and equipment that can be used for decommissioning several reactors
- provide refurbishment of reactor process equipment, such as valves, for reuse in other reactors.

These two services would be provided in conjunction with the central equipment decontamination services. The impact of central maintenance shops and services on decommissioning costs is included in the analyses presented in Subsection 8.3.4.1.

8.3.6 Laundry Services

An onsite laundry is judged to have a minimal impact on decommissioning costs. A representative of a vendor of protective clothing[a] expressed doubt that an onsite laundry would reduce costs because:

- payscales at a commercial laundry probably would be lower than at an onsite laundry.
- after making the capital investment in the equipment it is not easy for the reactor operator/s to install new improved equipment that would reduce costs.

(a) John Murray, Safety and Supply Company, Seattle, Washington.

The principal advantage of an onsite laundry would be that the service would be under the direct control of the utility, and would be less susceptible to transportation delays, strikes, and other scheduling problems.

8.3.7 Transportation Services

Onsite transportation services at a multiple-reactor station could provide:

- a variety of vehicles that match the needs more precisely, such as special heavy-equipment cask trailers, etc.
- potentially better availability and greater ease of scheduling.

The onsite capability would probably have to be augmented with other transportation services on occasion. Unit transportation costs would likely be about the same with or without onsite transportation services. However, scheduling should be easier with onsite transportation services, and offsite disruptions would be less likely to detrimentally affect the decommissioning effort.

8.3.8 Central Stores

A central stores installation at a multiple-reactor might achieve the cost advantage of quantity purchases of miscellaneous supplies. Reduced prices probably would not be available for special decommissioning tools and equipment because of the relatively small volume of these items required. No significant impact on decommissioning costs is perceived. The principal advantage of central stores would be more readily available stocks of miscellaneous supplies.

8.3.9 Summary of Centralized Services

Significant savings in decommissioning costs are achievable by providing some centralized services. Health physics services, security forces, solid waste processing, and decontamination services give the significant savings summarized in Table 8.3-8. Savings achievable for the different decommissioning alternatives range from about $2 million for the PWR to about $4 million for the BWR.

8.4 TYPE OF REACTOR

At multiple-reactor stations the two types of light water reactors being constructed are PWRs and BWRs. The estimated decommissioning costs for both

TABLE 8.3-8. Summary of Net Savings by Providing Centralized Services[a]

Decommissioning Alternative	Net Savings ($ thousands) Health Physics Services[b]	Security Forces[c]	Solid Waste Processing[d]	Decontamination Services[e]	Total
PWR					
DECON	462	459	133	1138	2193
SAFSTOR	718	808	144[f]	1141	2812
ENTOMB	462	459	133	1138	2193
BWR					
DECON	618	522	221	1402	2763
SAFSTOR	1054	1066	253[f]	1437	3810
ENTOMB	654	605	221	1402	2882

(a) Assumed to be a 10-reactor station.
(b) From Table 8.3-1.
(c) From Table 8.3-2.
(d) From Table 8.3-3.
(e) From Table 8.3-7.
(f) For deferred decontamination after 30 years of safe storage.

types are shown in Table 8.4-1 for DECON, SAFSTOR, and ENTOMB. These differences in decommissioning costs for the two types of LWRs are also experienced in decommissioning reactors at a multiple-reactor station. However, decommissioning costs for PWRs and BWRs are impacted to about the same extent at a multiple-reactor station as compared to a single-reactor station. Estimated cost impacts for both PWRs and BWRs are developed in Subsections 8.1, 8.2, and 8.3.

8.5 NUMBER OF REACTORS AT STATION

The number of reactors at the multiple-reactor station influences how the radioactive waste is disposed of, whether there is a continuing stable construction labor force, and whether or which centralized services are provided. With a small number of reactors at the station, say a quad, it is not likely that radioactive waste could be disposed of onsite. It is improbable that centralized services would be provided; however, special decommissioning tools

TABLE 8.4-1. Estimated Decommissioning Costs for Light Water Reactors at Single-Reactor Stations

Decommissioning Alternative	Cost ($ millions)[a] PWR[b]	BWR[c]
DECON	31.0	43.6
SAFSTOR[d]	39.7	55.0
ENTOMB[e]	28.7	44.5

(a) Costs are estimated in 1978 dollars and include a 25% contingency.
(b) From Reference 3.
(c) From Reference 2.
(d) Accumulated cost with deferred decontamination at 100 years.
(e) For entombment with reactor internals removed.

and equipment probably would be shared. Improvement and economies in planning the decommissioning of successive reactors would be realized for a few as well as many reactors at a multiple-reactor station. If only a few reactors are located at the station, the continuing stability of the labor force would not be assured. Therefore, there would not be a continuing availability of experienced decommissioning workers.

Detailed discussions of the multiple-reactor station scenarios in Section 10 illustrate the effect on decommissioning costs of the number of reactors at the station.

REFERENCES

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4. H. W. Arrowsmith, et al. Electropolishing as a Decontamination Process: Progress and Application, PNL-SA-6858, Pacific Northwest Laboratory, Richland, Washington, April 1978.

5. E. B. Moore, Jr., Facilitation of Decommissioning Light Water Reactors, NUREG/CR-0569, U.S. Nuclear Regulatory Commission Report by Pacific Northwest Laboratory, December 1979.

6. M. P. Nicholas, "Reconditioning Makes Old Valves 'New,'" Chemical Engineering, May 22, 1978, pp. 117 and 118.

9.0 IMPACT OF MULTIPLE REACTORS ON RADIATION DOSE FROM DECOMMISSIONING

The impact of decommissioning one of the reactors at a multiple-reactor power station on the radiation dose from decommissioning activities is estimated in this section by comparison with the radiation dose estimated for decommissioning a reactor at a single-reactor power station. The same factors examined in the cost analysis, Section 8, are considered in this analysis, including: 1) several different approaches to disposal of radioactive waste, 2) the dedication of the site in perpetuity to nuclear power generation, 3) the availability of centralized services, and 4) the type and number of reactors at the station. The changes in the estimated occupational radiation doses from decommissioning the reference reactors by DECON, SAFSTOR, and ENTOMB, relative to the base-case single-reactor studies for the factors given above, are summarized in Table 9.0-1.

TABLE 9.0-1. Occupational Radiation Dose for Decommissioning One Reactor - Summary of Differences

	Radiation Dose Differences (man-rem)					
	DECON		SAFSTOR[a]		ENTOMB	
Factor	PWR	BWR	PWR	BWR	PWR	BWR
Waste Disposal						
Onsite Interim Storage For:						
30 Years	+71.6	+46.7	-74.0	-68.0	+6.1	+33.3
50 Years	-72.0	-55.1	-77.4	-86.7	-11.6	-25.9
100 Years	-75.0	-59.7	-78.0	-87.9	-12.8	-29.3
Onsite Disposal	-89.8	-100.6	-90.1	-100.7	-22.8	-67.2
Site Dedication[b]	-75.0	-129.0	-21.0	-29.0	-62.0	-118.0
Central Services						
Solid Waste Processing	-3.8	-5.0	-1.6	-2.5	-3.8	-5.0

(a) For deferred decontamination after 30 years of safe storage.
(b) For a multiple-reactor station with five reactors of one type.

9.1 DISPOSAL OF NUCLEAR WASTE

Options for disposal of the nuclear waste generated by decommissioning a reactor at a multiple-reactor station are:

- burial offsite at a licensed disposal facility
- onsite interim storage with later transfer offsite to a licensed waste disposal facility
- burial onsite at a permanent nuclear waste disposal facility.

The impact of each of these options on the radiation dose from disposal of nuclear waste from reactor decommissioning is discussed in the following subsections.

9.1.1 Offsite Nuclear Waste Disposal

Decommissioning a reactor at a multiple-reactor station will generate the same quantity of nuclear waste as will decommissioning an identical reactor at a single-reactor station. The number of waste packages and shipments to the waste disposal site will be the same whether the reactor is at a single- or multiple-reactor station. Therefore, the occupational and public radiation doses are the same whether the reactor is alone on the site or is one of a number of reactors at a multiple-reactor station.

9.1.2 Onsite Interim Nuclear Waste Storage

The occupational radiation dose from disposal of the nuclear decommissioning waste is accumulated during shipment of the waste to the disposal site and during placement of the waste in the disposal facility. With onsite interim waste storage, each of the following tasks results in an occupational dose:

1. onsite transportation to the interim storage facility
2. placement of the waste in the interim storage facility
3. retrieval of the waste from the interim storage facility
4. transportation to the offsite disposal facility
5. placement of the waste in the offsite disposal facility.

Tasks 4 and 5 are the same as those for immediate disposal of the waste at an offsite nuclear waste disposal facility; however, the dose rates should be lower and there should be less waste for disposal after a number of years of onsite interim storage. The radiation doses to the workers are estimated for each of the five tasks. Exposure of the public occurs only during transportation of the waste to the offsite waste disposal facility.

The offsite transportation doses are estimated using the same dose rate assumptions as were used in Reference 1, p. 11-26, which gives an occupational dose rate of 0.073 man-rem per shipment and a public dose rate of 0.015 man-rem per shipment. For onsite transportation to the interim storage facility, it is assumed:

- The truck driver spends 2 hr in the cab while hauling the shipment and the dose rate is 2 mR/hr.
- The driver spends 20 min outside of the cab at a distance of 2 m from the cargo and the dose rate is 10 mR/hr.
- Since all movement is over private roads, there is no dose to the public.

The occupational onsite transport dose is [2 hr x 2 mR/hr + 1/3 hr x 10 mR/hr] x 1 driver x 0.001 = 0.0073 man-rem per shipment.

Details of the estimation of the occupational doses for the other tasks involved in onsite interim storage of the nuclear waste are given in Appendix C.

In the studies of decommissioning the reference PWR[1,2] and the reference BWR,[3] the radiation doses to the transport workers and the public were estimated, but the occupational doses to the workers at the waste disposal facility were not. In this study, however, estimates of the occupational doses to workers at the onsite nuclear waste disposal facility are included.

9.1.2.1 Radiation Doses from Onsite Interim Storage of Nuclear Waste from DECON

The estimated occupational radiation doses for disposal of the nuclear waste from decommissioning the reference PWR by DECON are given in Table 9.1-1; for the reference BWR, these estimates are given in Table 9.1-2. Also given in the tables are the differences between the occupational radiation doses for immediate offsite disposal and onsite interim storage followed by offsite

TABLE 9.1-1. Estimated Occupational Radiation Doses from Disposal of the Nuclear Waste from DECON of the Reference PWR

	Estimated Occupational Dose (man-rem)						
	Immediate Offsite Disposal			Onsite Interim Storage			
Waste Disposal Task	Neutron-Activated Material	Contaminated Material & Radwaste	Total	Neutron-Activated Material	Contaminated Material & Radwaste	Total	Difference from Immediate Offsite Disposal
Onsite Transport	--	--	--	1.6	8.4	10.0	10.0
Placement in Interim Storage	--	--	--	95.0	27.0	122.0	122.0
Retrieval from Interim Storage	--	--	--				
After 30 years	--	--	--	30.0	6.0	36.0	36.0
After 50 years	--	--	--	1.0	0.5	1.5	1.5
After 100 years	--	--	--	0.02	0.03	0.05	0.05
Offsite Transport	15.8	83.7	99.5				
After 30 years	--	--	--	13.0	73.4	86.4	(13.1)[(a)]
After 50 years	--	--	--	12.8	1.7	14.5	(85.0)
After 100 years	--	--	--	12.8	1.5	14.3	(85.2)
Placement in Offsite Disposal	95.0	27.0	122.0				
After 30 years	--	--	--	30.0	6.0	36.0	(86.0)
After 50 years	--	--	--	1.0	0.5	1.5	(120.5)
After 100 years	--	--	--	0.02	0.03	0.05	(121.9)
Total Difference							
After 30 years							71.6
After 50 years							(72.0)
After 100 years							(75.0)

(a) ( ) indicates a reduction in dose.

TABLE 9.1-2. Estimated Occupational Radiation Doses from Disposal of the Nuclear Waste from DECON of the Reference BWR

	Estimated Occupational Dose (man-rem)						
	Immediate Offsite Disposal			Onsite Interim Storage			
Waste Disposal Task	Neutron-Activated Material	Contaminated Material & Radwaste	Total	Neutron-Activated Material	Contaminated Material & Radwaste	Total	Difference from Immediate Offsite Disposal
Onsite Transport	--	--	--	1.8	6.8	8.6	8.6
Placement in Interim Storage	--	--	--	130.0	35.0	165.0	165.0
Retrieval from Interim Storage	--	--	--				
After 30 years	--	--	--	13.0	7.2	20.2	20.2
After 50 years	--	--	--	1.5	0.72	2.22	2.2
After 100 years	--	--	--	0.02	0.05	0.07	0.07
Offsite Transport	18.0	67.2	85.2				
After 30 years	--	--	--	17.3	65.6	82.9	(2.3)[a]
After 50 years	--	--	--	15.6	1.5	17.1	(68.1)
After 100 years	--	--	--	15.6	1.1	16.7	(68.5)
Placement in Offsite Disposal	130.0	35.0	165.0				
After 30 years	--	--	--	13.0	7.2	20.2	(144.8)
After 50 years	--	--	--	1.5	0.7	2.2	(162.8)
After 100 years	--	--	--	0.02	0.05	0.07	(164.9)
Total Difference							
After 30 years							46.7
After 50 years							(55.1)
After 100 years							(59.7)

(a) ( ) indicates a reduction in dose.

disposal after 30, 50, or 100 years of interim storage. With only 30 years of interim storage, the occupational radiation doses for disposal of radioactive waste from decommissioning for both the PWR and the BWR are greater than the occupational doses for immediate offsite waste disposal. With onsite interim storage for 50 or 100 years, there is a reduction of the occupational radiation dose for waste disposal when compared with immediate offsite disposal.

The estimated radiation doses received by the public from transportation of the radioactive waste from DECON to an offsite radioactive waste disposal facility are given in Table 9.1-3 for immediate disposal and for disposal after 30, 50, or 100 years of onsite interim storage. The public radiation dose from shipment of the radioactive decommissioning waste to an offsite waste disposal facility is lower with onsite interim storage of the waste than it is for immediate offsite disposal of the waste.

TABLE 9.1-3. Estimated Radiation Doses to the Public from Transportation of the Nuclear Waste from Decommissioning a Reactor by DECON

Reactor/Storage Type / Period (yr)	Public Radiation Dose (man-rem) Immediate Offsite Disposal	Onsite Interim Storage	Difference
PWR/0	21.0	--	
PWR/30	--	18.0	(3.0)[a]
PWR/50	--	3.0	(18.0)[a]
PWR/100	--	3.0	(18.0)[a]
BWR/0	22.4	--	
BWR/30	--	17.0	(5.4)[a]
BWR/50	--	3.5	(18.9)[a]
BWR/100	--	3.4	(19.0)[a]

(a) ( ) indicates a reduction of the dose.

9.1.2.2 Radiation Doses from Onsite Interim Storage of Nuclear Waste from SAFSTOR

The estimated occupational radiation doses from the disposal of the nuclear waste generated by decommissioning the reference PWR by SAFSTOR are given and compared with the doses from immediate offsite disposal in Table 9.1-4; for the reference BWR, these estimates are given and compared in Table 9.1-5. Differences between the occupational radiation doses from immediate offsite disposal of the waste from SAFSTOR and the doses from interim storage of the waste before offsite disposal are given in Table 9.1-6 for the PWR and in Table 9.1-7 for the BWR. For all combinations of safe storage periods and interim waste storage periods, the occupational radiation dose for waste disposal is reduced with onsite interim storage of the waste before it is finally sent to offsite storage.

The estimated radiation doses to the public from transportation of the nuclear waste from SAFSTOR to an offsite waste disposal facility are given in Table 9.1-8 for immediate offsite disposal and for disposal after 30, 50, or 100 years of onsite interim storage. The public doses shown include the doses from preparations for safe storage as well as those from deferred decontamination after 30, 50, or 100 years. For all combinations of deferred decontamination and onsite interim storage periods, the radiation dose received by the public from transportation of the decommissioning waste from SAFSTOR is lower if the waste is placed in interim storage before it is shipped to an offsite waste disposal facility.

9.1.2.3 Radiation Doses from Onsite Interim Storage of Nuclear Waste from ENTOMB

Estimated occupational radiation doses for disposal of the nuclear waste from decommissioning the reference PWR by ENTOMB are given in Table 9.1-9; for the reference BWR, these estimates are given in Table 9.1-10. The tables also show the differences between the occupational radiation doses for immediate offsite disposal after 30, 50, or 100 years of interim storage. When the nuclear waste is removed from onsite interim storage after 30 years, the total occupational radiation dose for waste disposal is greater than the occupational dose for immediate offsite disposal. With onsite interim storage of 50 or 100 years, the occupational radiation dose for waste disposal is reduced, compared with the dose for immediate offsite disposal.

The estimated radiation doses received by the public from transportation of the nuclear waste from ENTOMB to an offsite waste disposal facility are given

TABLE 9.1-4. Estimated Occupational Radiation Doses from Disposal of the Nuclear Waste from SAFSTOR of the Reference PWR

	Estimated Occupational Dose (man-rem)						
	Immediate Offsite Disposal			Onsite Interim Storage			
Waste Disposal Task	Neutron-Activated Material	Contaminated Material & Radwaste	Total	Neutron-Activated Material	Contaminated Material & Radwaste	Total	Difference from Immediate Offsite Disposal
		Preparations For Safe Storage					
Onsite Transport	--	--	--	--	0.9	0.9	0.9
Placement in Interim Storage	--	--	--	--	2.0	2.0	2.0
Retrieval from Interim Storage	--	--	--				
After 30 years	--	--	--	--	0.44	0.44	0.44
After 50 years	--	--	--	--	0.04	0.04	0.04
After 100 years	--	--	--	--	0.002	0.002	0.002
Offsite Transport	--	10.4	10.4				
After 30 years	--	--	--	--	2.1	2.1	(8.3)[a]
After 50 years	--	--	--	--	0.5	0.5	(9.9)
After 100 years	--	--	--		0.4	0.4	(10.0)
Placement in Offsite Disposal	--	2.0	2.0				
After 30 years	--	--	--	--	0.44	0.44	(1.6)
After 50 years	--	--	--	--	0.04	0.04	(1.96)
After 100 years	--	--	--	--	0.002	0.002	(1.998)
Total After 30 years							(6.6)
After 50 years							(8.9)
After 100 years							(9.1)

TABLE 9.1-4. (Contd)

Waste Disposal Task	Estimated Occupational Dose (man-rem): Immediate Offsite Disposal: Neutron-Activated Material	Immediate Offsite Disposal: Contaminated Material & Radwaste	Immediate Offsite Disposal: Total	Onsite Interim Storage: Neutron-Activated Material	Onsite Interim Storage: Contaminated Material & Radwaste	Onsite Interim Storage: Total	Difference from Immediate Offsite Disposal
	Deferred Decontamination After 30 Years						
Onsite Transport	--	--	--	1.3	7.30	8.6	8.6
Placement in Interim Storage	--	--	--	10.0	5.8	15.8	15.8
Retrieval from Interim Storage	--	--	--				
After 30 years	--	--	--	0.3	0.22	0.52	0.52
After 50 years	--	--	--	0.04	0.07	0.11	0.11
After 100 years	--	--	--	0.016	0.012	0.028	0.028
Offsite Transport	13.0	72.7	85.7				
After 30 years	--	--	--	7.7	0.95	8.65	(77.0)
After 50 years	--	--	--	7.7	0.73	8.43	(77.3)
After 100 years	--	--	--	7.7	0.51	8.21	(77.5)
Placement in Offsite Disposal	10.0	5.8	15.8				
After 30 years	--	--	--	0.3	0.22	0.52	(15.3)
After 50 years	--	--	--	0.04	0.07	0.11	(15.7)
After 100 years	--	--	--	0.016	0.012	0.028	(15.8)
Total After 30 years							(67.4)
After 50 years							(68.5)
After 100 years							(68.9)

TABLE 9.1-4. (Contd)

Waste Disposal Task	Estimated Occupational Dose (man-rem): Immediate Offsite Disposal: Neutron-Activated Material	Immediate Offsite Disposal: Contaminated Material & Radwaste	Immediate Offsite Disposal: Total	Onsite Interim Storage: Neutron-Activated Material	Onsite Interim Storage: Contaminated Material & Radwaste	Onsite Interim Storage: Total	Difference from Immediate Offsite Disposal
	Deferred Decontamination After 50 Years						
Onsite Transport	--	--	--	0.8	0.09	0.89	0.89
Placement in Interim Storage	--	--	--	1.0	0.51	1.51	1.51
Retrieval from Interim Storage	--	--	--				
After 30 years	--	--	--	0.04	0.07	0.11	0.11
After 50 years	--	--	--	0.016	0.03	0.046	0.046
After 100 years	--	--	--	0.011	0.007	0.018	0.018
Offsite Transport	7.7	0.95	8.65				
After 30 years	--	--	--	7.7	0.95	8.65	(0.0)
After 50 years	--	--	--	7.7	0.73	8.43	(0.2)
After 100 years	--	--	--	7.7	0.51	8.21	(0.4)
Placement in Offsite Disposal	1.0	0.51	1.51				
After 30 years	--	--	--	0.04	0.07	0.11	(1.4)
After 50 years	--	--	--	0.016	0.03	0.046	(1.5)
After 100 years	--	--	--	0.011	0.007	0.018	(1.5)
Total After 30 years							1.11
After 50 years							0.75
After 100 years							0.52

TABLE 9.1-4. (Contd)

Waste Disposal Task	Estimated Occupational Dose (man-rem): Immediate Offsite Disposal — Neutron-Activated Material	Immediate Offsite Disposal — Contaminated Material & Radwaste	Immediate Offsite Disposal — Total	Onsite Interim Storage — Neutron-Activated Material	Onsite Interim Storage — Contaminated Material & Radwaste	Onsite Interim Storage — Total	Difference from Immediate Offsite Disposal
	Deferred Decontamination After 100 Years						
Onsite Transport	--	--	--	0.8	0.07	0.87	0.87
Placement in Interim Storage	--	--	--	0.016	0.033	0.049	0.049
Retrieval from Interim Storage	--	--	--				
After 30 years	--	--	--	0.012	0.012	0.024	0.024
After 50 years	--	--	--	0.011	0.007	0.018	0.018
After 100 years	--	--	--	0.011	0.002	0.013	0.013
Offsite Transport	7.7	0.73	8.43				
After 30 years	--	--	--	7.7	0.51	8.21	(0.22)
After 50 years	--	--	--	7.7	0.44	8.14	(0.29)
After 100 years	--	--	--	7.7	0.37	8.07	(0.36)
Placement in Offsite Disposal	0.016	0.033	0.049				
After 30 years	--	--	--	0.012	0.012	0.024	(0.02)
After 50 years	--	--	--	0.011	0.007	0.018	(0.03)
After 100 years	--	--	--	0.011	0.002	0.013	(0.04)
Total After 30 years							0.70
After 50 years							0.62
After 100 years							0.53

(a) ( ) Indicates a reduction of the dose compared with immediate offsite disposal.

TABLE 9.1-5. Estimated Occupational Radiation Doses from Disposal of the Nuclear Waste from SAFSTOR of the Reference BWR

Waste Disposal Task	Estimated Occupational Dose (man-rem)						
	Immediate Offsite Disposal			Onsite Interim Storage			
	Neutron-Activated Material	Contaminated Material & Radwaste	Total	Neutron-Activated Material	Contaminated Material & Radwaste	Total	Difference from Immediate Offsite Disposal
	Preparations For Safe Storage						
Onsite Transport	--	--	--	--	0.7	0.7	0.7
Placement in Interim Storage	--	--	--	--	6.7	6.7	6.7
Retrieval from Interim Storage	--	--	--				
After 30 years	--	--	--	--	1.5	1.5	1.5
After 50 years	--	--	--	--	0.14	0.14	0.14
After 100 years	--	--	--	--	0.01	0.01	0.01
Offsite Transport	--	23.2	23.2				
After 30 years	--	--	--	--	2.8	2.8	(20.4)[(a)]
After 50 years	--	--	--	--	1.2	1.2	(22.01)
After 100 years	--	--	--	--	0.9	0.9	(22.3)
Placement in Offsite Disposal	--	6.7	6.7				
After 30 years	--	--	--	--	1.5	1.5	(5.2)
After 50 years	--	--	--	--	0.14	0.14	(6.6)
After 100 years	--	--	--	--	0.01	0.01	(6.7)
Total After 30 years							(16.7)
After 50 years							(21.1)
After 100 years							(21.6)

TABLE 9.1-5. (Contd)

Waste Disposal Task	Estimated Occupational Dose (man-rem)						
	Immediate Offsite Disposal			Onsite Interim Storage			
	Neutron-Activated Material	Contaminated Material & Radwaste	Total	Neutron-Activated Material	Contaminated Material Radwaste	Total	Difference from Immediate Offsite Disposal
	Deferred Decontamination After 30 Years						
Onsite Transport	--	--	--	1.7	6.0	7.7	7.7
Placement in Interim Storage	--	--	--	14.0	7.2	21.2	21.2
Retrieval from Interim Storage	--	--	--				
After 30 years	--	--	--	0.5	0.3	0.8	0.8
After 50 years	--	--	--	0.06	0.09	0.15	0.15
After 100 years	--	--	--	0.008	0.018	0.026	0.026
Offsite Transport	17.3	60.4	77.7				
After 30 years	--	--	--	15.3	1.8	17.1	(60.6)
After 50 years	--	--	--	2.7	1.5	4.2	(73.5)
After 100 years	--	--	--	2.7	1.0	3.7	(74.0)
Placement in Offsite Disposal	14.0	7.2	21.2				
After 30 years	--	--	--	0.5	0.3	0.8	(20.4)
After 50 years	--	--	--	0.06	0.09	0.15	(21.1)
After 100 years	--	--	--	0.08	0.018	0.026	(21.2)
Total After 30 years							(51.3)
After 50 years							(65.6)
After 100 years							(66.3)

TABLE 9.1-5. (Contd)

Waste Disposal Task	Estimated Occupational Dose (man-rem): Immediate Offsite Disposal: Neutron-Activated Material	Immediate Offsite Disposal: Contaminated Material & Radwaste	Immediate Offsite Disposal: Total	Onsite Interim Storage: Neutron-Activated Material	Onsite Interim Storage: Contaminated Material & Radwaste	Onsite Interim Storage: Total	Difference from Immediate Offsite Disposal
	Deferred Decontamination After 50 Years						
Onsite Transport	--	--	--	1.4	0.2	1.6	1.6
Placement in Interim Storage	--	--	--	1.6	0.8	2.4	2.4
Retrieval from Interim Storage	--	--	--				
After 30 years	--	--	--	0.06	0.3	0.36	0.36
After 50 years	--	--	--	0.02	0.05	0.07	0.07
After 100 years	--	--	--	0.008	0.01	0.018	0.018
Offsite Transport	14.4	1.8	16.2				
After 30 years	--	--	--	2.7	1.5	4.2	(12.0)
After 50 years	--	--	--	2.7	1.2	3.9	(12.3
After 100 years	--	--	--	2.7	0.9	3.6	(12.6)
Placement in Offsite Disposal	1.6	0.8	2.4				
After 30 years	--	--	--	0.06	0.3	0.36	(2.0)
After 50 years	--	--	--	0.02	0.05	0.07	(2.3)
After 100 years	--	--	--	0.008	0.01	0.018	(2.4)
Total After 30 years							(9.6)
After 50 years							(10.5)
After 100 years							(11.0)

TABLE 9.1-5. (Contd)

Waste Disposal Task	Estimated Occupational Dose (man-rem)						
	Immediate Offsite Disposal			Onsite Interim Storage			
	Neutron-Activated Material	Contaminated Material & Radwaste	Total	Neutron-Activated Material	Contaminated Material & Radwaste	Total	Difference from Immediate Offsite Disposal
	Deferred Decontamination After 100 Years						
Onsite Transport	--	--	--	0.2	0.1	0.3	0.3
Placement in Interim Storage	--	--	--	0.02	0.05	0.07	0.07
Retrieval from Interim Storage	--	--	--				
After 30 years	--	--	--	0.008	0.018	0.026	0.026
After 50 years	--	--	--	0.008	0.010	0.018	0.018
After 100 years	--	--	--	0.007	0.002	0.009	0.009
Offsite Transport	2.3	1.5	3.8				
After 30 years	--	--	--	2.3	1.0	3.3	(0.5)
After 50 years	--	--	--	2.3	0.9	3.2	(0.6)
After 100 years	--	--	--	2.3	0.8	3.1	(0.7)
Placement in Offsite Disposal	0.02	0.05	0.07				
After 30 years	--	--	--	0.008	0.018	0.026	(0.04)
After 50 years	--	--	--	0.008	0.010	0.018	(0.05)
After 100 years	--	--	--	0.007	0.002	0.009	(0.06)
Total After 30 years							(0.14)
After 50 years							(0.26)
After 100 years							(0.38)

(a) ( ) indicates a reduction of the dose compared with immediate offsite disposal.

TABLE 9.1-6. Summary of Occupational Doses from Disposal of Nuclear Waste from SAFSTOR of the Reference PWR

Deferred Decontamination After (years)	Dose Differences from Immediate Offsite Disposal (man-rem)[a] Interim Storage Period: 30 years	50 years	100 years
30	(74.0)[b]	(77.4)	(78.0)
50	(5.5)	(8.2)	(8.6)
100	(5.9)	(8.3)	(8.6)

(a) Includes sum of occupational doses from preparations for safe storage and deferred decontamination.
(b) ( ) indicates a reduction of the occupational radiation dose compared with immediate offsite disposal.

TABLE 9.1-7. Summary of Occupational Doses from Disposal of Nuclear Waste from SAFSTOR of the Reference BWR

Deferred Decontamination After (years)	Dose Differences from Immediate Offsite Disposal (man-rem)[a]: 30 years Interim Storage	50 years Interim Storage	100 years Interim Storage
30	(68.0)[b]	(86.7)	(87.9)
50	(26.3)	(31.6)	(32.6)
100	(16.8)	(21.4)	(22.0)

(a) Includes sum of occupational doses from preparations for safe storage and deferred decontamination.
(b) ( ) indicates a reduction of the occupational radiation dose compared with immediate offsite disposal.

in Table 9.1-11 for immediate offsite disposal and for disposal after 30, 50, or 100 years of onsite interim storage. The table shows that the public radiation dose is reduced by onsite interim storage of the nuclear waste before sending it to an offsite disposal facility.

9.1.3 Onsite Nuclear Waste Disposal

Onsite disposal of nuclear waste differs from offsite disposal in the shorter transport distance from the reactor site to the waste disposal facility. The occupational radiation dose for placement of the waste in the nuclear waste disposal facility is assumed to be the same for onsite disposal as it is for

TABLE 9.1-8. Estimated Radiation Doses to the Public from Transportation of the Nuclear Waste from Decommissioning a Reactor by SAFSTOR

Reactor/Storage Type / Period (yr)	Public Radiation Dose (man-rem)[a] Immediate Offsite Disposal	Onsite Interim Storage	Difference
PWR/0	19.7	--	
PWR/30	--	2.2	(17.5)[b]
PWR/50	--	1.8	(17.9)
PWR/100	--	1.8	(17.9)
BWR/0	20.8	--	
BWR/30	--	4.1	(16.7)
BWR/50	--	1.2	(19.6)
BWR/100	--	1.0	(19.8)
	Deferred Decontamination After 50 Years		
PWR/0	3.9	--	
PWR/30	--	2.1	(1.8)
PWR/50	--	1.8	(2.1)
PWR/100	--	1.8	(2.1)
BWR/0	8.1	--	
BWR/30	--	1.5	(6.6)
BWR/50	--	1.1	(7.0)
BWR/100	--	1.0	(7.1)
	Deferred Decontamination After 100 Years		
PWR/0	3.8	--	
PWR/30	--	2.1	(1.7)
PWR/50	--	1.8	(2.0)
PWR/100	--	1.8	(2.0)
BWR/0	5.6	--	
BWR/30	--	1.3	(4.3)
BWR/50	--	1.0	(4.6)
BWR/100	--	0.7	(4.9)

(a) Includes the dose from preparations for safe storage and from deferred decontamination.
(b) ( ) indicates reduction of the dose.

TABLE 9.1-9. Estimated Occupational Doses from Disposal of the Nuclear Waste from ENTOMB of the Reference PWR

Waste Disposal Task	Estimated Occupational Dose (man-rem): Immediate Offsite Disposal: Neutron-Activated Material	Immediate Offsite Disposal: Contaminated Material & Radwaste	Immediate Offsite Disposal: Total	Onsite Interim Storage: Neutron-Activated Material	Onsite Interim Storage: Contaminated Material & Radwaste	Onsite Interim Storage: Total	Difference from Immediate Offsite Disposal
Onsite Transport	--	--	--	0.6	1.6	2.2	2.2
Placement in Interim Storage	--	--	--	23.0	20.0	43.0	43.0
Retrieval from Interim Storage	--	--	--				
After 30 years	--	--	--	2.4	2.5	4.9	4.9
After 50 years	--	--	--	0.24	0.25	0.49	0.49
After 100 years	--	--	--	0.006	0.015	0.021	0.021
Offsite Transport	6.4	15.5	21.9				
After 30 years	--	--	--	6.1	9.9	16.0	(5.9)[a]
After 50 years	--	--	--	5.8	1.3	7.1	(14.8)
After 100 years	--	--	--	5.8	1.1	6.9	(15.0)
Placement in Offsite Disposal	23.0	20.0	43.0				
After 30 years	--	--	--	2.4	2.5	4.9	(38.1)
After 50 years	--	--	--	0.24	0.25	0.49	(42.5)
After 100 years	--	--	--	0.006	0.015	0.021	(43.0)
Total Difference							
After 30 years							6.1
After 50 years							(11.6)
After 100 years							(12.8)

(a) ( ) indicates a reduction in dose.

TABLE 9.1-10. Estimated Occupational Doses from Disposal of the Nuclear Waste from ENTOMB of the Reference BWR

	Estimated Occupational Dose (man-rem)						
	Immediate Offsite Disposal			Onsite Interim Storage			
Waste Disposal Task	Neutron-Activated Material	Contaminated Material & Radwaste	Total	Neutron-Activated Material	Contaminated Material & Radwaste	Total	Difference from Immediate Offsite Disposal
Onsite Transport	--	--	--	1.4	3.2	4.6	3.6
Placement in Interim Storage	--	--	--	115.0	20.0	135.0	135.0
Retrieval from Interim Storage	--	--	--				
After 30 years	--	--	--	11.5	4.2	15.7	15.7
After 50 years	--	--	--	1.1	0.4	1.5	1.5
After 100 years	--	--	--	0.014	0.03	0.04	0.04
Offsite Transport	14.2	32.5	46.7				
After 30 years	--	--	--	14.2	30.8	45.0	(1.7)[(a)]
After 50 years	--	--	--	12.7	1.5	14.2	(32.5)
After 100 years	--	--	--	12.7	1.1	13.8	(32.9)
Placement in Offsite Disposal	115.0	20.0	135.0				
After 30 years	--	--	--	11.5	4.2	15.7	(119.3)
After 50 years	--	--	--	1.1	0.4	1.5	(133.5)
After 100 years	--	--	--	0.014	0.03	0.04	(135.0)
Total Difference							
After 30 years							33.3
After 50 years							(25.9)
After 100 years							(29.3)

(a) ( ) indicates a reduction in dose.

TABLE 9.1-11. Estimated Radiation Doses to the Public from Transportation of the Nuclear Waste from Decommissioning a Reactor by ENTOMB

Reactor/Storage Type / Period (yr)	Public Radiation Dose (man-rem) Immediate Offsite Disposal	Onsite Interim Storage	Difference
PWR/0	4.5	--	
PWR/30	--	3.3	(1.2)[a]
PWR/50	--	1.5	(3.0)
PWR/100	--	1.4	(3.1)
BWR/0	9.6	--	
BWR/30	--	9.2	(0.4)
BWR/50	--	2.9	(6.7)
BWR/100	--	2.8	(6.8)

(a) ( ) indicates a reduction of the dose.

offsite disposal. Differences in the occupational radiation doses for onsite and offsite disposal are due to the shorter transport distance for onsite disposal. There will be no exposure of the public to radiation during transportation of the nuclear waste to the onsite disposal facility, since movement will be over private roads in a privately controlled area.

The estimated radiation doses to transportation workers are given in Table 9.1-12 for both offsite and onsite disposal of the nuclear waste from decommissioning the reference PWR and BWR. In all cases, the radiation dose for onsite disposal of the waste is less than 10% of the dose for offsite disposal.

9.2 SITE DEDICATION

Dedication of a site to nuclear power generation results in replacement reactors being constructed on a schedule to achieve startup of a new reactor as an old reactor is shut down. At such dedicated sites, either relatively long

TABLE 9.1-12. Estimated Transportation Doses from Disposal of Nuclear Decommissioning Waste

Decommissioning/Reactor Alternative / Type	Number of Shipments: Offsite Disposal	Number of Shipments: Onsite Disposal	Transportation Dose (man-rem): Offsite Disposal	Transportation Dose (man-rem): Onsite Disposal	Transportation Dose (man-rem): Difference
DECON/PWR	1363	1326	99.5	9.7	(89.8)[a]
DECON/BWR	1495	1168	109.1	8.5	(100.6)
SAFSTOR/PWR					
30 years Safe Stge.	1363	1288	99.5	9.4	(90.1)
50 years Safe Stge.	330	207	24.1	1.5	(22.6)
100 years Safe Stge.	324	204	23.7	1.5	(22.2)
SAFSTOR/BWR					
30 years Safe Stge.	1495	1148	109.1	8.4	(100.7)
50 years Safe Stge.	560	326	40.9	2.4	(38.5)
100 years Safe Stge.	555	157	40.5	1.1	(39.4)
ENTOMB/PWR	343	301	25.0	2.2	(22.8)
ENTOMB/BWR	985	639	71.9	4.7	(67.2)

(a) ( ) indicates a reduction of the dose.

periods of construction activity will occur periodically or there will be continuous construction activity at the site if the startup of the reactors is spaced to occur over a 30-year period.

It is expected that the efficiency of decommissioning the reactors at a multiple-reactor station will improve after the first reactor is decommissioned due to the learning process. In Subsection 8.2 of Section 8, the impact of site dedication on the efficiency of decommissioning reactors of the same type is estimated. Since the improved efficiency of the decommissioning operations is attributed to shortening the schedule, the cost reduction factors given in Table 8.2-1 should also apply to occupational radiation dose reduction.

In this subsection, the dose reductions expected are developed when four reactors of one type and five reactors of one type are decommissioned at a dedicated site.

9.2.1 Impact on Radiation Doses from DECON

The impact of site dedication on the occupational radiation doses from decommissioning the reference reactors by DECON is given in Table 9.2-1 for the PWR and in Table 9.2-2 for the BWR.

TABLE 9.2-1. Impact of Site Dedication on Estimated Occupational Radiation Doses from DECON of a PWR

Building	Average Occupational Dose (man-rem)			Dose Reduction (man-rem)	
	Single-Reactor Station[(a)]	4 Reactors of One Type[(b)]	5 Reactors of One Type[(b)]	4 Reactors of One Type	5 Reactors of One Type
Reactor Building	490	461	456	29	34
Auxiliary Building	227	213	211	14	16
Fuel Building	134	126	125	8	9
Ancillaries	233	219	217	14	16
Totals	1084	1019	1009	65	75

(a) From Table 11.3-1 of Reference 1.
(b) Dose reduction factors - 0.94 for 4 reactors of one type and 0.93 for 5 reactors of one type.

TABLE 9.2-2. Impact of Site Dedication on Estimated Occupational Radiation Doses from DECON of a BWR

Building	Average Occupational Dose (man-rem)			Dose Reduction (man-rem)	
	Single-Reactor Station[(a)]	4 Reactors of One Type[(b)]	5 Reactors of One Type[(b)]	4 Reactors of One Type	5 Reactors of One Type
Reactor Building	891	838	829	53	62
Turbine Generator Building	193	181	179	12	14
Radwaste & Control Building	530	498	493	32	37
Ancillaries	231	217	215	14	16
Totals	1845	1734	1716	111	129

(a) From Table 11.2-1 of Reference 3.
(b) Dose reduction factors - 0.94 for 4 reactors of one type and 0.93 for 5 reactors of one type.

Occupational dose reductions of 6% are estimated when four reactors of one type are decommissioned and of 7% when five reactors of one type are decommissioned.

9.2.2 Impact on Radiation Doses from SAFSTOR

The impact of site dedication on the occupational radiation doses from the preparations for safe storage is presented in Table 9.2-3 for the reference PWR and in Table 9.2-4 for the reference BWR.

Impacts on the occupational doses from deferred decontamination of the reference reactors are given in Table 9.2-5 for the PWR and in Table 9.2-6 for the BWR.

Estimated reductions of the occupational dose attributable to the efficiencies that can be achieved by decommissioning several reactors of one type by SAFSTOR at a multiple-reactor station are given for both reference reactors in Table 9.2-7.

9.2.3 Impact on Radiation Doses from ENTOMB

The impacts of site dedication on the occupational radiation dose from decommissioning the reference reactors by ENTOMB are presented in Table 9.2-8 for the reference PWR and in Table 9.2-9 for the reference BWR.

TABLE 9.2-3. Impact of Site Dedication on Estimated Occupational Radiation Doses from Preparations for Safe Storage of a PWR

Building	Average Occupational Dose (man-rem)			Dose Reduction (man-rem)	
	Single-Reactor Station[(a)]	4 Reactors of One Type[(b)]	5 Reactors of One Type[(b)]	4 Reactors of One Type	5 Reactors of One Type
Reactor Building	58	55	54	3	4
Auxiliary Building	30	28	28	2	2
Fuel Building	15	14	14	1	1
Ancillaries	176	165	164	11	12
Totals	279	262	260	17	19

(a) From Table 11.3-2 of Reference 1.
(b) Dose reduction factors - 0.94 for 4 reactors of one type and 0.93 for 5 reactors of one type.

TABLE 9.2-4. Impact of Site Dedication on Estimated Occupational Radiation Doses from Preparations for Safe Storage of a BWR

Building	Average Occupational Dose (man-rem)			Dose Reduction (man-rem)	
	Single-Reactor Station[a]	4 Reactors of One Type[b]	5 Reactors of One Type[b]	4 Reactors of One Type	5 Reactors of One Type
Reactor Building	155	146	144	9	11
Turbine Generator Building	18	17	17	1	1
Radwaste & Control Building	99	93	92	6	7
Ancillaries	103	97	96	6	7
Totals	375	353	349	22	26

(a) From Table 11.2-3 of Reference 3.
(b) Dose reduction factors - 0.94 for 4 reactors of one type and 0.93 for 5 reactors of one type.

TABLE 9.2-5. Impact of Site Dedication on Estimated Occupational Radiation Doses from Deferred Decontamination of a PWR

Years After Reactor Shutdown	Average Occupational Dose (man-rem)			Dose Reduction (man-rem)	
	Single-Reactor Station[a]	4 Reactors of One Type[b]	5 Reactors of One Type[b]	4 Reactors of One Type	5 Reactors of One Type
30	24	23	22	1	2
50	2	2	2	0	0
100	1	1	1	0	0

(a) From Table H.6-1 of Reference 1
(b) Dose reduction factors - 0.94 for 4 reactors of one type and 0.93 for 5 reactors of one type.

TABLE 9.2-6. Impact of Site Dedication on Estimated Occupational Radiation Doses from Deferred Decontamination of a BWR

Years After Reactor Shutdown	Average Occupational Dose (man-rem) Single-Reactor Station[a]	4 Reactors of One Type[b]	5 Reactors of One Type[b]	Dose Reduction (man-rem) 4 Reactors of One Type	5 Reactors of One Type
30	36	34	33	2	3
50	3	3	3	0	0
100	<1	<1	<1	0	0

(a) From Table 11.2-6 of Reference 3.
(b) Dose reduction factors - 0.94 for 4 reactors of one type and 0.93 for 5 reactors of one type.

TABLE 9.2-7. Estimated Dose Reductions from Decommissioning Several Reactors of One Type by SAFSTOR

Years of Safe Storage	Dose Reduction (man-rem)[a] PWR 4 Reactors of One Type	PWR 5 Reactors of One Type	BWR 4 Reactors of One Type	BWR 5 Reactors of One Type
30	18	21	24	29
50	17	19	22	26
100	17	19	22	26

(a) Includes the dose reductions from preparations for safe storage and from deferred decontamination.

TABLE 9.2-8. Impact of Site Dedication on Estimated Occupational Radiation Doses from ENTOMB of a PWR

Building	Average Occupational Dose (man-rem)			Dose Reduction (man-rem)	
	Single-Reactor Station[(a)]	4 Reactors of One Type[(b)]	5 Reactors of One Type[(b)]	4 Reactors of One Type	5 Reactors of One Type
Reactor Building	130	122	121	8	9
Auxiliary Building	292	274	272	18	20
Fuel Building	147	138	137	9	10
Ancillaries	378	355	352	23	26
Totals	947	889	882	58	65

(a) From Table 4.6-1 of Reference 2.

(b) Dose reduction factors - 0.94 for 4 reactors of one type and 0.93 for 5 reactors of one type.

TABLE 9.2-9. Impact of Site Dedication on Estmated Occupational Radiation Doses from ENTOMB of a BWR

Building	Average Occupational Dose (man-rem)			Dose Reduction (man-rem)	
	Single-Reactor Station[(a)]	4 Reactors of One Type[(b)]	5 Reactors of One Type[(b)]	4 Reactors of One Type	5 Reactors of One Type
Reactor Building	738	694	686	44	52
Turbine Generator Building	195	183	181	12	14
Radwaste & Control Building	521	490	485	31	36
Ancillaries	230	216	214	14	16
Totals	1684	1583	1566	101	118

(a) From Table 11.2-3 of Reference 3.

(b) Dose reduction factors - 0.94 for 4 reactors of one type and 0.93 for 5 reactors of one type.

9.3 CENTRALIZED SERVICES

Centralized services that may be available at a multiple-reactor station are:

- health physics services
- security forces
- solid waste processing
- equipment decontamination services
- maintenance shops and services
- laundry services
- transportation services
- central stores.

Consideration of the impact of these centralized services on the radiation doses from decommissioning the reactors shows the impact to be minor. Only one of these services, solid waste processing, is found to reduce the radiation doses.

Incineration of combustible solid wastes reduces the volume of these wastes by at least a factor of 5, resulting in less waste to be packaged for shipment and in fewer shipments to the waste disposal facility. Reduction of the volume of waste handled could lead to potential radiation dose reduction for:

- plant workers who prepare and package the waste for shipment
- transportation workers involved in the shipment of the waste
- members of the public along the waste transport route.

After incineration, the volume of combustible waste packaged and shipped offsite is reduced by a factor of 5, thus reducing both the time for packaging and the associated radiation dose. However, the extra steps of transporting the compacted waste to the incinerator and processing it involves some additional radiation dose to the workers involved. In this study, it is assumed that the extra dose offsets the dose reduction from reduced packing time.

Elimination of some of the shipments of combustible radioactive waste to the radioactive waste disposal facility results in lower radiation doses to the transportation workers and the public. In Reference 1, it is estimated that the radiation doses from transportation of waste to the offsite radioactive waste disposal facility are 0.073 man-rem per shipment for the transportation workers and 0.015 man-rem per shipment for the public. Table B.3-3 of Appendix B shows that incineration of combustible wastes give radiation-dose reductions for the transport workers of 3.8 man-rem for DECON or ENTOMB of a PWR and 5.0 man-rem for DECON or ENTOMB of a BWR. For SAFSTOR with 30-year deferred decontamination, the radiation dose reductions for transport workers are 1.6 man-rem for a PWR and 2.5 man-rem for a BWR. This table also shows radiation-dose reductions for the public of 0.8 man-rem for DECON or ENTOMB of a PWR and 1.0 man-rem for DECON or ENTOMB of a BWR.

Centralized health physics services reduce the number of management (overhead) personnel per reactor compared to such services for a single-reactor station. About the same number of health physics technicians are required at a reactor as would be required at a single-reactor station. The amount of radiation monitoring that must be performed is not reduced with a centralized health physics operation; therefore, the radiation exposure of the health physics personnel is not changed significantly.

The centralized security force at a multiple-reactor station also has a smaller number of management personnel per reactor than a reactor at a single-reactor station. However, about the same number of security patrolmen are required at each reactor. Security personnel receive only minimal exposure to radiation in the course of their work. Therefore, a centralized security force does not significantly impact the occupational radiation dose from decommissioning a reactor.

Although central decontamination services can result in cost savings as discussed in Subsection 8.3, the use of these services does not reduce the dose rates for the decommissioning tasks compared with the dose rates estimated for decommissioning a reactor at a single-reactor station. Therefore, central decontamination services do not have an impact on the occupational radiation doses from decommissioning a reactor.

Centralized maintenance shops, laundry services, transportation services, and central stores have no impact on the radiation dose rates where the decommissioning work is performed; therefore, these services have no impact on the occupational radiation dose.

9.4 TYPE OF REACTOR

At multiple-reactor stations, the two types of light water reactors being constructed are PWRs and BWRs. The estimated radiation doses for decommissioning both types are shown in Table 9.4-1 for DECON, SAFSTOR, and ENTOMB. Similar differences in radiation doses for the two types of LWRs are also experienced in decommissioning reactors at a multiple-reactor station. However, decommissioning doses for PWRs and BWRs are impacted to about the same extent at a multiple-reactor station as at a single-reactor station. Estimated impacts on the radiation doses from decommissioning both PWRs and BWRs are developed in Subsections 9.1, 9.2, and 9.3.

TABLE 9.4-1. Estimated Occupational Doses For Decommissioning LWRs

Decommissioning Alternative	Occupational Dose (man-rem)	
	PWR[a]	BWR[b]
DECON	1080	1850
SAFSTOR (30-year storage)	280	420
ENTOMB[c]	950	1680

(a) From References 1 and 2.
(b) From Reference 3.
(c) For ENTOMB with reactor internals removed.

9.5 NUMBER OF REACTORS AT STATION

The number of reactors at the multiple-reactor station influences how the radioactive waste is disposed of, whether there is a continuing stable construction labor force, and whether or which centralized services are provided. With a small number of reactors at the station (say, a quad), it is not likely that radioactive waste could be disposed of onsite. It is improbable that centralized services would be provided; however, special decommissioning tools and equipment probably would be shared. Improvement and economies in planning the decommissioning of successive reactors would be realized for a few as well as many reactors at a multiple-reactor station. If only a few reactors are located at the station, the continuing stability of the labor force would not be assured. Therefore, there would not be a continuing availability of experienced decommissioning workers.

Detailed discussions of the multiple-reactor station scenarios in Section 10 illustrate the effect of the number of reactors at the station on the radiation doses from decommissioning a reactor.

REFERENCES

1. R. I. Smith, G. J. Konzek, and W. E. Kennedy, Jr., Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station, NUREG/CR-0130, U.S. Nuclear Regulatory Commission Report by Pacific Northwest Laboratory, June 1978.

2. R. I. Smith and L. M. Polentz, Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station, NUREG/CR-0130 Addendum, U.S. Nuclear Regulatory Commission Report by Pacific Northwest Laboratory, August 1979.

3. H. D. Oak, G. M. Holter, W. E. Kennedy, Jr., and G. J. Konzek, Technology, Safety and Costs of Decommissioning a Reference Boiling Water Reactor Power Station, NUREG/CR-0672, U.S. Nuclear Regulatory Commission Report by Pacific Northwest Laboratory, June 1980.

10.0 MULTIPLE-REACTOR STATION DECOMMISSIONING SCENARIOS

Five scenarios for multiple-reactor stations are investigated in this section to determine the impact of the variables discussed in Subsection 3.3 on decommissioning costs and safety. These variables, the number of reactors at the multiple-reactor station, the type of reactor, the nuclear waste disposal option, the dedication of the site to nuclear power generation, and the provision of central services vary for the different scenarios. The three decommissioning alternatives, DECON, SAFSTOR, and ENTOMB, are studied for each scenario. The five scenarios described in Subsection 3.3 are shown in Figure 10.0-1.

The estimates of impacts on costs and radiation doses developed in Sections 8 and 9 are used to determine cost and radiation dose impacts for each of the scenarios.

SCENARIO NUMBER	NUMBER OF REACTORS	TYPE OF REACTOR		RETIRED AFTER 40 YR		OLD REACTOR REPLACED		WASTE DISPOSAL			CENTRAL FACILITIES	
		PWR	BWR	1 REACTOR EVERY 2 YR	1 REACTOR EVERY 4 YR	YES	NO	IMMEDIATE OFFSITE	ONSITE INTERIM STORAGE	ONSITE PERMANENT DISPOSAL	YES	NO
1	4	X		X		X			X			X
2	4		X		X		X	X				X
3	10	X	X		X	X		X				X
4	10	X	X		X	X			X		X	
5	10	X	X	X		X				X	X	

FIGURE 10.0-1. Multiple-Reactor Station Scenarios

10.1 SCENARIO NUMBER 1

In this scenario four PWRs are located at the multiple-reactor site. The reactors are started up at 2-year intervals; therefore, after 40 years of operation the reactors will be shut down and decommissioning started at 2-year intervals. At this station a new reactor is started up to take the place of each retired reactor. Nuclear waste from decommissioning the reactors is placed in onsite interim storage and at a later date removed to an offsite waste disposal facility. No central facilities are provided at this 4-reactor station. A lifetime schedule for this scenario is shown in Figure 6.2-1.

The cost of and radiation dose from decommissioning the reactors at this multiple-reactor station are impacted by the waste disposal option and by the experience gained in decommissioning several reactors of the same design. Onsite interim storage of the nuclear waste from decommissioning one of the PWRs results in a lesser volume of nuclear waste that must eventually be sent to an offsite waste disposal facility. The length of the interim storage period determines the amount of radioactive decay that occurs before the waste is sent to offsite disposal and, thus, impacts the cost and radiation dose. The impacts of interim onsite waste storage on costs are developed in Subsection 8.1.2, and the impacts of the radiation dose are developed in Subsection 9.1.2. Cost and radiation dose impacts resulting from improvement in the efficiency of decommissioning with the successive decommissioning of four reactors of the same type are estimated in Subsections 8.2 and 9.2, respectively.

Table 10.1-1 gives the estimated impacts on the cost of decommissioning one of four PWRs at a multiple-reactor station as compared to the cost of decommissioning a PWR at a single-reactor station. The net savings, as well as the estimated average decommissioning cost for the four PWRs, are given. Similarly, the estimated impacts on the occupational radiation doses are given in Table 10.1-2. These estimates of costs and radiation doses for the PWRs in the scenario are the averages for decommissioning four identical reactors.

Although the magnitudes of the decommissioning costs and occupational radiation doses are less, the relative standing of the costs and doses for the three decommissioning alternatives is not changed at the 4-reactor station compared to a single-reactor station. SAFSTOR results in the lowest occupational radiation dose but generally has a higher cost. ENTOMB, if the reactor can be released for unrestricted use after 100 years of surveillance, is estimated to have the lowest cost. DECON is estimated to have the highest radiation dose and an intermediate decommissioning cost.

TABLE 10.1-1. Multiple-Reactor Station Scenario 1 - Decommissioning Cost Impact (4 PWRs)

Decommissioning Alternative	Single-Reactor Station Decommissioning Unit Cost ($ thousands)	Cost Reduction Per Reactor Unit at a Multiple-Reactor Station ($ thousands): Waste Disposal: Onsite Interim Storage: Period (yr)	Cost	Onsite Permanent Disposal	Efficiency Improvement From Experience[a]	Central Services	Total Net Savings: $ thousands	% of Unit Cost	Net Cost at Multiple-Reactor Station ($ thousands)
DECON	24 821[b]	30	(1 640)[c,d]	--[e]	636	--[e]	(1 004)	(4.0)	25 825
		50	1 770[b]	--	636	--	2 406	9.7	22 415
		100	1 780[b]	--	636	--	2 416	9.7	22 405
SAFSTOR	30 yr[f] 32 600[g]	30	2 005[h]	--	1 041	--	3 046	9.3	29 554
		50	2 080[h]	--	1 041	--	3 121	9.6	29 479
		100	2 105[h]	--	1 041	--	3 146	9.7	29 454
	50 yr[f] 28 600[g]	30	660[h]	--	1 041	--	1 701	5.9	26 899
		50	720[h]	--	1 041	--	1 761	6.2	26 839
		100	750[h]	--	1 041	--	1 791	6.3	26 809
	100 yr[f] 31 800[g]	30	670[h]	--	1 041	--	1 711	5.4	30 089
		50	730[h]	--	1 041	--	1 771	5.6	30 029
		100	750[h]	--	1 041	--	1 791	5.6	30 009
ENTOMB	23 786[a]	30	946[j]	--	606	--	1 552	6.5	22 234
		50	1 392[j]	--	606	--	1 998	8.4	21 788
		100	1 405[j]	--	606	--	2 011	8.5	21 775

(a) Based on cost reduction factors in Table 8.2-1. 38% saving of planning and preparation and 6% saving of decommissioning operations costs.
(b) From Table 4.5-1, Reference 2. ENTOMB cost includes $4 million for 100 years' surveillance.
(c) From Table 8.1-3.
(d) ( ) indicates a negative number.
(e) Dashes indicate not used or not available.
(f) Safe storage period for the reactor.
(g) Based on Table H.5-4, Reference 1, with costs for spent fuel shipment and demolition services deleted.
(h) From Table 8.1-6.
(j) From Table 8.1-9.

TABLE 10.1-2. Multiple-Reactor Station Scenario 1 - Impact on Occupational Radiation Dose from Decommissioning (4 PWRs)

Decommissioning Alternative		Single-Reactor Station Radiation Dose From Decommissioning (man-rem)	Radiation Dose Reduction Per Reactor Unit at a Multiple-Reactor Station (man-rem): Waste Disposal: Onsite Interim Storage: Period (yr)	Dose	Onsite Permanent Disposal	Efficiency Improvement From Experience[a]	Central Services	Total Net Reduction: man-rem	Total Net Reduction: % of Single-Reactor Dose	Net Dose at Multiple-Reactor Station (man-rem)
DECON		1324[b]	30	(68.9)[c,d]	--[e]	73	--[e]	4.1	0.3	1320
			50	72.0[d]	--	73	--	145.0	11.0	1179
			100	75.0[d]	--	73	--	148.1	11.2	1176
SAFSTOR	30 yr[f]	554[g]	30	74.0[h]	--	26	--	100.0	18.1	454
			50	77.4[h]	--	26	--	103.4	18.7	451
			100	78.0[h]	--	26	--	104.0	18.8	450
	50 yr[f]	456[g]	30	5.5[h]	--	25	--	30.5	6.7	426
			50	8.2[h]	--	25	--	33.2	7.3	423
			100	8.6[h]	--	25	--	33.6	7.4	422
	100 yr[f]	455[g]	30	5.9[h]	--	25	--	30.9	6.8	424
			50	8.3[h]	--	25	--	33.3	7.3	422
			100	8.6[h]	--	25	--	33.6	7.4	421
ENTOMB		922[j]	30	(6.1)[c,k]	--	55	--	48.9	5.3	873
			50	11.6[k]	--	55	--	66.6	7.2	855
			100	12.8[k]	--	55	--	67.8	7.4	854

(a) Based on the dose reduction factors in Table 8.2-1. 38% saving on planning and preparation and 6% saving on decommissioning operations dose.
(b) From Table 11.3-1 of Reference 1 and Table 9.1-12 of this report.
(c) ( ) indicates an increase in the dose.
(d) From Table 9.1-1.
(e) Dashes indicate not used or not available.
(f) Safe storage period for reactor.
(g) Based on Tables 11.3-2, 11.3-4, and 11.3-5 of Reference 1 and Table 9.1-12 of this report.
(h) From Table 9.1-5.
(j) Based on Table 4.6-1 of Reference 2 corrected for radioactive decay and Table 9.1-12 of this report.
(k) From Table 9.1-9.

10.2 SCENARIO NUMBER 2

Scenario Number 2 has four BWRs of similar design that started up at 4-year intervals. At the end of their operating life, the reactors are shut down and decommissioned but are not replaced with new nuclear power plants. Nuclear waste from decommissioning the reactors is sent immediately to an offsite waste disposal facility. No central facilities are provided at this multiple-reactor station. A lifetime schedule for Scenario 2 is given in Figure 6.2-2.

Immediate offsite disposal of nuclear waste from decommissioning a reactor at a multiple-reactor station is accomplished for the same cost and results in the same occupational radiation dose as nuclear waste disposal from decommissioning a reactor at a single-reactor station. The only feature of this scenario that impacts the decommissioning cost and radiation dose is the improvement in the efficiency of the planning and execution of the work at four identical plants. These impacts are discussed generically in Subsections 8.2 and 9.2

Table 10.2-1 gives the estimated average decommissioning cost and the average net savings for decommissioning a BWR at this multiple-reactor station. Estimated costs are given for each of the decommissioning alternatives, DECON, SAFSTOR, and ENTOMB. The estimated average occupational decommissioning doses for decommissioning a BWR at this station are given in Table 10.2-2.

The greatest cost savings in this scenario are achieved when the BWR is decommissioned by SAFSTOR; however, it is still the most expensive of the three alternatives. SAFSTOR does result in the lowest occupational radiation dose for decommissioning one of the reactors. DECON is estimated to be the least expensive for decommissioning one of the BWRs.

10.3 SCENARID NUMBER 3

The multiple-reactor station of Scenario Number 3 has 10 reactors, 5 PWRs and 5 BWRs. Reactors are started up at 4-year intervals so that the station reaches the full generating capacity over a 36-year period (see Figure 6.2-3). With this construction schedule, the first reactor to start up is shut down 4 years after startup of the tenth reactor and is replaced by the eleventh

TABLE 10.2-1. Multiple-Reactor Station Scenario 2 - Decommissioning Cost Impact (4 BWRs)

Decommissioning Alternative		Single-Reactor Station Decommissioning Unit Cost ($ thousands)	Cost Reduction Per Reactor Unit at a Multiple-Reactor Station ($ thousands): Waste Disposal: Onsite Interim Storage: Period (yr)	Waste Disposal: Onsite Interim Storage: Cost	Waste Disposal: Onsite Permanent Disposal	Efficiency Improvement From Experience[a]	Central Services	Total Net Savings: $ thousands	Total Net Savings: % of Unit Cost	Net Cost at Multiple-Reactor Station ($ thousands)
DECON		34 840[b]	--[c]	--[c]	--[c]	1 362	--[c]	1 362	4.0	33 478
SAFSTOR	30 yr[d]	47 112[e]	--	--	--	3 222	--	3 222	6.8	43 890
SAFSTOR	50 yr[d]	41 060[e]	--	--	--	3 011	--	3 011	7.3	38 049
SAFSTOR	100 yr[d]	44 032[e]	--	--	--	3 011	--	3 011	6.8	41 021
ENTOMB		36 465[f]	--	--	--	1 378	--	1 378	3.8	35 087

(a) Based on cost reduction factors in Table 8.2-1. 38% saving on planning and preparation and 6% saving on decommissioning operations costs.
(b) From Table 10.1-1 of Reference 3.
(c) Dashes indicate not used or not available.
(d) Safe storage period for the reactor.
(e) Based on Table 10.4-2 of Reference 3, without the 25% contingency.
(f) From Table 10.3-1 of Reference 3. ENTOMB with reactor internals removed. Cost includes $4 million for 100 years' surveillance.

TABLE 10.2-2. Multiple-Reactor Station Scenario 2 - Impact on Occupational Radiation Dose from Decommissioning (4 BWRs)

Decommissioning Alternative		Single-Reactor Station Radiation Dose From Decommissioning (man-rem)	Radiation Dose Reduction Per Reactor Unit at a Multiple-Reactor Station (man-rem): Waste Disposal: Onsite Interim Storage: Period (yr)	Waste Disposal: Onsite Interim Storage: Dose	Waste Disposal: Onsite Permanent Disposal	Efficiency Improvement From Experience[a]	Central Services	Total Net Reduction: man-rem	Total Net Reduction: % of Single-Reactor Dose	Net Dose at Multiple-Reactor Station (man-rem)
DECON		1954[b]	--[c]	--[c]	--[c]	111[d]	--[c]	111	5.7	1843
SAFSTOR	30 yr[e]	527[b]	--	--	--	24[f]	--	24	4.6	503
	50 yr[e]	429[b]	--	--	--	22[f]	--	22	5.1	407
	100 yr[e]	427[b]	--	--	--	22[f]	--	22	5.2	405
ENTOMB		1756[g]	--	--	--	101[h]	--	101	5.8	1655

(a) Based on the dose reduction factors in Table 8.2-1. 38% saving on planning and preparation and 6% saving on decommissioning operations dose.
(b) From Table J.7-4 of Reference 3 and Table 9.1-12 of this report.
(c) Dashes indicate not used or not available.
(d) From Table 9.2-2.
(e) Safe storage period for reactor.
(f) From Table 9.2-7.
(g) From Table K.4-1 of Reference 3 and Table 9.1-12 of this report.
(h) From Table 9.2-9.

reactor. The site of this multiple-reactor station is dedicated to nuclear power generation, with each retired reactor replaced with a new reactor as it is shut down. Nuclear waste from reactor operation and decommissioning is shipped immediately to an offsite waste facility. Central services are not provided at this station. Lifetime schedules for this scenario with decommissioning by DECON and SAFSTOR are given in Figures 6.2-3 and 6.2-5, respectively.

Improvement in the planning and execution of reactor decommissioning resulting from a stable local workforce and the learning experience of successively decommissioning several reactors of the same type is the only feature of this multiple-reactor station scenario that impacts the costs of and radiation dose from decommissioning the reactors.

The average decommissioning costs and net savings for decommissioning a PWR and a BWR are given in Table 10.3-1. Oecommissioning costs are estimated for each of the alternatives, DECON, SAFSTOR, and ENTOMB. Occupational radiation dose estimates for decommissioning the reactors at this station are given in Table 10.3-2.

For both the PWRs and the BWRs, the estimated occupational radiation doses are lowest when the reactors are decommissioned by SAFSTOR and highest when decommissioned by DECON. Estimated average decommissioning costs for the PWRs are lowest for ENTOMB and highest for SAFSTOR. Decommissioning the BWRs is estimated to be most costly by the SAFSTOR alternative and least costly by the OECON alternative.

10.4 SCENARIO NUMBER 4

Ten reactors, 5 PWRs and 5 BWRs, are located at the multiple-reactor station in this scenario. A new reactor is started up every 4 years as shown in the lifetime schedules in Figures 6.2-3 and 6.2-5 for decommissioning by DECON and SAFSTOR with 30 years of safe storage, respectively. A new reactor is started up when an old reactor is retired, thus maintaining a full complement of 10 operating reactors after the tenth reactor has been started up. Nuclear waste from operation and decommissioning is placed in onsite interim storage

TABLE 10.3-1. Multiple-Reactor Station Scenario 3 - Decommissioning Cost Impact (5 PWRs and 5 BWRs)

Decommissioning Alternative		Single-Reactor Station Decommissioning Unit Cost ($ thousands)	Cost Reduction Per Reactor Unit at a Multiple-Reactor Station ($ thousands): Waste Disposal: Onsite Interim Storage: Period (yr)	Onsite Interim Storage: Cost	Onsite Permanent Disposal	Efficiency Improvement From Experience[a]	Central Services	Total Net Savings: $ thousands	Total Net Savings: % of Unit Cost	Net Cost at Multiple-Reactor Station ($ thousands)
			5 PWRs							
DECON		24 821[b]	--[c]	--[c]	--[c]	744	--[c]	744	3.0	24 077
SAFSTOR	30 yr[d]	32 600[e]	--	--	--	1 229	--	1 229	3.8	31 371
	50 yr[d]	28 600[e]	--	--	--	1 229	--	1 229	4.3	27 371
	100 yr[d]	31 800[e]	--	--	--	1 229	--	1 229	3.9	30 571
ENTOMB		23 786[b]	--	--	--	709	--	709	3.0	23 077
			5 BWRs							
DECON		34 840[f]	--	--	--	1 538	--	1 538	4.4	33 302
SAFSTOR	30 yr[d]	47 112[g]	--	--	--	3 538	--	3 538	7.5	43 574
	50 yr[d]	41 060[g]	--	--	--	3 290	--	3 290	8.0	37 770
	100 yr[d]	44 032[g]	--	--	--	3 290	--	3 290	7.5	40 742
ENTOMB		36 465[h]	--	--	--	1 570	--	1 570	4.3	34 895

(a) Based on cost reduction factors in Table 8.2-1. 40% saving on planning and preparation and 7% saving on decommissioning operations costs.
(b) From Table 4.5-1 of Reference 2. ENTOMB cost includes $4 million for 100 years of surveillance.
(c) Dashes indicate not used or not available.
(d) Safe storage period for the reactor.
(e) From Table H.5-4 of Reference 1, with costs for spent fuel shipment and demolition services deleted.
(f) From Table 10.1-1 of Reference 3.
(g) From Table 10.4-2 of Reference 3, without the 25% contingency.
(h) From Table 10.3-1 of Reference 3. ENTOMB with reactor internals removed. Cost includes $4 million for 100 years' surveillance.

TABLE 10.3-2. Multiple-Reactor Station Scenario 3 - Impact on Occupational Radiation Dose from Decommissioning (5 PWRs and 5 BWRs)

Decommissioning Alternative		Single-Reactor Station Radiation Dose From Decommissioning (man-rem)	Radiation Dose Reduction Per Reactor Unit at a Multiple-Reactor Station (man-rem): Waste Disposal: Onsite Interim Storage: Period (yr)	Waste Disposal: Onsite Interim Storage: Dose	Waste Disposal: Onsite Permanent Disposal	Efficiency Improvement From Experience	Central Services	Total Net Reduction: man-rem	Total Net Reduction: % of Single-Reactor Dose	Net Dose at Multiple-Reactor Station (man-rem)
5 PWRs										
DECON		1324[a]	--[b]	--[b]	--[b]	85[c]	--[b]	85	6.4	1239
SAFSTOR	30 yr[d]	554[e]	--	--	--	31[f]	--	31	5.6	523
	50 yr[d]	456[e]	--	--	--	29[f]	--	29	6.4	427
	100 yr[d]	455[e]	--	--	--	29[f]	--	29	6.4	426
ENTOMB		922[g]	--	--	--	62[h]	--	62	6.7	860
5 BWRs										
DECON		1954[j]	--	--	--	129[k]	--	129	6.6	1825
SAFSTOR	30 yr[d]	527[j]	--	--	--	29[f]	--	29	5.5	498
	50 yr[d]	429[j]	--	--	--	26[f]	--	26	6.1	403
	100 yr[d]	427[j]	--	--	--	26[f]	--	26	6.1	401
ENTOMB		1756[m]	--	--	--	118[n]	--	118	6.7	1638

(a) From Table 11.3-1 of Reference 1 and Table 9.1-12 of this report.
(b) Dashes indicate not used or not available.
(c) From Table 9.2-1.
(d) Safe storage period for reactor.
(e) Based on Tables 11.3-2, 11.3-4 and 11.3-5 of Reference 1 and Table 9.1-12 of this report.
(f) From Table 9.2-7.
(g) Based on Table 4.6-1 of Reference 2 corrected for radioactive decay and Table 9.1-12 of this report.
(h) From Table 9.2-8.
(j) From Table J.7-4 of Reference 3 and Table 9.1-12 of this report.
(k) From Table 9.2-2.
(m) From Table K.4-1 of Reference 3 and Table 9.1-12 of this report.
(n) From Table 9.2-9.

for a significant decay period before it is transferred offsite, either to a licensed waste disposal facility or, if releasable, to a nonradioactive waste disposal facility. Centralized facilities are provided at this multiple-reactor station.

Nuclear waste disposal, experience gained in successively decommissioning a number of identical reactors, and the availability of central services at this multiple-reactor station have an impact on the average occupational dose and cost of decommissioning the reactors. Radioactive decay during the period of onsite interim storage results in reducing the amount of waste that must be sent to an offsite waste disposal facility and in reducing the curie and liner surcharges on the waste sent to an offsite waste facility. Details of the estimates of the impacts on costs and occupational radiation doses of onsite interim storage of the nuclear waste are given in Subsections 8.1.2 and 9.1.2, respectively. Cost and radiation dose impacts resulting from improvement in the efficiency of the successive decommissioning of five identical reactors are developed in Subsections 8.2 and 9.2, respectively.

Centralized services at this multiple-reactor station that impact cost are health physics services, security forces, solid waste processing, and decontamination services. Estimation of the cost impacts of these centralized services is discussed in detail in Subsection 8.3. The impact of the centralized services on radiation dose is minor. Only one of the services, solid waste processing, reduces the radiation dose. This is discussed in greater detail in Subsection 9.3.

The decommissioning cost at this multiple-reactor station and the net savings compared to the decommissioning cost at a single-reactor station are given in Table 10.4-1 for the five PWRs and in Table 10.4-2 for the five BWRs. Average occupational doses and dose reductions compared to the doses for decommissioning a reactor at a single-reactor station are given in Table 10.4-3 for the PWRs and in Table 10.4-4 for the BWRs.

Savings in the costs of decommissioning the reactors are greater for this scenario than for the first three scenarios, ranging from 5 to 19% for the PWRs

TABLE 10.4-1. Multiple-Reactor Station Scenario 4a - PWRs - Decommissioning Cost Impact (5 PWRs and 5 BWRs)

Decommissioning Alternative		Single-Reactor Station Decommissioning Unit Cost ($ thousands)	Cost Reduction Per Reactor Unit at a Multiple-Reactor Station ($ thousands): Waste Disposal: Onsite Interim Storage: Period (yr)	Onsite Interim Storage: Cost	Onsite Permanent Disposal	Efficiency Improvement From Experience[a]	Central Services[b]	Total Net Savings: $ thousands	Total Net Savings: % of Unit Cost	Net Cost at Multiple-Reactor Station ($ thousands)
DECON		24 821[c]	30	(1 640)[d]	--[e]	744	2 193	1 297	5.2	23 524
			50	1 770[d]	--	744	2 193	4 707	19.0	20 114
			100	1 780[d]	--	744	2 193	4 717	19.0	20 104
SAFSTOR	30 yr[f]	32 600[g]	30	2 005[h]	--	1 229	2 812	6 046	18.5	26 554
			50	2 080[h]	--	1 229	2 812	6 121	18.8	26 479
			100	2 105[h]	--	1 229	2 812	6 146	18.9	26 454
	50 yr[f]	28 600[g]	30	660[h]	--	1 229	2 776	4 665	16.3	23 935
			50	720[h]	--	1 229	2 776	4 725	16.5	23 875
			100	750[h]	--	1 229	2 776	4 755	16.6	23 845
	100 yr[f]	31 800[g]	30	670[h]	--	1 229	2 753	4 652	14.6	27 148
			50	730[h]	--	1 229	2 753	4 712	14.8	27 088
			100	750[h]	--	1 229	2 753	4 732	14.9	27 068
ENTOMB		23 786[c]	30	946[d]	--	709	2 193	3 848	16.2	19 938
			50	1 392[d]	--	709	2 193	4 294	18.1	19 492
			100	1 405[d]	--	709	2 193	4 307	18.1	19 479

(a) Based on cost reduction factors in Table 8.2-1. 40% saving on planning and preparation and 7% saving on decommissioning operations costs.
(b) From Tables 8.3-8 and 8.3-3.
(c) From Table 4.5-1 of Reference 2. ENTOMB cost includes $4 million for 100 years' surveillance.
(d) From Table 8.0-1.
(e) Dashes indicate not used.
(f) Safe storage period for the reactor.
(g) Based on Table H.5-4 of Reference 1, with costs for spent fuel shipment and demolition services deleted.
(h) From Table 8.1-6.

TABLE 10.4-2. Multiple-Reactor Station Scenario 4b - BWRs - Decommissioning Cost Impact (5 PWRs and 5 BWRs)

Decommissioning Alternative		Single-Reactor Station Decommissioning Unit Cost ($ thousands)	Cost Reduction Per Reactor Unit at a Multiple-Reactor Station ($ thousands): Waste Disposal: Onsite Interim Storage: Period (yr)	Cost	Onsite Permanent Disposal	Efficiency Improvement From Experience[(a)]	Central Services[(b)]	Total Net Savings: $ thousands	% of Unit Cost	Net Cost at Multiple-Reactor Station ($ thousands)
DECON		34 840[(c)]	30	(410)[(d,e)]	--[(f)]	1 538	2 763	3 891	11.2	30 949
			50	3 100[(e)]	--	1 538	2 763	7 401	21.2	27 439
			100	3 160[(e)]	--	1 538	2 763	7 461	21.4	27 379
SAFSTOR	30 yr[(g)]	47 112[(h)]	30	2 984[(j)]	--	3 538	3 809	10 331	21.9	36 781
			50	3 611[(j)]	--	3 538	3 809	10 958	23.3	36 154
			100	3 656[(j)]	--	3 538	3 809	11 003	23.4	36 109
	50 yr[(g)]	41 060[(h)]	30	2 245[(j)]	--	3 290	3 775	9 310	22.7	31 750
			50	2 410[(j)]	--	3 290	3 775	9 475	23.1	31 585
			100	2 444[(j)]	--	3 290	3 775	9 509	23.2	31 551
	100 yr[(g)]	44 032[(h)]	30	2 381[(j)]	--	3 290	3 730	9 401	21.4	34 631
			50	2 504[(j)]	--	3 290	3 730	9 524	21.6	34 508
			100	2 532[(j)]	--	3 290	3 730	9 552	21.7	34 480
ENTOMB		36 465[(k)]	30	908[(e)]	--	1 570	2 881	5 359	14.7	31 106
			50	2 502[(e)]	--	1 570	2 881	6 953	19.1	29 512
			100	2 561[(e)]	--	1 570	2 881	7 012	19.2	29 453

(a) Based on cost reduction factors in Table 8.2-1. 40% saving on planning and preparation and 7% saving on decommissioning operations costs.
(b) Based on Tables 8.3-3 and 8.3-8.
(c) From Table 10.1-1 of Reference 3.
(d) ( ) indicates a negative number.
(e) From Table 8.0-1.
(f) Dashes indicate not used.
(g) Safe storage period for the reactor.
(h) Based on Table 10.4-2 of Reference 3, 25% contingency deleted.
(j) From Table 8.1-6.
(k) From Table 10.3-1 of Reference 3. ENTOMB with internals removed. Cost includes $4 million for 100 years' surveillance.

TABLE 10.4-3. Multiple-Reactor Station Scenario 4a - PWRs - Impact on Occupational Radiation Dose from Decommissioning (5 PWRs and 5 BWRs)

Decommissioning Alternative	Single-Reactor Station Radiation Dose From Decommissioning (man-rem)	Radiation Dose Reduction Per Reactor Unit at a Multiple-Reactor Station (man-rem): Waste Disposal – Onsite Interim Storage – Period (yr)	Waste Disposal – Onsite Interim Storage – Dose	Waste Disposal – Onsite Permanent Disposal	Efficiency Improvement From Experience	Central Services[a]	Total Net Reduction – man-rem	Total Net Reduction – % of Single-Reactor Dose	Net Dose at Multiple-Reactor Station (man-rem)
DECON	1324[b]	30	(68.9)[c,d]	--[e]	85[f]	3.8	19.9	1.5	1304
		50	72.0[d]	--	85[f]	3.8	160.8	12.1	1163
		100	75.0[d]	--	85[f]	3.8	163.8	12.4	1160
SAFSTOR: 30 yr[g]	554[h]	30	74.0[j]	--	31[k]	1.6	106.6	19.2	447
		50	77.4[j]	--	31[k]	1.6	110.0	19.9	444
		100	78.0[j]	--	31[k]	1.6	110.6	20.0	443
SAFSTOR: 50 yr[g]	446[h]	30	5.5[j]	--	29[k]	1.5	36.0	7.9	420
		50	8.2[j]	--	29[k]	1.5	38.7	8.5	417
		100	8.6[j]	--	29[k]	1.5	39.1	8.6	417
SAFSTOR: 100 yr[g]	344[h]	30	5.9[j]	--	29[k]	1.3	36.2	8.0	419
		50	8.3[j]	--	29[k]	1.3	38.6	8.5	416
		100	8.6[j]	--	29[k]	1.3	38.9	8.5	416
ENTOMB	922[m]	30	(6.1)[c,n]	--	62[o]	3.8	59.7	6.5	862
		50	11.6[n]	--	62[o]	3.8	77.4	8.4	845
		100	12.8[n]	--	62[o]	3.8	78.6	8.5	843

(a) From Table B.3-3 of Appendix B.
(b) From Table 11.3-1 of Reference 1 and Table 9.1-12 of this report.
(c) ( ) indicates increase in dose.
(d) From Table 9.1-1.
(e) Dashes indicate not used.
(f) From Table 9.2-1.
(g) Safe storage period for reactor.
(h) Based on Tables 11.3-2, 11.3-4, and 11.3-5 of Reference 1 and Table 9.1-12 of this report.
(j) From Table 9.1-5.
(k) From Table 9.2-7.
(m) Based on Table 4.6-1 and Reference 2 corrected for radioactive decay and Table 9.1-12 of this report.
(n) From Table 9.1-9.
(o) From Table 9.2-8.

TABLE 10.4-4. Multiple-Reactor Station Scenario 4b - BWRs - Impact on Occupational Radiation Dose from Decommissioning (5 PWRs and 5 BWRs)

Decommissioning Alternative		Single-Reactor Station Radiation Dose From Decommissioning (man-rem)	Radiation Dose Reduction Per Reactor Unit at a Multiple-Reactor Station (man-rem): Waste Disposal: Onsite Interim Storage: Period (yr)	Dose	Onsite Permanent Disposal	Efficiency Improvement From Experience	Central Services[a]	Total Net Reduction: man-rem	Total Net Reduction: % of Single-Reactor Dose	Net Dose at Multiple-Reactor Station (man-rem)
DECON		1954[b]	30	(46.7)[c,d]	--[e]	129[d]	5.0	87.3	4.5	1867
			50	55.1[d]	--	129[d]	5.0	189.1	9.7	1765
			100	59.7[d]	--	129[d]	5.0	193.7	9.9	1760
SAFSTOR	30 yr[f]	527[b]	30	68.0[g]	--	29[h]	2.5	99.5	18.9	427
			50	86.7[g]	--	29[h]	2.5	118.2	22.4	409
			100	87.9[g]	--	29[h]	2.5	119.4	22.7	408
	50 yr[f]	429[b]	30	26.3[g]	--	26[h]	2.4	54.7	12.8	374
			50	31.6[g]	--	26[h]	2.4	60.0	14.0	369
			100	32.6[g]	--	26[h]	2.4	61.0	14.2	368
	100 yr[f]	427[b]	30	16.8[g]	--	26[h]	2.2	45.0	10.5	382
			50	21.4[g]	--	26[h]	2.2	49.6	11.6	377
			100	22.0[g]	--	26[h]	2.2	50.2	11.8	377
ENTOMB		1756[j]	30	(33.3)[c,d]	--	118[d]	5.0	89.7	5.1	1666
			50	25.9[d]	--	118[d]	5.0	148.9	8.5	1607
			100	29.3[d]	--	118[d]	5.0	152.3	8.7	1603

(a) From Table B.3-3.
(b) From Table J.7-4 of Reference 3 and Table 9.1-2 of this report.
(c) ( ) indicates increase in dose.
(d) From Table 9.0-1.
(e) Dashes indicate not used.
(f) Safe storage period for the reactor.
(g) From Table 9.1-7.
(h) From Table 9.2-7.
(j) From Table K.4-1 of Reference 3 and Table 9.1-12 of this report.

and 11 to 23% for the BWRs. ENTOMB gives the lowest decommissioning cost for the PWRs and SAFSTOR the highest. For the BWRs the costs of DECON are lowest and the costs of SAFSTOR highest.

Dose reductions are also generally greater for this scenario than for the first three, ranging up to 20% for the PWRs and up to 23% for the BWRs. Again, occupational doses are lowest for SAFSTOR and highest for DECON.

10.5 SCENARIO NUMBER 5

Five PWRs and five BWRs are located at the multiple-reactor station of Scenario Number 5. The reactors are started up and, after 40 years of operation, shut down at 2-year intervals. As each old reactor is shut down, it is replaced with a new reactor so that a full complement of 10 reactors is maintained on line. A permanent nuclear waste disposal facility is located onsite. Central facilities are provided at this multiple-reactor station.

Onsite permanent disposal of the waste, as well as the improvement in efficiency with successive decommissioning of several reactors and the availability of centralized services, will reduce the average cost and occupational radiation dose from decommissioning the reactors at this multiple-reactor station compared to a single-reactor station. Details of the cost estimates for onsite disposal of nuclear wastes are discussed in Subsection 8.1.3.

Table 10.5-1 gives the estimated average decommissioning costs and net savings for decommissioning the reactors at this multiple-reactor station. The average occupational radiation doses and net dose reduction for decommissioning the reactors are given in Table 10.5-2.

The reductions in cost and occupational radiation dose for decommissioning a reactor at a multiple-reactor station compared to a single-reactor station are greater in this scenario than in any of the other scenarios. Cost reductions range from about 17 to 24% for the PWRs and from about 22 to 25% for the PWRs. Dose reductions range from about 10 to 22% for the PWRs and 11 to 25% for the BWRs.

TABLE 10.5-1. Multiple-Reactor Station Scenario 5 - Decommissioning Cost Impact (5 PWRs and 5 BWRs)

Decommissioning Alternative		Single-Reactor Station Decommissioning Unit Cost ($ thousands)	Cost Reduction Per Reactor Unit at a Multiple-Reactor Station ($ thousands): Waste Disposal: Onsite Interim Storage: Period (yr)	Cost	Onsite Permanent Disposal	Efficiency Improvement From Experience[a]	Central Services[b]	Total Net Savings: $ thousands	% of Unit Cost	Net Cost at Multiple-Reactor Station ($ thousands)
5 PWRs										
DECON		24 821[c]	--[d]	--[d]	2 968[e]	744	2 193	5 905	23.8	18 916
SAFSTOR	30 yr[f]	32 600[g]	--	--	3 098[h]	1 229	2 812	7 139	21.9	25 461
	50 yr[f]	28 600[g]	--	--	1 432[h]	1 229	2 776	5 437	19.0	23 163
	100 yr[f]	31 800[g]	--	--	1 394[h]	1 229	2 753	5 376	16.9	26 424
ENTOMB		23 786[c]	--	--	2 076[j]	709	2 193	4 978	20.9	18 808
5 BWRs										
DECON		34 840[k]	--	--	4 485[e]	1 538	2 763	8 786	25.2	26 054
SAFSTOR	30 yr[f]	47 112[m]	--	--	4 342[h]	3 538	3 809	11 689	24.8	35 473
	50 yr[f]	41 060[m]	--	--	2 910[h]	3 290	3 775	9 975	24.3	31 085
	100 yr[f]	44 032[m]	--	--	2 950[h]	3 290	3 730	9 970	22.6	34 062
ENTOMB		36 465[n]	--	--	3 547[j]	1 570	2 881	7 998	21.9	28 467

(a) Based on cost reduction factors in Table 8.2-1. 40% saving on planning and preparation and 7% saving on decommissioning operations costs.
(b) Based on Tables 8.3-3 and 8.3-8.
(c) From Table 4.5-1 of Reference 2. ENTOMB cost includes $4 million for 100 years' surveillance.
(d) Dashes indicate not used.
(e) From Table 8.1-10.
(f) Safe storage period for the reactor.
(g) Based on Table H.5-4 of Reference 1, with costs for spent fuel shipment and demolition services deleted.
(h) From Table 8.1-11.
(j) From Table 8.1-12.
(k) From Table 10.1-1 of Reference 3.
(m) Based on Table 10.4-2 of Reference 3. 25% contingency deleted.
(n) From Table 10.3-1 of Reference 3. ENTOMB with internals removed. Cost includes $4 million for 100 years' surveillance.

TABLE 10.5-2. Multiple-Reactor Station Scenario 5 - Impact on Occupational Radiation Dose from Decommissioning (5 PWRs and 5 BWRs)

Decommissioning Alternative		Single-Reactor Station Radiation Dose From Decommissioning (man-rem)	Radiation Dose Reduction Per Reactor Unit at a Multiple Reactor Station (man-rem): Waste Disposal: Onsite Interim Storage: Period (yr)	Waste Disposal: Onsite Interim Storage: Dose	Waste Disposal: Onsite Permanent Disposal[a]	Efficiency Improvement From Experience	Central Services[b]	Total Net Reduction: man-rem	Total Net Reduction: % of Single-Reactor Dose	Net Dose at Multiple-Reactor Station (man-rem)
			5 PWRs							
DECON		1324[c]	--[d]	--[d]	89.8	85[e]	3.8	178.6	13.5	1145
SAFSTOR	30 yr[f]	554[g]	--	--	90.1	31[h]	1.6	122.7	22.1	431
	50 yr[f]	456[g]	--	--	22.6	29[h]	1.5	53.1	11.6	403
	100 yr[f]	455[g]	--	--	22.2	29[h]	1.3	52.5	11.5	403
ENTOMB		922[j]	--	--	22.8	62[e]	3.8	88.6	9.6	833
			5 BWRs							
DECON		1954[k]	--	--	100.6	129[e]	5.0	234.6	12.0	1719
SAFSTOR	30 yr[f]	527[k]	--	--	100.7	29[h]	2.5	132.2	25.1	395
	50 yr[f]	429[k]	--	--	38.5	26[h]	2.4	66.9	15.6	362
	100 yr[f]	427[k]	--	--	39.4	26[h]	2.2	67.6	15.8	359
ENTOMB		1756[m]	--	--	67.2	118[e]	5.0	190.2	10.8	1566

(a) From Table 9.1-12.
(b) From Table B.3-3 of Appendix B.
(c) From Table 11.3-1 of Reference 1 and Table 9.1-12 of this report.
(d) Dashes indicate not used.
(e) From Table 9.0-1.
(f) Safe storage period for reactor.
(g) Based on Tables 11.3-2, 11.3-4 and 11.3-5 of Reference 1 and Table 9.1-12 of this report.
(h) From Table 9.2-7.
(j) Based on Table 4.6-1 of Reference 2 corrected for radioactive decay and Table 9.1-12 of this report.
(k) From Table J.7-4 of Reference 3 and Table 9.1-12 of this report.
(m) From Table K.4-1 of Reference 3 and Table 9.1-12 of this report.

REFERENCES

1. R. I. Smith, G. J. Konzek and W. E. Kennedy, Jr., Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station, NUREG/CR-0130, U.S. Nuclear Regulatory Commission Report by Pacific Northwest Laboratory, June 1978.

2. R. I. Smith and L. M. Polentz, Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station, NUREG/CR-0130 Addendum, U.S. Nuclear Regulatory Commission Report by Pacific Northwest Laboratory, August 1979.

3. H. D. Oak, G. M. Holter, W. E. Kennedy, Jr., and G. J. Konzek, Technology, Safety and Costs of Decommissioning a Reference Boiling Water Reactor Power Station, NUREG/CR-0672, U.S. Nuclear Regulatory Commission Report by Pacific Northwest Laboratory, June 1980.

11.0 FACILITATION OF DECOMMISSIONING

The principal purpose of decommissioning facilitation is to reduce occupational and public radiation doses resulting from decommissioning activities. Other purposes include improving the safety of decommissioning, reducing the volume of radioactive waste, and reducing the cost of decommissioning. These purposes apply equally to single-reactor stations and to multiple-reactor stations; but they can often be more effectively achieved at multiple-reactor stations because of collocation of the reactors and sequential decommissioning. A recent discussion of the facilitation of decommissioning light water reactors, without particular regard to multiple-reactor stations, appears in NUREG/CR-0569.[1] The decommissioning facilitation alternatives presented in Reference 1 are reviewed briefly in Subsection 11.2. Facilitation of decommissioning a multiple-reactor station is discussed in Subsection 11.3, and the possibilities of conversion to a different steam supply system or refurbishment of the original nuclear steam supply system are discussed in Subsection 11.4.

11.1 FACILITATION PLANNING

The best way to facilitate the decommissioning of a reactor is to plan for decommissioning during the design phase. This is true because many decommissioning facilitation alternatives require design and construction modifications. It is also true because advantage can be taken of a facilitation alternative that also facilitates reactor maintenance and operation. In decommissioning, an opportunity exists only once to reduce radiation dose and cost, but in maintenance, an opportunity exists every year to reduce radiation dose and cost.

Planning at the design phase is especially appropriate for a multiple-reactor station because advantage can be taken of collocation of the reactors, standardized design and construction, centralized services, and sequential decommissioning. At the very least, crew preparation and training time will be minimized and the decommissioning can be more efficiently carried out because the decommissioning procedures will be the same for similar reactors and because the same crews can be used for sequential decommissioning.

In Subsections 11.1.1 and 11.1.2, we comment briefly on the reduction of radiation doses and costs and on the advantages of selecting decommissioning facilitation alternatives that also facilitate maintenance. In Subsection 11.3, we discuss decommissioning facilitation techniques that are unique to multiple-reactor stations or that improve decommissioning at multiple reactor stations.

11.1.1 Radiation Dose Reduction

Any radiation dose reduction that can be effected by decommissioning facilitation will be some fraction of the total radiation dose expected from decommissioning. A suitable standard of comparison for a PWR is the 1080 man-rem calculated for DECON of an 1175-MWe PWR single-reactor station (Reference 2, pp. 11-17). This value does not include the radiation dose from removal of the last core. A similar standard of comparison for a BWR is the 1760 man-rem calculated for DECON of an 1155-MWe BWR at a single-reactor station (Reference 3, pp. 11-7 and 11-8).

Of perhaps even greater importance than the reduction of radiation dose during decommissioning is the reduction of radiation dose during operation and maintenance of the reactor that might be made possible by any decommissioning facilitation alternative. The opportunities are much greater for dose reduction during maintenance than during decommissioning. The observed maintenance occupational radiation dose is presently about 450 man-rem per year for PWRs and about 500 man-rem per year for BWRs, or about 18,000 and 20,000 man-rem, respectively, over the 40-year operating lifetime of the reactor. (See Reference 1, Section 2.3.) Obviously, strategic decommissioning facilitation planning requires careful consideration to determine if a facilitation alternative will also facilitate maintenance.

11.1.2 Cost Reduction

Costs associated with decommissioning facilitation alternatives include capital costs, costs of maintenance and operation (during both reactor operation and maintenance and decommissioning) and any cost savings during decommissioning. Some facilitation alternatives that will reduce the decommissioning radiation dose may involve an overall cost increase. Again, appropriate standards of comparison are the costs to DECON a reference, single-reactor station, 1175-MWe PWR and a reference, single-reactor station, 1155-MWe BWR, which are $31 million and $43.6 million, respectively. These costs do not include the costs for disposal of the final core or those for demolition of non-radioactive structures.

A cost reduction potentially much larger than any cost increase or cost reduction associated with decommissioning facilitation is the cost reduction associated with reduced downtime for maintenance. If a utility must buy replacement power from outside its system during maintenance periods, each day of maintenance will cost the utility approximately $500,000 per day per reactor (assuming the utility must pay 2¢ per kilowatt hour to replace the power from a 1200-MWe reactor). Thus, any decommissioning facilitation alternative that also reduces the time the reactor is out of service for maintenance (thereby eliminating the cost that must be paid for replacement power while the reactor is out of service) has the potential to pay for itself and perhaps for most of the decommissioning as well.

An obvious cost reduction strategy, then, is to look for decommissioning facilitation alternatives that will also increase operating time and decrease maintenance time. This must be done while the reactor is in the design phase.

11.2 FACILITATION ALTERNATIVES

Selected design features, special equipment, and construction techniques from Reference 1 that would facilitate decommissioning of single-reactor stations are reviewed briefly in this subsection. These alternatives obviously would also be useful in facilitating the decommissioning of reactors at a multiple-reactor station.

11.2.1 Improved Documentation

Documentation is the foundation of decommissioning facilitation. Correct as-built drawings; good construction photographs; scale models showing equipment arrangement, concrete pours, concrete penetrations, and the location of rebar; and accurate written and photographic maintenence records are vital to decommissioning. The value of these records is particularly evident when deferred decontamination is selected as the decommissioning alternative, because an operating crew knowledgeable about the facility will not be on hand to assist in the decommissioning.

11.2.2 Improved Access

Access to contaminated equipment can be improved by the installation of removable roof and wall panels. These panels are already in place in some newer reactors. Improved access simplifies removal of equipment for maintenance, replacement, and for disposal during decommissioning.

11.2.3 Substitution and Purification of Materials

Removal of ^{59}Co from stainless steels subject to activation will reduce the amount of ^{60}Co produced. ^{60}Co is responsible for a large fraction of the radiation dose received by workers during immediate decontamination. Substitution of alloys such as Zircalloy for stainless steels in areas subject to activation will also reduce the amount of ^{60}Co formed. However, care must be taken in situations where structural materials are involved, where reactor neutron physics might be affected, and where other materials might be activated to form even less desirable activation products. Elimination of ^{60}Co in this manner would not be particularly helpful if safe storage of 30 to 50 years followed by deferred decontamination were selected as the decommissioning alternative, because much of the ^{60}Co would decay to innocuous levels during the storage period.

11.2.4 Design of the Biological Shield for Easy Removal

Two alternatives for improving the safety of removing the biological shield are: 1) elimination of the need to drill blasting holes under high dose rate conditions at the time of dismantlement by designing holes into the biological shield during construction, and 2) elimination of the blasting process altogether by installing a modular biological shield that can be disassembled by means of a remote crane.

Preplacement of the vertical blasting holes during construction would eliminate the need for post-shutdown drilling by remote means. Biological shield thickness could be maintained by filling the holes with sand prior to pouring each succeeding vertical lift.

Design of the biological shield as a series of modularized components may be reasonably accomplished in a BWR, where the shield serves only the function of personnel and equipment shielding. In a PWR, the biological shield also supports the reactor vessel and must be designed primarily for this purpose, with its secondary function being to provide sufficient shielding thickness. The support structure would consist of a frame of heavy carbon steel I-beams designed to support the reactor and to provide a receptacle for precast concrete panels, which are inserted and pressure-grouted in place after insertion. The biological shield would be made of layers of preformed concrete in onion-like layers held in place by the structural steel I-beams. Removal of the panels would be accomplished by remote-crane operation, which would exert enough lifting force to fracture the grout, allowing each panel to be put into proper containers for shipping. A modular design of the biological shield might also expedite removal of the reactor pressure vessel, should that become necessary during the life of the reactor. Careful attention would need to be paid to the design of the biological shield to assure structural strength and integrity under postulated accident scenarios.

11.2.5 Techniques for Improved Protection of Concrete and Improved Removal of Contaminated Concrete

At least three alternatives are possible to protect concrete surfaces from contamination or to facilitate the removal of contaminated concrete. The first is to protect all contaminable but non-submerged concrete surfaces with carbon steel liners. Care would need to be taken in the design of the facility to assure the structural integrity required to support the weight of the liner. The second alternative is to protect these same surfaces with protective coatings. If the coating could be maintained intact throughout the operating lifetime of the plant, then any contamination could be readily washed off. The third alternative would eliminate drilling and simplify spalling through the installation of a carbon steel sandwich inside of potentially contaminable, but non-submerged, floors and walls at a depth of 4 inches. Air or liquid pressure applied between the plates would provide the spalling force. Again, careful attention would need to be paid to structural design.

11.2.6 Special Shielded Maintenance Shop

Expanded maintenance shops with added special shielding would allow shielded laydown, maintenance, and dismantling of all but the largest pieces of reactor equipment. In this way, predismantling outside the shop, which usually involves unshielded operations and less efficient equipment, could be avoided.

11.2.7 Improved Shielding for Maintenance and Decommissioning

Two possible alternatives for the direct protection of personnel from radiation are: 1) pipe shielding to reduce background levels in work spaces, and 2) a self-contained, shielded vehicle with manipulator arms that can perform functions equivalent to remote cell manipulators. Lead shielding with an air gap or insulation could be added to piping to provide both thermal and radiation shielding. Background radiation would be reduced at mechanical equipment, valves, and pumps that require the major portion of maintenance in an operating plant. Some redesign of pipe supports would be required to support the additional weight. A self-contained, shielded vehicle equipped with manipulator arms could be developed that would permit maintenance and decommissioning activities to proceed in a manner similar to that employed in stationary manipulator-equipped shielded cells. This vehicle might require larger access areas with adequate room for maneuvering and enough distance between components requiring maintenance to permit reasonably close approach by the mobile unit, which would be mounted on a tracked vehicle and contain its own life-support system. Fail-safe power units would be required to ensure that the operator(s) could always leave the area.

11.2.8 Reduction of Radwaste Volume by Incineration

Reduction of the radwaste volume by incineration is discussed in detail in Subsections 8.3.3 and 9.3 and in Section B.3 of Appendix B.

11.2.9 Electropolishing

The impact of a central electropolishing facility at a multiple-reactor station is discussed in detail in Subsection 8.3.4 and in Section B.4 of Appendix B.

11.2.10 Remote Maintenance and Decommissioning

Remote-controlled equipment offers the possibility of carrying out maintenance, monitoring, and decommissioning activities in high-radiation fields where contact maintenance results in excessive occupational radiation doses. A state-of-the-art robot could perform basic maintenance and decommissioning functions at a substantial reduction in radiation dose. Remote units capable of carrying out radiation surveillance, simple routine maintenance, and visual examination in medium- to high-radiation fields should require little maintenance, be reasonably compact, be reasonably inexpensive, be readily decontaminable, be mobile (both unit and console), and be remotely controlled. Ordinary industry requirements include limited space capability, operation in a range of temperatures and hazardous locations (i.e., little or no air, underwater), and ability to perform boring jobs without fatiguing. Nuclear requirements differ from these only in that they require operation in radiation fields. Reliability cannot be overemphasized, since a breakdown in service would not only delay a key operation, but could also compound the situation by adding robot removal and repair to the problem at hand.

11.2.11 Special Decommissioning Tools and Techniques

Unique problems caused by the presence of radiation fields call for the development of special decommissioning tools and techniques that speed cutting, drilling, and separation of radioactive components or that permit decommissioning workers to carry out their activities in lower radiation fields. Possible options include plasma-arc torch improvement, arc-saw improvement, explosive cutting, and a mobile, shielded, crane-mounted enclosure.

The plasma-arc torch is a metal-cutting device operated either in air or under water in which a high-temperature, high-velocity, small-diameter gaseous arc is struck between an electrode in the torch and the metal piece to be cut. The combined heat and force of the arc stream melt the metal and produce a high-quality, saw-like cut. The required improvements include the development of improved manipulation techniques and the development of torches that would cut 70-mm-thick stainless steel under water and 240-mm-thick carbon steel in air.

A prototype arc saw has been developed with a 36-inch-diameter saw blade capable of being operated either in air or under water. Scaling up the saw blade to a diameter of 3 m appears to be feasible, which would allow cutting large-diameter pipes, heat exchangers, and tanks.

Explosive cutting appears particularly well-adapted for removing pipes up to 40 mm thick or for cutting small pieces of difficult geometry. Its particular advantages include unattended operation and ability to operate in areas inaccessible to other cutting techniques. Design work is needed to solve the problems of water pluming in underwater cuts, of insuring good explosive-to-surface contact, and of placement on difficult-to-reach surfaces.

A shielded, crane-mounted enclosure would permit direct observation and control of decommissioning operations being handled by the crane. It would also protect personnel conducting operations in the spent fuel storage pool or in the pressure vessel from intense radiation fields.

11.3 FACILITATION OF DECOMMISSIONING AT MULTIPLE-REACTOR STATIONS

All of the decommissioning facilitation options discussed in Subsection 11.2 apply, both individually and collectively, to reactors at a multiple-reactor station. Several of the factors discussed in Section 8 are facilitation options in and of themselves and are discussed briefly in the following subsections.

11.3.1 Site Dedication

Dedication of a site to nuclear power generation fosters standardization of design, sequential construction, collocation, and sequential decommissioning of the reactor plants. The improvement in decommissioning efficiency by sequentially decommissioning several reactors of the same type is discussed in Subsection 8.2. For decommissioning four reactors of a single type, it is estimated that the cost and dose reduction factor for the planning and preparation phase is 0.62 and for the decommissioning phase is 0.94. The lower costs and radiation dose are a direct result of identical design and construction, more efficient planning, optimum use of crews familiar with the reactors, and more efficient use of dismantling tools and equipment.

11.3.2 Onsite Nuclear Waste Storage or Disposal

Onsite interim storage of low-level nuclear waste with subsequent removal to an offsite waste disposal facility or onsite permanent nuclear waste disposal results in lower radiation doses and lower costs for most cases when compared with immediate offsite disposal of nuclear waste from decommissioning. Only for the DECON and ENTOMB decommissioning alternatives with 30 years of interim waste storage are the estimated occupational radiation doses greater than for immediate offsite disposal. The costs for disposal of the nuclear waste from DECON are also greater for onsite interim storage for 30 years when compared with immediate offsite disposal. For longer periods of onsite interim waste storage, both dose and cost reductions are realized.

Dnsite permanent nuclear waste disposal yields dose and cost reductions by virtue of the shorter hauling distance over which the waste is moved to the disposal facility.

11.3.3 Central Services

Providing radiation monitoring, security, solid waste processing, and decontamination services as central services at a multiple-reactor station yields decommissioning cost reductions for each of the services when compared with a single-reactor station. Details of the estimation of the cost reductions achieved with central services are discussed in Subsection 8.3 and in Appendix B.

Of the central services mentioned above, only centralized solid waste processing results in reduction of occupational radiation dose.

11.4 REUSE OF THE FACILITY

One of the alternatives for reactor retirement given in NRC Regulatory Guide 1.86 is:

> "Conversion to a New Nuclear System or a Fossil Fuel System. This alternative, which applies only to nuclear power plants, utilizes the existing steam turbine system with a new steam supply system. The original nuclear steam supply system should

be separated from the electric generating system and disposed of in accordance with one of the previous three retirement alternatives."

Reuse of those facilities at a nuclear power station that can be refurbished makes good economic sense. Based on capital cost studies for PWRs[4] and BWRs,[5] the structures and equipment other than the nuclear steam supply systems have capital costs (in 1978 dollars) of $335 million for the PWR and $357 million for the BWR.

In a study of the economic feasibility of extended-life operation of LWRs, C. A. Negin, et al.,[6] concluded that everything within a nuclear power plant that may degrade with age is refurbishable or replaceable. Removal and replacement of large components in the containment building of a nuclear power reactor has been demonstrated with the replacement of the steam generators at the Surry Nuclear Power Station. At the Duane Arnold Nuclear Station, the reactor pressure vessel nozzle safe ends were successfully replaced. Cost estimates for steam generator replacement at Surry and Turkey Point range from $50 million to $100 million and for replacement of the safe ends at Duane Arnold, about $20 million.[6]

Replacement of the nuclear reactor pressure vessel could prove to be difficult in some of the existing reactor containment buildings. The reactor internals can be segmented and removed from the containment building as described in the PWR and BWR decommissioning studies.[2,3] Similarly, the reactor pressure vessel can be cut up, packaged for shipment, and removed from the containment vessel as described in these decommissioning studies. However, the equipment hatches on some of the reactor containment buildings may be too small to accommodate a new reactor pressure vessel. The capacity of reactor containment building cranes is usually insufficient to lift heavy pieces of equipment such as reactor pressure vessels. The reactor pressure vessel in the reference PWR, for example, weighs about 300 Mg and the reactor building crane has a capacity of only 113 Mg. So, to remove the reactor vessel from the reference PWR, special hoisting equipment would have to be set up in the reactor containment building. In order to handle the reactor vessel without adding an excessive amount of shielding, the reactor vessel internals, the most highly radioactive components in the nuclear plant, would be segmented, packaged, and shipped to a nuclear waste disposal site as described in References 2 and 3.

11.4.1 Removal of the Intact PWR Reactor Pressure Vessel

Layout of the reactor containment building and the fuel building of the reference PWR does not lend itself to convenient removal and replacement of the reactor pressure vessel. The laydown area on the operating floor level of the containment building is hardly adequate for handling the reactor pressure vessel while closure plates are welded over each of the nozzle openings in preparation for moving the vessel to an interim storage facility. Furthermore, although the containment building has an equipment hatch that is slightly larger in diameter than the reactor pressure vessel, the concrete shielding wall around the steam generator nearest the equipment hatch would prevent lining up the reactor vessel horizontally to pass through the equipment hatch. The laydown area in the fuel building adjacent to the equipment hatch is adequate for handling the old reactor pressure vessel and the new reactor vessel. However, the hoistway in the fuel building is not wide enough to accommodate the reactor pressure vessel, so the old vessel would have to be removed with an exterior, high-capacity crane through a hole cut in the roof of the fuel building.

An alternative to removing the reactor pressure vessel through the equipment hatch is to cut a hole in the dome of the reactor containment building for removing the vessel by vertical lift and laying the vessel down on a transporter. This alternative is not studied in detail because of the difficulty of restoring the integrity of the reactor containment structure after installation of the new reactor pressure vessel.

The reactor pressure vessel and the reactor internals are decontaminated before removal of the internals. The decontamination process is described in Section F.1.1 of Reference 2. Removal, packaging, and disposal of the reactor internals are accomplished as discussed in Appendix G of Reference 2.

Before the intact reactor pressure vessel can be removed from the reactor cavity, the lines connected to the reactor pressure vessel must be cut. Since there is no access to the external surface of the reactor pressure vessel inside the biological shield, the pipes must be cut using internal cutting devices. Sections of the pipes outboard of the biological shield are removed so that internal cutting devices can be inserted in the pipes to cut the pipes adjacent to the reactor vessel wall.

A temporary, 400-Mg capacity crane is used for lifting the reactor pressure vessel out of the reactor cavity. Contamination control is achieved by use of a temporary "greenhouse" over the refueling pool. The external surface of the reactor pressure vessel is cleaned by hoisting the vessel through a ring of high-pressure water jets. Before the reactor pressure vessel is moved from the reactor containment building, plates are welded over all of the nozzle openings.

A specialty rigging contractor is engaged for moving the reactor pressure vessel from the reactor containment building to the onsite interim storage facility.

The charges for placement of the reactor pressure vessel in the interim storage facility and retrieval therefrom are sufficient to cover the costs of construction, operation, and decommissioning of the storage cell.

The sequence for removal of the intact reactor pressure vessel from the reference PWR follows:

1. Remove, package, and ship the reactor internals to a nuclear waste disposal facility.
2. Remove a section of each line connected to the reactor vessel at the outer surface of the biological shield so that internal cutting tools can be inserted into the pipes.
3. Cut off the coolant loop nozzles just outboard of the reactor pressure vessel supports.
4. Cut off the remaining nozzles at the outer surface of the reactor pressure vessel.
5. Remove and package accessible insulation.

6. Weld closures on bottom head nozzles.

7. Remove the control rod drives from the reactor vessel head, package, and ship them to a licensed nuclear waste disposal facility.

8. Seal the openings in the reactor vessel top head.

9. Install steel seal plate on top of the reactor pressure vessel.

10. Remove the steam generator shielding above the operating floor level that interferes with the laydown of the reactor vessel.

11. Install a temporary 400-Mg crane above the operating floor.

12. Install a "greenhouse" over the refueling pool.

13. Install a high-pressure water-jet ring in the refueling pool for vessel decontamination.

14. Attach hoisting gear to the reactor vessel.

15. Lift the reactor vessel through the high-pressure water jet ring.

16. Weld closures on coolant inlet and outlet nozzles.

17. Remove "greenhouse."

18. Hoist the vessel from the reactor cavity and lay it down on a roller support in line with the equipment hatch.

19. Cut a hole in the roof of the fuel building through which the reactor pressure vessel can be removed.

20. Move the reactor vessel out of the containment building into the fuel building.

21. Lift the reactor vessel out of the fuel building and place it on an over-the-road transporter.

22. Move the pressure vessel to the onsite interim storage facility and place it in the storage cell.

23. Segment the vessel and package the segments for ultimate disposal at a licensed nuclear waste disposal facility, after the radiation dose rate has decayed to a level that permits contact work.

A summary of the estimated cost of removing the intact reactor pressure vessel, storing it for 50 years, and segmenting, packaging, and disposing of the vessel is given in Table 11.4-1. The estimated total cost, $8,200,000, is greater than the estimated cost of $5,157,000 for removing the reactor pressure vessel in segments and disposing of the segments immediately, based on the cost estimates given in Reference 2.

TABLE 11.4-1. Summary of Estimated Costs for Removal of the Intact Reactor Pressure Vessel from the Reference PWR

Cost Category	Estimated Cost ($ thousands)
Removal and Disposal of Reactor Internals	3028
Decommissioning Worker Labor	261
Shielding for Vessel Transport	23
Special Tools and Equipment	270
Disposal of Control Rods, Drives, & Pipe Sections	44
Vessel Removal & Transport	3460
Interim Storage Costs (50-Year Storage)	136
Segment Vessel	74
Disposal of Vessel Segments	915
Total	8211

The estimated occupational dose for removal of the intact reactor pressure vessel, storage for 50 years, and segmenting, packaging, and disposal of the segments is 172 man-rem. This estimate is about the same as the estimated occupational dose of 178 man-rem for removing the reactor pressure vessel in segments and disposing of the segments immediately, based on the occupational dose estimates given in Reference 2.

11.4.2 Removal of the Intact BWR Reactor Pressure Vessel

The Mark II containment of the reference BWR lends itself to relatively easy removal of the intact reactor pressure vessel. With the upper and lower shield plugs removed, the drywell head removed, and the section of the reactor building roof over the reactor removed, the reactor pressure vessel can be lifted vertically out of the building. A new reactor pressure vessel can be put in place by reversing the procedure.

Before the nuclear steam supply system is dismantled, the reactor pressure vessel and selected piping systems are chemically decontaminated. The procedures used and the costs incurred to perform this operation are discussed in Section H.5 of Reference 3. The procedures used and costs incurred to remove, package, and dispose of the reactor internals are described in Appendix I of Reference 3.

The four steam lines and four instrument lines are connected to the reactor pressure vessel above the sacrificial shield and are accessible for cutting at the reactor pressure vessel wall. An additional 31 lines penetrate the reactor vessel wall in the region of the sacrificial shield. In order to cut these lines at the outer surface of the reactor pressure vessel, a section of each line adjacent to the sacrificial shield is removed to provide access for the internal pipe-cutting tools or torches. Each of these 31 lines is cut at the outer surface of the reactor pressure vessel wall.

Two lines are cut and 185 control rod drives are removed from the bottom head of the reactor pressure vessel, which is accessible through the control rod gallery.

A temporary crane with a lifting capacity of 700 Mg is used to hoist the reactor pressure vessel out of the reactor cavity. As the vessel is hoisted from the reactor cavity, high-pressure water jets are directed at the outer surface of the vessel to remove any contamination. Seal plates for contamination control are welded over the nozzle openings while the vessel is suspended from the temporary crane.

The reactor pressure vessel is lifted out of the reactor building through a hole in the roof and transported to the onsite interim storage facility by a contractor specializing in lifting and transporting very heavy vessels.

The charges for placement of the reactor pressure vessel in the interim storage facility and retrieval therefrom are sufficient to cover the costs of construction, operation, and decommissioning of the interim storage cell.

The sequence for removal of the intact reactor pressure vessel from the reference BWR is:

1. Remove, package, and ship the reactor internals to a nuclear waste disposal facility.
2. Cut the four main steam lines at the reactor vessel wall and remove a section of each line.
3. Cut the four instrument lines that enter the reactor vessel above the sacrificial shield.
4. Cut the remainder of the lines at the outer surface of the sacrificial shield and remove a section of each line so that internal cutting tools can be inserted into the pipes.
5. Cut each of the lines at the outer surface of the reactor vessel wall.
6. Remove the 185 control rod drive housings from the bottom head and seal the openings.
7. Cut off the lines connected to the bottom head and seal the openings.
8. Remove and package accessible insulation.
9. Install steel seal plate on top vessel flange.
10. Install a temporary 700-Mg crane over the reactor cavity.
11. Install a "greenhouse" over the reactor well.
12. Install a high-pressure water jet ring in the reactor well.
13. Attach hoisting gear to the reactor pressure vessel.
14. Lift the reactor pressure vessel through ring of high-pressure water jets.
15. Lift the vessel so that seal plates can be welded over the nozzle openings.
16. Lower the reactor vessel onto the pedestal.
17. Remove the "greenhouse."
18. Remove the section of the reactor building roof that is over the reactor cavity.

19. Lift the reactor vessel out of the reactor building and place it on an over-the-road transporter, using a long-boomed crane.

20. Move the reactor pressure vessel to the onsite interim storage facility and place it in a storage cell.

21. Segment the reactor vessel and package the segments for disposal at a licensed nuclear waste disposal facility, after the radiation dose rate has decayed to a level that permits contact work.

The estimated costs of removing the intact reactor pressure vessel from the reference BWR, storing it for 50 years, and segmenting, packaging, and disposing of the segments are summarized in Table 11.4-2. The estimated total cost, $9,093,000, is greater than the estimated cost of $8,483,000 for removing the vessel in segments immediately, based on the cost estimates given in Reference 3.

TABLE 11.4-2. Summary of Estimated Costs for Removal of the Intact Reactor Pressure Vessel from the Reference BWR

Cost Category	Estimated Cost ($ thousands)
Removal and Disposal of Reactor Internals	5333
Decommissioning Worker Labor	499
Special Tools and Equipment	326
Disposal of Control Rods, Drives, & Pipe Sections	58
Vessel Removal & Transport	2308
Interim Storage Costs (50-Year Storage)	268
Segment Vessel	118
Disposal of Vessel Segments	183
Total	9093

The estimated occupational dose for removal of the intact reactor pressure vessel, storage for 50 years, and segmenting, packaging, and disposal of the segments is 281 man-rem. This estimate is greater than the estimated occupational dose of 164 man-rem for removing the vessel in segments and disposing of the segments immediately, based on the occupational dose estimates given in Reference 3.

11.4.3 Other Intact Vessel Removal Analyses

As part of the DOE-sponsored Shippingport Decommissioning Project, Burns and Roe, with support from Nuclear Energy Services, is performing analyses on a variety of scenarios for the removal and disposal of the reactor pressure vessel and its internals from the Shippingport Station during immediate dismantlement. These analyses are expected to be documented during CY-1982. While no quantitative estimates are presently available, initial results suggest that intact removal, transport, and disposal of the vessel and its internals may result in lower costs and occupational radiation dose than the other alternatives considered, for the particular situation at Shippingport Station. From calculations of the quantity and distribution of radioactivity in the vessel and its internals, it appears that the radioactivity will be sufficiently small to permit the assembly to be transported by barge as low specific activity (LSA) material shipment. The size and weight of the intact assembly precludes consideration of truck or rail shipment.

The much higher levels of radioactivity anticipated in the reactor vessels and their internals for the reference PWR and BWR appear to make intact removal and disposal of those vessels a less than optimum alternative, as indicated in the two preceding subsections.

11.4.4 Modular Biological Shield

A modular biological shield could conceivably reduce the occupational radiation dose from DECON of the facility or from installation of a new reactor pressure vessel if the facility is to be reused. However, a modular biological shield would have little impact on the cost and occupational radiation dose for removal of the intact reactor pressure vessel, since the modular biological shield would not be removed until after the reactor pressure vessel had been removed.

Neutron activation of the concrete and steel in the biological shield is greatest at the inner surface of the shield and decreases rapidly through the wall of the shield. Virtually all of the activated material in the biological shield is present in the inner 1-m layer of the shield. In the modular shield concept shown in Figure 11.4-1, only that portion of the shield that will be activated during reactor operation is modularized. The modules form a right-circular cylinder 6.1 m inside diameter, 7.9 m outside diameter, and 7.3 m high.

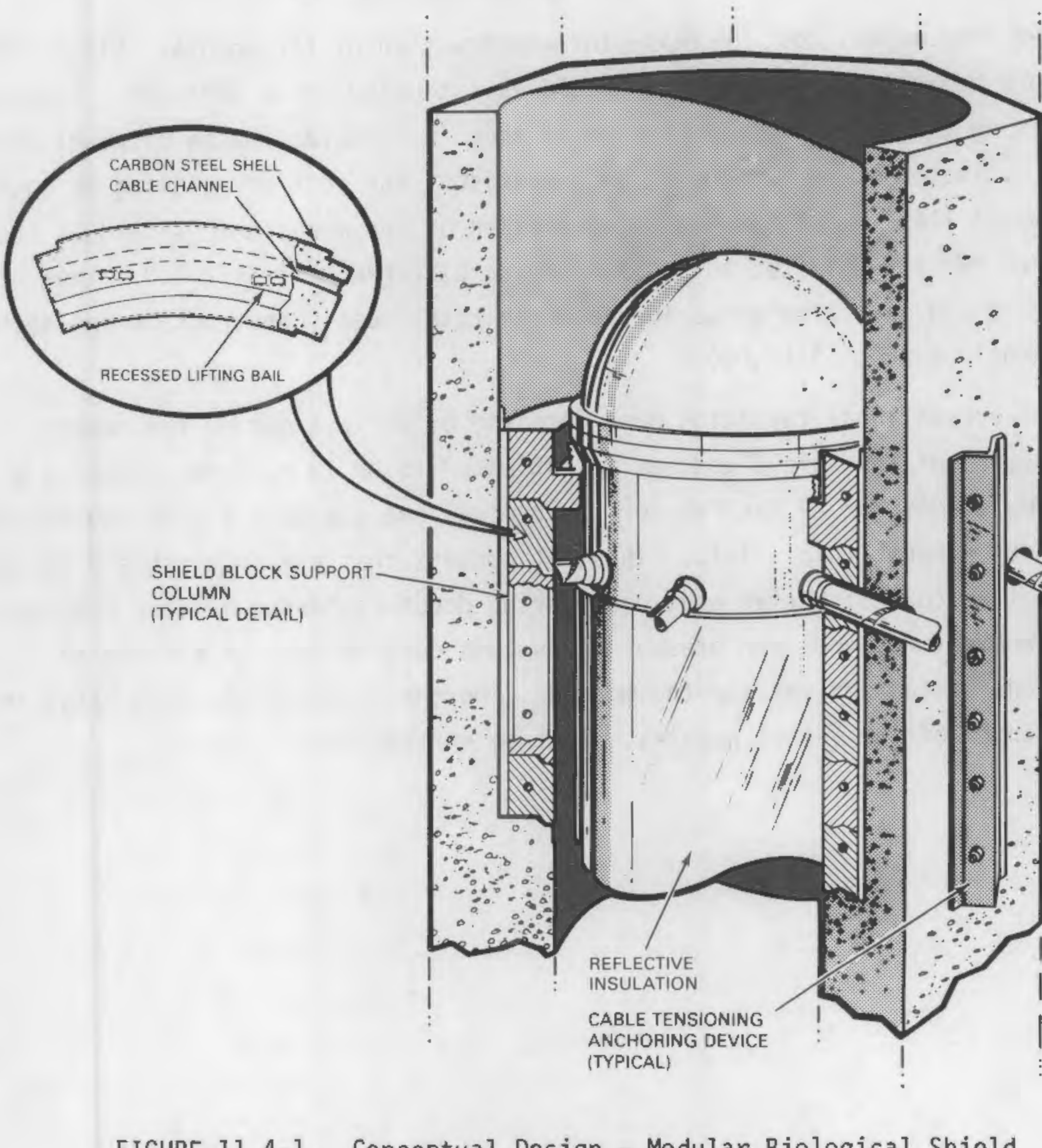

FIGURE 11.4-1. Conceptual Design - Modular Biological Shield

There are six rings of modules. Each ring is 1.2 m high and contains eight modules. Each module weighs about 8 Mg. The modules are constructed by pouring concrete into carbon steel shells that are fabricated to close dimensional tolerances. As shown in Figure 11.4-1, the modules are stepped at the top and bottom to minimize radiation streaming and to provide lateral stability. Circumferential post-tensioned cables provide additional structural stability to that provided by the eight wide-flange I-beam columns. Each module has two recessed lifting bails in the top of the block. These bails are designed for engaging the lifting hooks semi-remotely, using long-handled tools.

The incremental cost increase for construction of the modular shield relative to a conventional monolithic shield is estimated to be $884,000. The cost of removing the modules and disposing of them in a nuclear waste disposal facility is estimated to be $205,000. By comparison, the cost of removing an equivalent amount (145 m^3) of the activated portion of the monolithic shield at the reference PWR is estimated to be $337,000, a difference of $172,000. Thus, the modular shield is estimated to increase the total cost (construction and decommissioning) by about $712,000.

The occupational radiation dose received by workers during the removal and disposal of the shield modules is estimated to be 13 man-rem, compared with an estimated dose of 29 man-rem for the removal and disposal of the equivalent portion of a monolithic shield. Thus, it appears that a modular shield design would not be cost-effective when considering decommissioning alone. However, if replacement of a reactor pressure vessel is considered, the ability to remove and restack or replace the modules, thereby reducing the dose rates in the vicinity of the vessel nozzles, might be worthwhile.

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6. C. A. Negin, et al., "Planning Study and Economic Feasibility for Extended Life Operation of Light Water Reactor Plants," in Proceedings of ANS Topical Meeting on Decontamination and Decommissioning of Nuclear Facilities, ed., M. M. Osterhout, pp. 471-484, Plenum Press, New York and London, 1979.

APPENDICES

APPENDIX A

NUCLEAR WASTE DISPOSAL COST ESTIMATES

Three options for disposing of nuclear waste from reactor decommissioning are examined in this study: 1) immediate offsite disposal, 2) onsite interim storage with later removal to offsite disposal, and 3) onsite disposal. Cost estimates for immediate offsite disposal of nuclear waste from multiple-reactor decommissioning are not discussed here because they are the same as for single-reactor decommissioning.

Waste disposal costs are estimated for decommissioning each type of reactor (PWR and BWR) by each of the three alternative methods, DECON, SAFSTOR, and ENTOMB. The nuclear waste disposal costs are estimated separately for neutron-activated material, contaminated material, and radioactive waste.

A.1 ONSITE INTERIM STORAGE

Onsite interim storage of nuclear waste from the decommissioning of reactors may be used to reduce the cost of waste disposal. It is conceived that the nuclear waste at a multiple-reactor station could be placed in interim onsite storage for a period long enough for radioactive decay to reduce the quantity of waste that must be disposed of in a licensed burial facility. In this study, onsite interim storage periods of 30, 50, and 100 years are used in the cost estimates. At the end of the storage period, the nuclear waste is retrieved from the interim storage facility, checked for radiation dose rate, and shipped to an offsite licensed waste disposal facility.

Assumptions made in estimating the costs of onsite interim storage of nuclear waste are:

1. The quantity of nuclear waste placed in onsite interim waste storage is the same as would be sent to an offsite waste disposal facility.
2. The packaging used for disposal of radioactive material is able to withstand interim storage, retrieval from storage, and relocation to an offsite permanent disposal facility without requiring repackaging.

3. Since transport to interim onsite waste storage is over private roads within a privately owned and controlled area, it is assumed that it is not necessary to meet the DOT surface radiation dose rate requirement. Shielding is provided for the truck cab to limit the dose rate to 2 mR/hr. The radiation dose of workers is controlled to assure that it does not exceed the 10 CFR 20 limits. This assumption should result in fewer cask loads and the use of fewer shielded cask liners.

4. The onsite interim waste storage facility is 24 km from the reactor and the onsite transport cost is \$1.43/km for a truck.

5. The cost of placing and maintaining nuclear waste in interim storage is equal to the disposal charge at a licensed waste disposal site (\$93.57/m^3).[a]

6. There are no liner or curie surcharges at the onsite storage facility.

7. The cost of retrieving the waste from interim storage is the same as the disposal charge at a licensed waste disposal site (\$93.57/m^3).[a]

8. After interim storage for 30 to 100 years, some of the contaminated material will have decayed to levels permitting unrestricted release. Therefore, the quantity of nuclear wastes that eventually must be sent to offsite disposal is less than would be sent immediately to offsite disposal.

9. The liner and curie surcharges at the commercial waste disposal facility are lower after temporary onsite storage because of radioactive decay that has occurred.

10. For neutron-activated material, the radioactive decay during temporary storage of even 100 years is insufficient to permit unrestricted release of the material. Therefore, all of the neutron-activated material must be relocated to a licensed waste disposal facility after interim onsite storage.

(a) It is estimated that these placement and retrieval charges are greater than the cost of construction, operation, depreciation, and decommissioning of the interim waste storage facility.

A.1.1 Reference PWR Decommissioning Wastes

Data for determining the impact on costs of onsite interim storage of the nuclear wastes from decommissioning the reference PWR are taken from the study of decommissioning a reference PWR by Smith et al.[1] Radioactive decay factors for neutron-activated material used in the cost analyses are given in Table A.1-1 for the radioactivity levels and the dose rates.

TABLE A.1-1. Decay Factors for Radioactivity Levels and Dose Rates of Neutron-Activated Materials in the Reference PWR

Time After Shutdown (Years)	Decay Factors[a]	
	Radioactivity Level	Dose Rate
30	5.2×10^{-2}	1.9×10^{-2}
50	4.6×10^{-2}	1.4×10^{-3}
60	4.3×10^{-2}	3.7×10^{-4}
80	3.7×10^{-2}	3.7×10^{-5}
100	3.2×10^{-2}	1.3×10^{-5}
130	2.6×10^{-2}	1.15×10^{-5}
150	2.2×10^{-2}	1.1×10^{-5}
200	1.5×10^{-2}	1.1×10^{-5}

(a) Based on Figure C.3-1 of Reference 1.

The costs for disposal of the neutron-activated materials at 30, 50, and 100 years after shutdown are given in Table A.1-2.

A.1.1.1 Waste from DECON

In the following subsections, estimated costs for disposal of each type of nuclear waste from DECON are developed for onsite interim storage and later offsite disposal of the waste.

TABLE A.1-2. PWR Costs for Disposal of Neutron-Activated Materials at Various Times after Shutdown (Based on Table G.4-3, Reference 1)

Component	Weight (kg)[a]	Estimated Radioactivity (Ci)	Number of Pieces	Number of Containers[b]	Container Cost ($)[c]	Cask Rental ($)[d]	Number of Shipments	Transportation Cost ($)[e]	Handling Cost ($)[f]	Burial Volume (m^3)[g]	Burial Cost ($)[f]	Liner Surcharge ($)[f]	Curie Surcharge ($)[f]	Total Disposal Costs ($)[h]
30 Years After Shutdown														
Pressure Vessel Wall	269 800	177	70	38	380 000	0	38	70 680	11 400	108	10 070	0	0	472 150
Pressure Vessel Head	88 450	<1	20	20	200 000	0	5	9 300	0	57	5 300	0	0	214 600
Pressure Vessel Bottom	38 870	<1	20	20	200 000	0	2	3 720	0	57	5 300	0	0	209 020
Upper Core Support Assembly	12 020	<1	12	4	40 000	2 000	4	7 440	1 200	11	1 060	0	0	51 700
Upper Support Columns	11 110	<4	96	4	40 000	2 000	4	7 440	1 200	11	1 060	0	0	51 700
Upper Core Barrel	2 720	<43	10	2	20 000	1 000	2	3 720	600	6	530	250	0	26 100
Upper Core Grid Plate	4 630	1 080	9	5	50 000	2 500	5	9 300	2 200	14	1 325	625	1 500	67 450
Guide Tubes	15 100	<4	122	6	60 000	0	1	1 860	0	17	1 590	0	0	63 450
Lower Core Barrel	42 640	33 500	64	32	320 000	16 000	32	59 520	9 600	91	8 480	4 000	10 800	428 400
Thermal Shields	10 430	7 310	12	6	60 000	3 000	6	11 160	1 800	17	1 590	750	2 080	80 380
Core Shroud	12 290	152 000	96	4	40 000	2 000	4	7 440	1 200	11	1 060	500	27 320	79 520
Lower Grid Plate	3 950	24 600	9	5	50 000	2 500	5	9 300	2 200	14	1 325	625	4 750	70 700
Lower Support Columns	3 360	430	96	1	10 000	500	1	1 860	300	3	265	125	310	13 360
Lower Core Forging	36 470	108	25	11	110 000	5 500	11	20 460	3 300	31	2 915	1 375	0	143 550
Misc. Internals	36 290	86	80	8	80 000	4 000	8	14 880	2 400	23	2 120	1 000	0	104 400
Bio-Shield Concrete	884 500	<86	--	195	78 000	0	49	91 140	0	707	66 144	0	0	235 284
Reactor Cavity Liner	14 510	<1	--	4	1 600	0	1	1 860	0	14	1 357	0	0	4 817
Totals	1 487 140	219 432	741	365	1 739 600	41 000	178	331 080	37 400	1 192	111 491	9 250	46 760	2 316 581
50 Years After Shutdown														
Pressure Vessel Wall	269 800	92	70	38	380 000	0	38	70 680	11 400	108	10 070	0	0	472 150
Pressure Vessel Head	88 450	<1	20	20	200 000	0	5	9 300	0	57	5 300	0	0	214 600
Pressure Vessel Bottom	38 870	<1	20	20	200 000	0	2	3 720	0	57	5 300	0	0	209 020
Upper Core Support Assembly	12 020	<1	12	4	40 000	0	1	1 860	0	11	1 060	0	0	42 920
Upper Support Columns	11 110	<3	96	4	40 000	2 000	4	7 440	1 200	11	1 060	0	0	51 700
Upper Core Barrel	2 720	<33	10	2	20 000	1 000	2	3 720	600	6	530	0	0	25 850
Upper Core Grid Plate	4 630	797	9	5	50 000	2 500	5	9 300	2 200	14	1 325	0	1 500	66 825
Guide Tubes	15 100	<3	122	6	60 000	0	1	1 860	0	17	1 590	0	0	63 450
Lower Core Barrel	42 640	25 700	64	32	320 000	16 000	32	59 520	9 600	91	8 480	0	10 400	424 000
Thermal Shields	10 430	5 530	12	6	60 000	3 000	6	11 160	1 800	17	1 590	0	1 990	79 540
Core Shroud	12 290	113 000	96	4	40 000	2 000	4	7 440	1 200	11	1 060	0	25 320	77 020
Lower Grid Plate	3 950	18 200	9	5	50 000	2 500	5	9 300	2 200	14	1 325	0	4 400	69 725
Lower Support Columns	3 360	330	96	1	10 000	500	1	1 860	300	3	265	0	305	13 230
Lower Core Forging	36 470	83	25	11	110 000	5 500	11	20 460	3 300	31	2 915	0	0	142 175
Misc. Internals	36 290	66	80	8	80 000	4 000	8	14 880	2 400	23	2 120	0	0	103 400
Bio-Shield Concrete	884 500	<66	--	195	78 000	0	49	91 140	0	707	66 144	0	0	235 284
Reactor Cavity Liner	14 510	<1	--	4	1 600	0	1	1 860	0	14	1 357	0	0	4 817
Totals	1 487 140	163 907	741	365	1 739 600	39 000	175	325 500	36 200	1 192	111 491	0	43 915	2 295 710

TABLE A.1-2. PWR Costs for Disposal of Neutron-Activated Materials at Various Times after Shutdown (Based on Table G.4-3, Reference 1)

TABLE A.1-2. (contd)

Component	Weight (kg)[a]	Estimated Radioactivity (Ci)	Number of Pieces	Number of Containers[b]	Container Cost ($)[c]	Cask Rental ($)[d]	Number of Shipments	Transportation Cost ($)[e]	Handling Cost ($)[f]	Burial Volume (m^3)[g]	Burial Cost ($)[f]	Liner Surcharge ($)[f]	Curie Surcharge ($)[f]	Total Disposal Costs ($)[h]
					100 Years After Shutdown									
Pressure Vessel Wall	269 800	64	70	38	380 000	0	38	70 680	11 400	108	10 070	0	0	472 150
Pressure Vessel Head	88 450	<1	20	20	200 000	0	5	9 300	0	57	5 300	0	0	214 600
Pressure Vessel Bottom	38 870	<1	20	20	200 000	0	2	3 720	0	57	5 300	0	0	209 020
Upper Core Support Assembly	12 020	<1	12	4	40 000	0	1	1 860	0	11	1 060	0	0	42 920
Upper Support Columns	11 110	2	96	4	40 000	2 000	4	7 440	1 200	11	1 060	0	0	51 700
Upper Core Barrel	2 720	22	10	2	20 000	1 000	2	3 720	600	6	530	0	0	25 850
Upper Core Grid Plate	4 630	557	9	5	50 000	2 500	5	9 300	2 200	14	1 325	0	1 500	66 825
Guide Tubes	15 100	2	122	6	60 000	0	1	1 860	0	17	1 590	0	0	63 450
Lower Core Barrel	42 640	18 000	64	32	320 000	16 000	32	59 520	9 600	91	8 480	0	10 020	423 620
Thermal Shields	10 430	3 870	12	6	60 000	3 000	6	11 160	1 800	17	1 590	0	1 900	79 450
Core Shroud	12 290	78 500	96	4	40 000	2 000	4	7 440	1 200	11	1 060	0	23 600	75 300
Lower Grid Plate	3 950	12 700	9	5	50 000	2 500	5	9 300	2 200	14	1 325	0	4 110	69 435
Lower Support Columns	3 360	220	96	1	10 000	500	1	1 860	300	3	265	0	300	13 225
Lower Core Forging	36 470	55	25	11	110 000	5 500	11	20 460	3 300	31	2 915	0	0	142 175
Misc. Internals	36 290	44	80	8	80 000	4 000	8	14 880	2 400	23	2 120	0	0	103 400
Bio-Shield Concrete	884 500	<44	--	195	78 000	0	49	91 140	0	707	66 144	0	0	235 284
Reactor Cavity Liner	14 510	<1	--	4	1 600	0	1	1 860	0	14	1 357	0	0	4 817
Totals	1 487 140	114 040	741	365	1 739 600	39 000	175	325 500	36 200	1 192	111 491	0	41 430	2 293 220

(a) Weights approximate, calculated from dimensions or obtained from Trojan FSAR.
(b) Indicative of volume only. Actual pieces are distributed throughout all containers to satisfy the 50,000 Ci/container limit for burial.
(c) Based on Table I.2-1, Reference 1.
(d) Based on Table I.3-1, Reference 1.
(e) Based on Table I.4-4, Reference 1.
(f) Based on Table I.5-1, Reference 1.
(g) Volume includes the disposable container.
(h) The number of figures shown is for computational accuracy and does not imply precision to that many significant figures.

TABLE A.1-2. (contd)

A.1.1.1.1 Neutron-Activated Material. The two major operations involved in disposal of the nuclear waste with onsite interim storage are: 1) placement of the waste in interim storage and 2) removal of the waste to permanent offsite disposal.

Placement in Interim Storage. Several components of the cost of putting the neutron-activated material in interim storage are container cost, cask rental, transportation cost, handling cost, and placement cost. The estimated costs of putting the neutron-activated material from DECON of a reference PWR in onsite interim storage are presented in Table A.1-3.

TABLE A.1-3. Estimated Costs of Onsite Interim Storage of Neutron-Activated Material from DECON of a PWR

Cost Component	Cost($)
Containers	1 739 600[(a)]
Cask Rental	16 600[(b)]
Onsite Transportation	14 840[(c)]
Handling	50 600[(a)]
Placement	111 491[(a)]
Total	1 933 130

(a) From Table G.4-3, Reference 1.
(b) 1-day cask rental (1/5 the cost given in Table G.4-3, Reference 1).
(c) 216 shipments with a round-trip distance of 48 km. 216 x 48 x 1.431 = $14,840

Removal to Offsite Disposal. Details of the cost estimates for removal of the neutron-activated material to an offsite licensed disposal facility are summarized in Table A.1-4.

TABLE A.1-4. Estimated Cost of Removal to Offsite Oisposal of the Neutron-Activated Material from DECON of a PWR

Cost Component	Costs ($) After Interim Storage Period of[a]		
	30 Year	50 Year	100 Year
Retrieve From Interim Storage	111 490	111 490	111 490
Cask Rental	41 000	39 000	39 000
Transportation	331 080	325 500	325 500
Handling	37 400	36 200	36 200
Burial	111 490	111 490	111 490
Liner Surcharge	9 250	0	0
Curie Surcharge	46 760	43 918	41 430
Totals	688 470	667 600	665 110

(a) From Table A.1-2.

A.1.1.1.2 Contaminated Material. The costs for the two major operations involved in disposal of contaminated material by onsite interim storage are estimated below.

Placement in Interim Storage. Estimated costs of putting the contaminated material from DECON of a reference PWR in onsite interim storage are given in Table A.1-5.

TABLE A.1-5. Estimated Costs of Onsite Interim Storage of Contaminated Material from DECON of a PWR

Cost Component	Cost($)
Containers	1 857 200[a]
Onsite Transportation	66 330[b]
Handling	39 320[c]
Placement	1 504 598
Total	3 467 450

(a) From Tables G.4-4 and G.4-5, Reference 1.
(b) 967 shipments with a round-trip distance of 48 km.
(c) From Table G.4-4, Reference 1.

Removal to Offsite Disposal. Details of the cost estimates for removal of the contaminated material to an offsite licensed disposal facility are summarized in Table A.1-6.

TABLE A.1-6. Estimated Costs of Removal to Offsite Disposal of the Contaminated Material from DECON of a PWR

Cost Component	Costs ($) After Interim Storage Period of 30 Year	50 Year	100 Year
Retrieve from Interim Storage	310 720[(a)]	310 720[(a)]	310 720[(a)]
Transportation	1 781 680[(b)]	11 520[(d)]	11 520[(d)]
Handling	39 320[(c)]	0	0
Burial	1 504 600[(b)]	9 357[(d)]	9 357[(d)]
Totals	3 636 320	331 597	331 597

(a) 4154 containers: Assume 4 man-hr per container; $18.70 per man-hr. 4154 x 4 x 18.70 = $310,720.
(b) From Tables G.4-4 and G.4-5, Reference 1.
(c) From Table G.4-4, Reference 1.
(d) Based on 100 m^3 of contaminated material sent to an offsite licensed burial facility.

A.1.1.1.3 Radioactive Waste. Estimated costs for placement of the radioactive waste in onsite interim storage and later removal to offsite permanent disposal are shown in Tables A.1-7 and A.1-8, respectively.

A.1.1.2 Waste from SAFSTOR

SAFSTOR involves two major activities that generate radioactive waste: 1) preparations for safe storage and 2) deferred decontamination at the end of the storage period. Waste disposal costs are estimated for deferred decontamination after storage periods of 30, 50, and 100 years. Since onsite interim storage of waste is being examined for storage periods of 30, 50, and 100 years, the cost of removal of the radioactive waste to an offsite licensed disposal facility is estimated for times after shutdown ranging from 60 to 200 years.

TABLE A.1-7. Estimated Costs of Onsite Interim Storage of Radioactive Waste from DECON of a PWR

Cost Component	Cost ($)
Containers	136 650[a]
Cask Rental	12 000[b]
Onsite Transportation	9 820[c]
Handling	24 000[d]
Placement	57 876[a]
Total	240 350

(a) From Table G.4-6, Reference 1.
(b) Assumed that shielded casks would be needed only for spent resins, spent filter cartridges, and evaporator bottom liquids. One day cask rental per shipment.
(c) 143 shipments with a round-trip distance of 48 km. 143 x 48 x 1.431 = $9820.
(d) Handling costs from Table G.4-6, Reference 1, for spent resins spent filter cartridges, and evaporator bottom liquids.

TABLE A.1-8. Estimated Costs of Removal to Offsite Disposal of Radioactive Waste from DECON of a PWR

Cost Component	Costs ($) After Interim Storage Period of 30 Year	50 Year	100 Year
Retrieval from Interim Storage	112 650[a]	112 650[a]	112 650[a]
Cask Rental	10 000[b]	0	0
Transportation	84 480[c]	32 640[d]	26 880[e]
Liner Surcharge	2 500	0	0
Burial	49 780[f]	35 740[g]	31 070[h]
Totals	259 410	181 300	170 600

(a) 1506 containers at 4 man-hr per container with a charge-out rate of $18.70 per man-hr.
(b) Casks needed only for spent resins.
(c) 44 shipments at $1920 per shipment.
(d) 17 shipments at $1920 per shipment.
(e) 14 shipments at $1920 per shipment.
(f) 532 m^3 at $93.57 per m^3.
(g) 382 m^3 at $93.57 per m^3.
(h) 332 m^3 at $93.57 per m^3.

The estimated costs for the disposal of each type of nuclear waste from SAFSTOR of the reference PWR are developed in the following subsections for onsite interim storage and eventual offsite disposal.

A.1.1.2.1 Neutron-Activated Material. No neutron-activated material is removed from the reactor during the preparations for safe storage. During deferred decontamination, all of the neutron-activated material is removed from the reactor, packaged, and sent to onsite interim storage. The estimated costs for placement of the neutron-activated material in onsite interim storage are summarized in Table A.1-9.

TABLE A.1-9. Estimated Costs of Onsite Interim Storage of Neutron-Activated Material from Deferred Decontamination of a PWR

Cost Component	Costs ($) After Safe Storage Period of		
	30 Year	50 Year	100 Year
Containers	1 739 600[a]	1 739 600[a]	1 739 600[a]
Cask Rental	11 200[b]	0	0
Onsite Transportation	12 230[c]	7 290[d]	7 290[d]
Handling	35 000[e]	0	0
Placement	111 490[a]	111 490[a]	111 490[a]
Totals	1 909 520	1 858 380	1 858 380

(a) From Table G.4-3, Reference 1.
(b) Casks used only for cask liners with a surface dose rate >1.0 R/hr.
(c) 178 shipments with a round-trip distance of 48 km. 178 x 48 x 1.431 = $12,230
(d) 106 shipments 106 x 48 x 1.431 = $7,290
(e) For cask shipments.

Estimated costs for removal of the neutron-activated material from onsite interim storage and disposal at an offsite licensed disposal facility are shown in Table A.1-10. Onsite interim storage periods of 30, 50, and 100 years are used in the cost estimates. For deferred decontamination 30 years after reactor shutdown, removal to offsite disposal would occur 60, 80, and 100 years after reactor shutdown.

TABLE A.1-10. Estimated Costs of Removal to Offsite Disposal of Neutron-Activated Material from Deferred Decontamination of a PWR

Cost Component	Offsite Disposal Costs ($) After Interim Storage Period of 30 Year	50 Year	100 Year
	Deferred Decontamination 30 Years After Shutdown[a]		
Retrieve From Interim Storage	111 490	111 490	111 490
Transportation	203 520	203 520	203 520
Curie Surcharge	16 060	14 630	11 910
Burial	111 490	111 490	111 490
Totals	442 560	441 130	438 410
	Deferred Decontamination 50 Years After Shutdown[b]		
Retrieve From Interim Storage	111 490	111 490	111 490
Transportation	203 520	203 520	203 520
Curie Surcharge	14 630	13 400	11 010
Burial	111 490	111 490	111 490
Totals	441 130	439 900	437 510
	Deferred Decontamination 100 Years After Shutdown[c]		
Retrieve From Interim Storage	111 490	111 490	111 490
Transportation	203 520	203 520	203 520
Curie Surcharge	11 910	11 010	9 380
Burial	111 490	111 490	111 490
Totals	438 410	437 510	435 880

(a) For deferred decontamination 30 years after shutdown, offsite disposal will take place 60, 80, and 130 years after shutdown.
(b) For deferred decontamination 50 years after shutdown, offsite disposal will take place 80, 100, and 150 years after shutdown.
(c) For deferred decontamination 100 years after shutdown, offsite disposal will take place 130, 150, and 200 years after shutdown.

A.1.1.2.2 Contaminated Material. Contaminated material is removed from the reactor and placed in onsite interim storage during deferred decontamination, not during preparations for safe storage. Estimated costs for placement of the contaminated material in onsite interim storage are given in Table A.1-11.

Estimated costs for removal to offsite disposal of the contaminated material from onsite interim storage are shown in Table A.1-12.

TABLE A.1-11. Estimated Costs of Onsite Interim Storage of Contaminated Material from Deferred Decontamination of a PWR

Cost Component	Costs ($) After Safe Storage Period of		
	30 Year	50 Year[a]	100 Year[a]
Containers	1 857 200	11 200	11 200
Onsite Transportation	66 330	350	350
Handling	39 320	0	0
Placement	1 504 600	9 360	9 360
Totals	3 467 450	20 910	20 910

(a) Based on 100 m^3 of contaminated material for disposal. See Table H.5-1, Reference 1.

TABLE A.1-12. Estimated Costs of Removal to Offsite Disposal of Contaminated Material from Deferred Decontamination of a PWR

Cost Component	Offsite Disposal Costs ($) After Interim Storage Period of		
	30 Year	50 Year	100 Year
	Deferred Decontamination 30 Years After Shutdown[a]		
Retrieve From Interim Storage	310 550	310 550	310 550
Transportation	9 600	9 600	5 760
Burial	9 360	9 360	4 680
Totals	329 510	329 510	320 990
	Deferred Decontamination 50 Years After Shutdown[b]		
Retrieve From Interim Storage	2 100	2 100	2 100
Transportation	9 600	9 600	5 760
Burial	9 360	9 360	4 680
Totals	21 060	21 060	12 540
	Deferred Decontamination 100 Years After Shutdown[c]		
Retrieve From Interim Storage	2 100	2 100	2 100
Transportation	5 760	5 760	3 840
Burial	4 680	4 680	2 810
Totals	12 540	12 540	8 750

(a) For deferred decontamination 30 years after shutdown, offsite disposal will occur 60, 80, and 130 years after shutdown.
(b) For deferred decontamination 50 years after shutdown, offsite disposal will occur 80, 100, and 150 years after shutdown.
(c) For deferred decontamination 100 years after shutdown, offsite disposal will occur 130, 150, and 200 years after shutdown.

A.1.1.2.3 Radioactive Waste. All of the wet solid waste and some of the dry solid waste generated by SAFSTOR are disposed of during preparations for safe storage. Disposal costs are developed in two steps: 1) for those radioactive wastes generated during preparations for safe storage and 2) for those radioactive wastes generated during deferred decontamination.

Preparations for Safe Storage. Estimated costs for placement in onsite interim storage of the radioactive waste from preparations for safe storage are summarized in Table A.1-13.

TABLE A.1-13. Estimated Costs of Onsite Interim Storage of Radioactive Waste from Preparations for Safe Storage of a PWR

Cost Component	Cost ($)
Containers	114 970[a]
Cask Rental	12 000[b]
Onsite Transportation	8 450[c]
Handling	24 000[d]
Placement	36 330[e]
Total	195 750

(a) From Table H.3-2, Reference 1.
(b) One day cask rental for each shipment. Casks used only for cask liners with a surface dose rate >1 R/hr.
(c) 139 shipments with round-trip distance of 48 km.
(d) For spent resins, spent filter cartridges, and evaporator bottoms liquids.
(e) Assumed to be the same as the burial cost given in Table H.3-2, Reference 1.

The estimated costs for removal to offsite disposal of the radioactive waste from preparations for safe storage are given in Table A.1-14.

TABLE A.1-14. Estimated Costs of Removal to Offsite Disposal of Radioactive Waste from Preparations for Safe Storage of a PWR

Cost Component	Offsite Disposal Costs ($) After Interim Storage Period of 30 Year	50 Year	100 Year
Retrieve From Interim Storage	31 550[a]	31 550[a]	31 550[a]
Cask Rental	10 000[b]	0	0
Transportation	55 680[c]	13 440[d]	9 600[e]
Liner Surcharge	2 500	0	0
Burial	21 520[f]	14 040[g]	9 360[h]
Totals	121 250	59 030	50 510

(a) 422 containers at 4 man-hr per container with a charge-out rate of $18.70 per man-hr.
(b) Casks used only for those shipments with a cask-liner dose rate >1 R/hr. 5-day cask rental for each shipment.
(c) 29 shipments at $1,920 per shipment.
(d) 7 shipments at $1,920 per shipment.
(e) 5 shipments at $1,920 per shipment.
(f) 230 m^3 at $93.57 per m^3.
(g) 150 m^3 at $93.57 per m^3.
(h) 100 m^3 at $93.57 per m^3.

Deferred Decontamination. Deferred decontamination after safe storage periods of 30, 50, and 100 years is studied. The estimated costs of placing the radioactive waste in onsite interim storage is shown in Table A.1-15, an the estimated costs of removal of the waste to offsite disposal is shown in Table A.1-16.

TABLE A.1-15. Estimated Costs of Onsite Interim Storage of Radioactive Waste from Deferred Decontamination of a PWR

Cost Component	Costs ($) After Safe Storage Period of 30 Year[a]	50 Year[a]	100 Year[a]
Containers	21 900	14 300	9 540
Onsite Transportation	2 000[b]	550[b]	340[b]
Placement	21 520	14 040	9 360
Totals	45 420	28 890	19 240

(a) Waste volumes assumed: 30 year - 230 m^3; 50 year - 150 m^3; 100 year - 100 m^3.
(b) Onsite round trip of 48 km at $1.431 per km. Number of shipments: 30 year - 29; 50 year - 8; 100 year - 5.

TABLE A.1-16. Estimated Costs of Removal to Offsite Disposal of Radioactive Waste from Deferred Decontamination of a PWR

Cost Component	Offsite Disposal Costs ($) After Interim Storage Period of 30 Year	50 Year	100 Year
	Deferred Decontamination 30 Years After Shutdown[(a)]		
Retrieve From Interim Storage[(b)]	81 860	81 860	81 860
Transportation[(c)]	15 360	9 600	7 680
Burial[(d)]	14 040	9 360	7 020
Totals	111 260	100 820	95 560
	Deferred Decontamination 50 Years After Shutdown[(e)]		
Retrieve From Interim Storage[(f)]	53 450	53 450	53 450
Transportation[(g)]	9 600	9 600	5 760
Burial[(h)]	9 360	9 360	5 610
Totals	72 410	72 410	64 820
	Deferred Decontamination 100 Years After Shutdown[(i)]		
Retrieve From Interim Storage[(j)]	35 660	35 660	35 660
Transportation[(k)]	7 680	5 760	5 760
Burial[(m)]	7 020	5 610	4 680
Totals	50 360	47 030	46 100

(a) For deferred decontamination 30 years after shutdown, offsite disposal will occur 60, 80, and 130 years after shutdown.
(b) 1095 drums of waste. 4 man-hr per drum to check, segregate, and repackage. $18.70 per man-hr charge-out rate.
(c) 8 shipments for 30 years storage; 5 shipments for 50 years storage; 4 shipments for 100 years storage.
(d) Burial volumes of waste assumed: 150 m^3 at 30 years; 100 m^3 at 50 years; 75 m^3 at 100 years.
(e) For deferred decontamination 50 years after shutdown, offsite disposal will occur 80, 100, and 150 years after shutdown.
(f) 715 drums of waste retrieved, checked, segregated, and repackaged where necessary.
(g) 5 shipments for 30 or 50 years storage; 3 shipments for 100 years storage.
(h) Burial volumes of waste assumed: 100 m^3 at 30 and 50 years storage; 60 m^3 at 100 years storage.
(i) For deferred decontamination 100 years after shutdown, offsite disposal will occur 130, 150, and 200 years after shutdown.
(j) 477 drums of waste retrieved, checked, and segregated.
(k) 4 shipments for 30 years storage; 3 shipments for 50 and 100 years storage.
(m) Burial volumes of waste assumed: 75 m^3 at 30 years; 60 m^3 at 50 years; 50 m^3 at 100 years.

A.1.1.3 Waste from ENTOMB

Decommissioning the PWR by ENTOMB utilizes the space below the operating floor of the containment building as a nuclear waste repository. Non-combustible contaminated materials from outside of the entombment space are placed in the voids in the entombment space; however, there is insufficient space to accommodate all of the contaminated material at the nuclear power plant. The remaining contaminated material and the radioactive waste are disposed of in the same manner as the contaminated material from DECON of a PWR. Two scenarios were proposed for ENTOMB in the PWR and BWR decommissioning studies.[1,2] In the first scenario, the neutron-activated reactor internals are removed and sent to waste disposal, and in the second scenario, the reactor internals are entombed. In this study, waste disposal for the first entombment scenario, with the reactor internals removed, is studied in detail. The impact on costs should be similar for the second scenario, but this impact is not examined in detail in this study.

Estimated costs for disposal of each type of radioactive material from ENTOMB by interim storage of the waste onsite followed by later removal to an offsite licensed disposal facility are developed in this subsection.

A.1.1.3.1 Neutron-Activated Material. Reactor internals are the only neutron-activated material removed during ENTOMB of the reference PWR. The estimated costs of placing the reactor internals in onsite interim storage are given in Table A.1-17. The estimated costs of removal of the reactor internals to offsite disposal after onsite interim storage periods of 30, 50, and 100 years are presented in Table A.1-18.

A.1.1.3.2 Contaminated Material. About 50% of the contaminated material in the PWR power plant is placed in the entombment structure. The estimated cost of onsite interim storage for the contaminated material not entombed is given in Table A.1-19. The cost estimates for removal of this material to an offsite licensed waste disposal facility are presented in Table A.1-20 for interim storage periods of 30, 50, and 100 years.

A.1.1.3.3 Radioactive Waste. In Reference 3 it is assumed that the quantity of radioactive waste generated by ENTOMB of the reactor is the same

TABLE A.1-17. Estimated Costs of Onsite Interim Storage of the Reactor Internals from ENTOMB of a PWR

Component	Costs ($)[a]					
	Container	Casks[b]	Handling	Transportation	Placement	Total
Upper Core Support Assembly	40 000	400	1 200	275	1 060	42 935
Upper Support Columns	40 000	400	1 200	275	1 060	42 935
Upper Core Barrel	20 000	200	600	137	530	21 467
Upper Core Grid Plate	50 000	500	2 200	345	1 325	54 370
Guide Tubes	60 000	600	1 200	412	1 590	63 802
Lower Core Barrel	320 000	3 200	9 600	2 198	8 480	343 478
Thermal Shield	60 000	600	1 800	412	1 590	64 402
Core Shroud	40 000	400	1 200	275	1 060	42 935
Lower Grid Plate	50 000	500	2 200	345	1 325	54 370
Lower Support Columns	10 000	100	300	70	265	10 735
Lower Core Forging	110 000	1 100	3 300	756	2 915	118 071
Misc. Internals	80 000	800	2 400	550	2 120	85 870
Totals	880 000	8 800	27 200	6 050	23 320	945 370

(a) Based on Table G.4-3, Reference 1.
(b) One-day cask rental.

TABLE A.1-18. Estimated Costs of Removal to Offsite Disposal of the Reactor Internals from ENTOMB of a PWR

Cost Component	Offsite Disposal Costs ($) After Interim Storage Period of		
	30 Year	50 Year	100 Year
Retrieve From Interim Storage[a]	23 320	23 320	23 320
Cask Rental	41 000	39 000	39 000
Transportation	154 380	148 800	148 800
Handling	26 000	24 800	24 800
Liner Surcharge	15 750	13 150	13 150
Curie Surcharge	46 770	43 920	41 430
Burial	23 320	23 320	23 320
Totals	330 540	316 310	313 820

(a) Assumed to be the same as the placement cost in Table A.1-17.

TABLE A.1-19. Estimated Costs of Onsite Interim Storage of Contaminated Material from ENTOMB of a PWR

Component	Volume (m^3)[a]	Costs ($) Containers[a]	Onsite Transportation	Placement[a]	Total
Tanks	406	44 800	960	37 990	83 750
Service Water System	160	17 600	410	14 925	32 935
Component Cooling System	450	49 600	1 030	42 061	92 691
Condensate Storage System	101	11 200	210	9 498	20 908
Turbine Generator	558	61 600	1 510	52 237	115 347
Compressed Air System	51	5 600	140	4 749	10 489
Glycol Heating System	29	3 200	70	2 714	5 984
Extraction Steam System	188	20 800	480	17 638	38 918
Totals	1 943	214 400	4 810	181 812	401 022

(a) Based on Table G.4-5 of Reference 1.

TABLE A.1-20. Estimated Costs of Removal to Offsite Disposal of Contaminated Material from ENTOMB of a PWR

Cost Component	Offsite Disposal Costs ($) After Interim Storage Period of 30 Year	50 Year	100 Year
Retrieve From Interim Storage[a]	181 810	181 810	181 810
Transportation[b]	174 720	1 920	1 920
Burial[c]	181 810	1 120	1 120
Totals	538 340	184 850	184 850

(a) Assumed to be the same as the cost to place the material in interim storage.
(b) 21.4 m^3/shipment and $1,920/shipment.
(c) $93.57/$m^3$.

as the quantity generated by DECON. Therefore, the costs given below for the onsite interim storage and later offsite disposal of the radioactive waste from ENTOMB are the same as the costs developed for DECON of the reactor.

Place in interim storage - $240,350

Remove to offsite disposal
After: 30 years storage - $259,410
50 years storage - $181,030
100 years storage - $170,600.

A.1.2 Reference BWR Decommissioning Wastes

The study of decommissioning a reference BWR by Oak et al.[2] is the source of the data for estimating the impact on costs of onsite interim storage of the nuclear wastes from decommissioning the reference BWR. Radioactive decay factors for neutron-activated material used in the cost analyses are given in Table A.1-21 for the radioactivity levels and the dose rates.

TABLE A.1-21. Decay Factors for Radioactivity Levels and Dose Rates of Activated Material in the Reference BWR

Time After Shutdown (Years)	Decay Factors[a]	
	Radioactivity Level	Dose Rate
30	5.1×10^{-2}	1.9×10^{-2}
50	4.0×10^{-2}	1.4×10^{-3}
60	3.8×10^{-2}	3.7×10^{-4}
80	3.4×10^{-2}	3.0×10^{-5}
100	3.0×10^{-2}	9.6×10^{-6}
130	2.4×10^{-2}	5.3×10^{-6}
150	1.9×10^{-2}	5.2×10^{-6}
200	1.0×10^{-2}	4.8×10^{-6}

(a) Based on Figure E.1-6 of Reference 2.

The costs of disposal of neutron-activated material from the reference BWR at 30, 50, and 100 years after shutdown are presented in Table A.1-22.

A.1.2.1 Waste from DECON

Estimates of the costs for disposal of each type of nuclear waste from DECON are developed in the following subsections for onsite interim storage and later offsite disposal of the waste.

A.1.2.1.1 Neutron-Activated Material. Estimated costs of onsite interim storage of the neutron-activated material from DECON of a BWR are summarized in Table A.1-23. Since transport of the neutron-activated material to the

TABLE A.1-22. BWR Costs for Disposal of Neutron-Activated Materials at Various Times after Shutdown (Based on Table I.3-3, Reference 2)

Component	Weight (kg)[a]	Estimated Radioactivity (Ci)	Number of Pieces	Number of Containers	Container Cost ($)[b]	Cask Rental ($)[c]	Number of Shipments	Transportation Cost ($)[d]	Handling Cost ($)[e]	Burial Volume (m^3)[f]	Burial Cost ($)[g]	Liner Surcharge ($)[h]	Curie Surcharge ($)[i]	Total Disposal Costs ($)[j]
30 Years After Shutdown														
Steam Separator Assembly	9 500	260	951	28	12 600	14 000	14	26 880	5 600	10	940	9 100	0	69 120
Fuel Support Pieces	5 420	19	740	14	6 300	7 000	7	13 440	2 800	5	470	1 750	0	31 760
Control Rods & In-Core Instruments	19 810	5 122	610	8	48 000	27 600	8	15 360	12 310	15	1 400	12 410	2 760	119 840
Control Rod Guide Tubes	3 500	3	370	12	5 400	6 000	6	11 520	2 400	4	380	600	0	26 300
Jet Pump Assemblies	6 000	542	110	40	18 000	20 000	20	38 400	8 000	14	1 310	16 000	0	101 710
Top Fuel Guide	2 300	816	408	72	32 400	36 000	72	138 240	14 400	24	2 250	28 800	0	252 090
Core Support Plate	18 500	18	258	31	13 950	15 500	16	30 720	6 200	11	1 030	900	0	68 300
Core Shroud	32 000	170 730	558	70	31 500	35 000	70	134 400	14 000	24	2 200	28 000	36 030	281 130
Reactor Vessel Wall	157 700	20	576	22	9 900	0	10	19 200	4 400	8	680	1 100	0	35 280
Sacrifical Shield	272 000	<1	14	14	84 000	0	14	26 880	5 600	90	9 530	0	0	126 010
Totals	526 730	172 946	4 595	311	262 050	161 100	237	455 040	75 710	205	20 190	98 660	38 790	1 111 540
50 Years After Shutdown														
Steam Separator Assembly	9 500	213	951	28	12 600	14 000	14	26 880	5 600	10	940	3 500	0	63 520
Fuel Support Pieces	5 420	16	740	14	6 300	7 000	2	2 360	0	5	470	0	0	16 130
Control Rods & In-Core Instruments	19 810	4 200	610	8	48 000	27 600	8	15 360	12 310	15	1 400	4 400	2 660	111 730
Control Rod Guide Tubes	3 500	2	370	12	5 400	6 000	1	1 180	0	4	380	0	0	12 960
Jet Pump Assemblies	6 000	444	110	40	18 000	20 000	20	38 400	8 000	14	1 310	5 000	0	90 710
Top Fuel Guide	2 300	669	408	72	32 400	36 000	72	138 240	19 400	24	2 250	9 000	0	232 290
Core Support Plate	18 500	14	258	31	13 950	15 500	6	7 080	0	11	1 030	0	0	37 560
Core Shroud	32 000	140 000	558	70	31 500	35 000	70	134 400	14 000	24	2 200	8 750	32 610	258 460
Reactor Vessel Wall	157 700	16	576	22	9 900	0	10	19 200	4 400	8	680	0	0	34 180
Sacrificial Shield	272 000	<1	14	14	84 000	0	14	26 880	5 600	90	9 530	0	0	126 010
Totals	526 730	145 575	4 595	311	262 050	161 100	217	409 980	64 310	205	20 190	30 650	35 270	983 550
100 Years After Shutdown														
Steam Separator Assembly	9 500	141	951	28	12 600	14 000	14	26 880	5 600	10	940	0	0	60 020
Fuel Support Pieces	5 420	10	740	14	6 300	7 000	2	2 360	0	5	470	0	0	16 130
Control Rods & In-Core Instruments	19 810	2 778	610	8	48 000	27 600	8	15 360	12 310	15	1 400	400	2 570	107 640
Control Rod Guide Tubes	3 500	2	370	12	5 400	0	1	1 180	0	4	380	0	0	6 960
Jet Pump Assemblies	6 000	294	110	40	18 000	20 000	20	38 400	8 000	14	1 310	0	0	85 710
Top Fuel Guide	2 300	442	408	72	32 400	36 000	72	138 240	14 400	24	2 250	0	0	223 290
Core Support Plate	18 500	10	258	31	13 950	15 500	6	7 060	0	11	1 030	0	0	37 560
Core Shroud	32 000	92 600	558	70	31 500	35 000	70	134 400	14 000	24	2 200	0	29 500	246 600
Reactor Vessel Wall	157 700	11	576	22	9 900	0	10	19 200	4 400	8	680	0	0	34 180
Sacrificial Shield	272 000	<1	14	14	84 000	0	14	26 860	5 600	90	9 530	0	0	126 010
Totals	526 730	96 289	4 595	311	262 050	155 100	217	409 980	64 310	205	20 190	400	32 070	944 100

(a) Estimated from volumes presented in Table E.1-6, Reference 2.
(b) Based on information in Section M.2, Reference 2.
(c) Based on Table M.3-1, Reference 2.
(d) Based on Table M.4-4, Reference 2.
(e) Based on cask handling fee in Table M.5-1, Reference 2.
(f) Includes the disposable container; rounded to nearest whole m^3.
(g) Based on Table M.5-1, Reference 2; based on volume only; rounded to nearest $10.
(h) Based on Table M.5-1, Reference 2, for the estimated dose rate at the container surface.
(i) Based on Table M.5-1, Reference 2, for the estimated curie inventory per shipment.
(j) The number of figures shown is for computational completeness only and does not imply accuracy to that many significant figures.

TABLE A.1-22. BWR Costs for Disposal of Neutron-Activated Materials at Various Times after Shutdown (Based on Table I.3-3, Reference 2)

TABLE A.1-23. Estimated Costs of Onsite Interim Storage of Neutron-Activated Material from DECON of a BWR

Cost Component	Cost ($)
Containers	262 050[a]
Cask Rental	34 420[b]
Onsite Transportation	16 970[c]
Handling	75 710[d]
Placement	20 190[d]
Total	409 340

(a) From Table A.1-22.
(b) One-day cask rental for each shipment.
(c) 247 shipments with a round-trip distance of 48 km.
(d) From Table I.3-3 of Reference 2.

onsite interim storage facility is over private roads within a privately owned and controlled reservation, it is assumed that the surface dose rate on the shipping cask can be greater than DOT regulation permit on public highways. In order to pack more of the neutron-activated material in the cask liners, the thickness of the shielding installed in the cask liners is reduced to the amount needed to meet DOT requirements after 30 years of radioactive decay. For the core shroud this permits doubling the amount of core shroud segments packed in each cask liner.

The estimated costs for removal of the neutron-activated material to an offsite licensed disposal facility after interim storage for 30, 50, and 100 years are given in Table A.1-24.

A.1.2.1.2 Contaminated Material. The estimated costs of onsite interim storage of the contaminated material from DECON of a BWR are given in Table A.1-25.

Estimated costs of removal of the contaminated material to an offsite licensed disposal facility are presented in Table A.1-26.

TABLE A.1-24. Estimated Costs of Removal to Offsite Disposal of Neutron-Activated Material from DECON of a BWR

Cost Component	Costs ($) After Interim Storage Period of 30 Year	50 Year	100 Year
Retrieve From Temporary Storage[(a)]	20 190	20 190	20 190
Cask Rental[(b)]	161 100	161 100	155 100
Transportation[(b)]	455 040	409 980	409 980
Handling[(b)]	75 710	64 310	64 310
Liner Surcharge[(b)]	98 660	30 650	400
Curie Surcharge[(b)]	38 790	35 270	32 070
Burial[(b)]	20 190	20 190	20 190
Totals	869 680	741 690	702 240

(a) Assumed to be the same as the burial cost.
(b) From Table A.1-22.

TABLE A.1-25. Estimated Costs of Onsite Interim Storage of Contaminated Material from DECON of a BWR

Cost Component	Cost ($)
Containers	1 669 320[(a)]
Onsite Transportation	55 370[(b)]
Placement	1 612 410[(a)]
Total	3 337 100

(a) From Table I.3-4 of Reference 1.
(b) 806 shipments with round-trip distance of 48 km.

A.1.2.1.3 Radioactive Waste. In Table A.1-27 the estimated costs of onsite interim storage of the radioactive waste from DECON of the reference BWR are presented.

TABLE A.1-26. Estimated Costs of Removal to Offsite Disposal of Contaminated Material from DECON of a BWR

Cost Component	Costs($) After Interim Storage Period of 30 Year	50 Year	100 Year
Retrieve From Interim Storage[a]	292 980	292 980	292 980
Transportation[b]	1 547 520	5 760	5 760
Burial	1 611 180	14 040	14 040
Totals	3 451 680	312 780	312 780

(a) 3919 containers. 4 man-hr per container for checking and segregating. $18.70 per man-hr charge-out rate.
(b) After 30 years there are 806 shipments, and after 50 and 100 years there are 3 shipments.
(c) Burial cost $93.57 per m^3.

TABLE A.1-27 Estimated Costs of Onsite Interim Storage of Radioactive Waste from DECON of a BWR

Cost Component	Cost ($)
Containers[a]	281 370
Cask Rental[b]	5 200
Handling	10 400
Onsite Transportation[c]	7 900
Placement[d]	142 130
Total	447 000

(a) From Tables H.5-10 and I.3-5 of Reference 2.
(b) Casks used only for containers with surface dose rates >1 R/hr. One day rental per shipment.
(c) 115 shipments with round-trip distance of 48 km.
(d) Same as burial costs given in Tables H.5-10 and I.3-5 of Reference 2.

The estimated costs of removal of the nuclear waste from DECON of the reference BWR to an offsite licensed disposal facility are given in Table A.1-28.

A.1.2.2 Waste from SAFSTOR

The two major decommissioning phases that generate nuclear waste are: 1) preparations for safe storage and 2) deferred decontamination at the end of the storage period. The rationale for estimating the waste disposal costs is the same for the reference BWR as that described for the reference PWR in subsection A.1.1.2.

Estimated costs for the disposal of each type of nuclear waste from SAFSTOR of the reference BWR are developed in the following subsections for onsite interim storage and eventual offsite disposal.

TABLE A.1-28. Estimated Costs of Removal to Offsite Disposal of Radioactive Waste from DECON of a BWR

Cost Component	Costs ($) After Interim Storage Period of		
	30 Year	50 Year	100 Year
Retrieve From Interim Storage[a]	262 410	262 410	262 410
Cask Rental[b]	26 000	0	0
Transportation[c]	176 640	32 640	23 040
Handling	10 400	0	0
Liner Surcharge	2 600	0	0
Burial[d]	93 570	32 750	22 460
Totals	571 620	327 800	307 910

(a) 3510 containers at 4 man-hr per container and charge-out rate of \$18.70 per man-hr.
(b) Casks used only for containers with surface dose rate >0.2 R/hr.
(c) Transportation costs based on 92 shipments after 30 years, 17 shipments after 50 years, and 12 shipments after 100 years, at \$1920 per shipment.
(d) Burial volumes assumed - 1000 m^3 after 30 years, 350 m^3 after 50 years, and 240 m^3 after 100 years.

A.1.2.2.1 Neutron-Activated Material. No neutron-activated material is removed from the reactor during preparations for safe storage. During deferred decontamination, all of the neutron-activated material is removed from the reactor, packaged, and sent to onsite interim storage. The estimated costs for placement in onsite interim storage of the neutron-activated material removed during deferred decontamination are presented in Table A.1-29.

Estimated costs for removal to offsite disposal of the neutron-activated material from deferred decontamination after interim storage periods of 30, 50, and 100 years are given in Table A.1-30.

A.1.2.2.2 Contaminated Material. Contaminated material is not removed from the reactor during preparations for safe storage. The contaminated material is removed and placed in onsite interim storage during deferred decontamination. Estimated costs for placement of this material in onsite interim storage are presented in Table A.1-31.

TABLE A.1-29. Estimated Costs of Onsite Interim Storage of Neutron-Activated Material from Deferred Decontamination of a BWR

Cost Component	Costs ($) After Safe Storage Period of		
	30 Year	50 Year	100 Year
Containers	262 050[a]	262 050[a]	262 050[a]
Cask Rental[b]	27 920	23 720	0
Onsite Transportation[c]	16 280	13 530	2 200
Handling	67 110	48 710	0
Placement	20 190[a]	20 190[a]	20 190[a]
Totals	393 550	368 200	284 440

(a) From Table A.1-22.
(b) Casks used only if cask liner surface dose rate >1 R/hr.
(c) Round-trip distance 48 km. 237 trips after 30 years; 197 trips after 50 years, and 32 trips after 100 years.

TABLE A.1-30. Estimated Costs of Removal to Offsite Disposal of Neutron-Activated Material from Deferred Decontamination of a BWR

Cost Component	Offsite Disposal Costs ($) After Interim Storage Period of 30 Year	50 Year	100 Year
	Deferred Decontamination 30 Years After Shutdown[a]		
Retrieve From Interim Storage	20 190	20 190	20 190
Cask Rental	132 600	27 600	27 600
Transportation	403 200	71 040	71 040
Handling	64 310	22 310	22 310
Liner Surcharge	13 100	1 000	400
Curie Surcharge	34 080	32 530	30 990
Burial	20 190	20 190	20 190
Totals	687 670	194 860	192 720
	Deferred Decontamination 50 Years After Shutdown[b]		
Retrieve From Interim Storage	20 190	20 190	20 190
Cask Rental	27 600	27 600	27 600
Transportation	71 040	71 040	71 040
Handling	22 310	22 310	22 310
Liner Surcharge	1 000	400	400
Curie Surcharge	32 530	740	680
Burial	20 190	20 190	20 190
Totals	194 860	162 470	162 410
	Deferred Decontamination 100 Years After Shutdown[c]		
Retrieve From Interim Storage	20 190	20 190	20 190
Cask Rental	27 600	27 600	27 600
Transportation	71 040	71 040	71 040
Handling	22 310	22 310	22 310
Liner Surcharge	400	400	400
Curie Surcharge	700	680	630
Burial	20 190	20 190	20 190
Totals	162 430	162 410	162 360

(a) For deferred decontamination 30 years after shutdown, offsite disposal occurs 60, 80, and 130 years after shutdown.
(b) For deferred decontamination 50 years after shutdown, offsite disposal occurs 80, 100, and 150 years after shutdown.
(c) For deferred decontamination 100 years after shutdown, offsite disposal occurs 130, 150, and 200 years after shutdown.

TABLE A.1-31. Estimated Costs of Onsite Interim Storage of Contaminated Material from Deferred Decontamination of a BWR

Cost Component	Costs ($) After Safe Storage Period of		
	30 Year[a]	50 Year	100 Year
Containers	1 669 320	16 800[b]	16 800[b]
Onsite Transportation	55 370	550[c]	550[c]
Placement	1 612 410	14 035[b]	14 035[b]
Totals	3 337 100	31 385	31 385

(a) Table J.7-1 of Reference 2 shows the volume of contaminated waste to be the same after 30 years of safe storage as it is for DECON; therefore the costs should be the same. These costs are from Table A.1-25.
(b) Based on volume of 150 m^3 after 30 years of safe storage, 42 containers.
(c) 8 shipments with a round-trip distance of 48 km.

The estimated costs of removal to offsite disposal of the contaminated material from deferred decontamination of the reference BWR are summarized in Table A.1-32.

A.1.2.2.3 Radioactive Waste. All of the wet solid radioactive waste and some of the dry solid radioactive waste generated by SAFSTOR are disposed of during preparations for safe storage. Disposal costs are developed in two steps: 1) for those radioactive wastes generated during preparations for safe storage and 2) for those radioactive wastes generated during deferred decontamination.

Preparations for Safe Storage. The estimated costs for placement in onsite interim storage of the radioactive waste from preparations for safe storage are summarized in Table A.1-33.

Estimated costs for removal to offsite disposal of the radioactive waste from preparations for safe storage are given in Table A.1-34.

Deferred Decontamination. The estimated costs of placing in onsite interim storage the radioactive waste from deferred decontamination after safe storage periods of 30, 50, and 100 years are presented in Table A.1-35.

TABLE A.1-32. Estimated Costs of Removal to Offsite Disposal of the Contaminated Material from Deferred Decontamination of a BWR

Cost Component	Offsite Disposal Costs ($) After Interim Storage Period of 30 Year	50 Year	100 Year
	Deferred Decontamination 30 Years After Shutdown[a]		
Retrieve From Interim Storage	292 980	292 980	292 980
Transportation	13 440	11 520	7 680
Burial	14 040	11 700	7 950
Totals	320 460	316 200	308 610
	Deferred Decontamination 50 Years After Shutdown[b]		
Retrieve From Interim Storage	3 140	3 140	3 140
Transportation	11 520	9 600	7 680
Burial	11 700	9 360	7 020
Totals	26 360	22 100	17 840
	Deferred Decontamination 100 Years After Shutdown[c]		
Retrieve From Interim Storage	3 140	3 140	3 140
Transportation	7 680	7 680	5 760
Burial	7 960	7 020	5 610
Totals	18 780	17 840	14 510

(a) For deferred decontamination 30 years after shutdown, offsite disposal will occur 60, 80, and 130 years after shutdown.
(b) For deferred decontamination 50 years after shutdown, offsite disposal will occur 80, 100, and 150 years after shutdown.
(c) For deferred decontamination 100 years after shutdown, offsite disposal will occur 130, 150, and 200 years after shutdown.

TABLE A.1-33. Estimated Costs of Onsite Interim Storage of Radioactive Waste from Preparations for Safe Storage of a BWR

Cost Components	Cost ($)
Containers	239 670[a]
Cask Rental	5 200[b]
Onsite Transportation	6 450[c]
Handling	10 400
Placement	99 470[d]
Total	361 190

(a) From Tables H.5-10 and J.5-3 of Reference 2.
(b) Casks used only for the 52 containers with surface dose rates >1 R/hr. 1 day per shipment.
(c) 94 shipments with round-trip distance of 48 km.
(d) Assumed to be the same as the burial cost.

TABLE A.1-34. Estimated Costs of Removal to Offsite Disposal of Radioactive Waste from Preparations for Safe Storage of a BWR

Cost Component	Offsite Disposal Costs ($) After Interim Storage Period of 30 Year	50 Year	100 Year
Retrieve From Interim Storage[a]	106 590	106 590	106 590
Cask Rental[b]	26 000	0	0
Transportation	72 960[c]	32 640[d]	23 040[e]
Handling	10 400	0	0
Burial[f]	74 860	32 750	22 460
Totals	290 810	171 980	152 090

(a) 1425 containers at 4 man-hr per container with a charge-out rate of $18.70 per man-hr.
(b) Casks used only for those shipments with a cask liner surface dose rate >1 R/hr. 5-day cask rental for a shipment.
(c) 38 shipments at $1920 per shipment.
(d) 17 shipments at $1920 per shipment.
(e) 12 shipments at $1920 per shipment.
(f) Burial volumes - 800 m^3 after 30 years; 350 m3 after 50 years; 240 m^3 after 100 years.

TABLE A.1-35. Estimated Costs of Onsite Interim Storage of Radioactive Waste from Deferred Decontamination of a BWR

Cost Component	Costs ($) After Safe Storage Period of 30 Year[a]	50 Year[a]	100 Year[a]
Containers	41 620	33 340	22 860
Onsite Transportation[b]	1 440	1 170	820
Placement	40 890	32 750	22 460
Totals	83 950	67 260	46 140

(a) Waste volumes assumed: 30 yr - 437 m^3; 50 yr - 350 m^3; 100 yr - 240 m^3.
(b) Onsite round trip of 48 km. Number of shipments: 30 yr - 21; 50 yr - 17; 100 yr - 12.

Costs of the removal of the radioactive waste from deferred decontamination to offsite disposal after a period of interim storage are estimated and summarized in Table A.1-36.

TABLE A.1-36. Estimated Costs of Removal to Offsite Disposal of Radioactive Waste from Deferred Decontamination of a BWR

Cost Component	Offsite Disposal Costs ($) After Interim Storage Period of 30 Year	50 Year	100 Year
	Deferred Decontamination 30 Years After Shutdown[a]		
Retrieve From Interim Storage	155 500	155 500	155 500
Transportation	32 640	26 880	19 200
Burial	32 750	27 140	19 650
Totals	220 890	209 520	194 350
	Deferred Decontamination 50 Years After Shutdown[b]		
Retrieve From Interim Storage	124 620	124 620	124 620
Transportation	26 880	23 040	17 280
Burial	27 135	22 460	17 780
Totals	178 635	170 120	159 680
	Deferred Decontamination 100 Years After Shutdown[c]		
Retrieve From Interim Storage	85 450	85 450	85 450
Transportation	19 200	17 280	15 360
Burial	19 650	17 780	14 970
Totals	124 300	120 510	115 780

(a) For deferred decontamination 30 years after shutdown, offsite disposal will occur 60, 80, and 130 years after shutdown.
(b) For deferred decontamination 50 years after shutdown, offsite disposal will occur 80, 100, and 150 years after shutdown.
(c) For deferred decontamination 100 years after shutdown, offsite disposal will occur 130, 150, and 200 years after shutdown.

A.1.2.3 Waste from ENTOMB

The primary containment vessel is used as the entombment structure for decommissioning the reference BWR by ENTOMB. The free space inside the containment vessel is filled with contaminated material from outside the containment vessel. Contaminated material in excess of the containment vessel capacity and the radioactive waste are sent to a waste disposal facility. As is the case for the reference PWR, the ENTOMB scenario with the reactor internals removed is studied in detail in this study.

Estimated costs for disposal of each type of nuclear waste from ENTOMB by interim storage of the waste onsite followed by later removal to an offsite licensed disposal facility are covered in this subsection.

A.1.2.3.1 Neutron-Activated Material. The reactor internals are the only neutron-activated material removed during ENTOMB of the reference BWR. Estimated costs of placing the reactor internals in onsite interim storage are given in Table A.1-37, and estimated costs for the removal of the reactor internals to an offsite disposal facility after onsite interim storage of 30, 50, and 100 years are presented in Table A.1-38.

A.1.2.3.2 Contaminated Material. About two-thirds of the contaminated material located outside the containment vessel is placed in the vessel for entombment. The remainder of this material is considered here to be placed in onsite interim storage and later moved to an offsite licensed waste disposal facility. The estimated costs for onsite interim storage of this remaining contaminated material are given in Table A.1-39. In Table A.1-40 the estimated costs are presented for the removal of the contaminated material from ENTOMB to an offsite licensed disposal facility after interim storage periods of 30, 50, and 100 years.

A.1.2.3.3 Radioactive Waste. In Reference 2 it is assumed that the quantity of radioactive waste generated by ENTOMB of the reactor is the same as the quantity generated by DECON. Therefore, the costs shown below for the onsite interim storage and later offsite disposal of the radioactive waste from ENTOMB are the same as the costs developed for DECON of the reactor.

Place in interim storage - $447,000

Removal to offsite storage
After: 30 years storage - $571,620
50 years storage - $327,800
100 years storage - $307,910

TABLE A.1-37. Estimated Costs of Onsite Interim Storage of BWR Reactor Internals

Component	Costs ($)[a] Containers	Casks[b]	Transportation[c]	Handling	Placement	Total
Steam Separator Assembly	12 600	2 800	960	5 600	940	22 900
Orificed Fuel Supports	6 300	1 400	480	2 800	470	11 450
Control Rods and In-Core Instruments	48 000	9 600	550	12 310	1 400	71 860
Control Rod Guide Tubes	5 400	1 200	410	2 400	380	9 790
Jet Pump Assemblies	38 400	4 000	1 370	8 000	1 310	53 080
Top Fuel Guide	111 600	7 200	4 950	14 400	2 250	140 400
Core Support Plate	13 950	3 100	1 100	6 200	1 030	25 380
Core Shroud	129 130	5 100	3 500	10 200	1 600	149 530
Totals	365 380	34 400	13 320	61 910	9 380	484 390

(a) Based on Table K.3-3 of Reference 2.
(b) One-day cask rental per shipment.
(c) Round-trip distance to onsite interim storage facility - 48 km.

TABLE A.1-38. Estimated Costs of Removal to Offsite Disposal of the Reactor Internals from ENTOMB of a BWR

Cost Component	Offsite Disposal Costs ($) After Interim Storage Period of 30 Year	50 Year	100 Year
Retrieve From Interim Storage[a]	9 380	9 380	9 380
Cask Rental	151 600	151 600	145 600
Transportation	372 480	327 420	327 420
Handling	61 910	50 150	50 150
Liner Surcharge	97 560	30 650	400
Curie Surcharge	38 790	35 270	32 070
Burial	9 380	9 380	9 380
Totals	741 100	613 850	574 400

(a) Assumed to be the same as the placement cost in Table A.1-37.

TABLE A.1-39. Estimated Costs of Onsite Interim Storage of Contaminated Material from ENTOMB of a BWR

Cost Component	Cost ($)
Containers	561 320[a]
Onsite Transportation	22 670[b]
Handling	45 360[a]
Placement	600 720[c]
Total	1 230 070

(a) From Table K.3-4 of Reference 2.
(b) 330 shipments with round-trip distance of 48 km.
(c) 6420 m^3 at $93.57 per m^3.

TABLE A.1-40. Estimated Costs of Removal to Offsite Disposal of Contaminated Material from ENTOMB of a BWR

Cost Component	Offsite Disposal Costs ($) After Interim Storage Period of 30 Year	50 Year	100 Year
Retrieve From Interim Storage[a]	92 930	92 930	92 930
Transportation[b]	633 600	5 760	5 760
Burial	600 720	5 240	5 240
Totals	1 327 250	103 930	103 930

(a) 1243 containers. Assumed 4 man-hr per container at a charge-out rate of $18.70 per man-hr.
(b) 330 shipments after 30 years and 3 shipments after 50 or 100 years.

A.2 ONSITE DISPOSAL OF NUCLEAR WASTE

Onsite disposal of nuclear waste involves essentially the same operations as placing radioactive material in onsite interim storage. In this study, it is assumed that the onsite disposal facility is operated by the operating utility and that liner surcharges and curie surcharges are not levied. It is further assumed that the onsite disposal facility is located 24 km from the reactor(s) being decommissioned, the same distance assumed for the onsite interim storage facility. With these assumptions, the estimated costs for onsite disposal of radioactive waste are the same as the costs for onsite interim storage of the waste.

For DECON of the PWR, the estimated costs for onsite disposal of the nuclear wastes are the same as the costs given in Tables A.1-3, A.1-5, and A.1-7. For DECON of the BWR, the estimated costs for onsite disposal of the nuclear wastes are the same as those given in Tables A.1-23, A.1-25, and A.1-27.

Estimated costs for disposal of the nuclear wastes from SAFSTOR of the PWR are the same as those given in Tables A.1-9, A.1-11, A.1-13, and A.1-15. For SAFSTOR of the BWR, the estimated costs of onsite disposal of the nuclear wastes are the same as the costs given in Tables A.1-29, A.1-31, A.1-33, and A.1-35.

Estimated costs for disposal of the nuclear wastes from ENTOMB of the reference PWR are the same as the costs presented in Tables A.1-17 and A.1-19. For the BWR, the costs are the same as those given in Tables A.1-37 and A.1-39.

REFERENCES

1. R. I. Smith, G. J. Konzek, W. E. Kennedy, Jr., Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station, NUREG/CR-0130, U.S. Nuclear Regulatory Commission Report by Pacific Northwest Laboratory, June 1978.

2. H. D. Oak, G. M. Holter, W. E. Kennedy, Jr., and G. J. Konzek, Technology, Safety, and Costs of Decommissioning a Reference Boiling Water Reactor Power Station, NUREG/CR-0672, U.S. Nuclear Regulatory Commission Report by Pacific Northwest Laboratory, June 1980.

3. R. I. Smith and L. M. Polenz, Technology, Safety, and Costs of Decommissioning a Pressurized Water Reactor Power Station, NUREG/CR-0130 Addendum, U.S. Nuclear Regulatory Commission Report by Pacific Northwest Laboratory, August 1979.

APPENDIX B

DETAILS OF THE IMPACTS OF CENTRALIZED SERVICES ON DECOMMISSIONING AT A MULTIPLE-REACTOR STATION

The costs and radiation doses associated with decommissioning a single reactor located on a multiple-reactor station may be affected by the availability of centralized site services. The impacts associated with the following centralized services are examined in this study:

- health physics services
- security forces
- solid waste processing
- equipment decontamination services
- maintenance shops and services
- laundry services
- transportation services
- central site stores.

In this appendix, details of the analyses of the impacts associated with centralized services are presented. Only the first four services listed above are analyzed in detail in this study and, therefore, only these four are considered in this appendix. The analyses are developed based on estimates for decommissioning reactors at single-reactor sites, as presented in References 1 through 3.

B.1 HEALTH PHYSICS SERVICES

Centralized health physics services are anticipated to reduce the costs of health physics activities at a reactor sited on a multiple-reactor station during both operation and decommissioning. Two factors are postulated to contribute to this cost reduction:

- The overhead structure for each reactor can be reduced by sharing certain staff members between reactors.
- The large pool of health physics technicians at the site can be shared between reactors, reducing the peak-load staffing requirements per reactor.

Centralization of the health physics services is not anticipated to change the occupational radiation dose for decommissioning a reactor.

The health physics staff labor requirements and costs during decommissioning, both with and without centralized health physics services, are presented here for the various combinations of reactor types and decommissioning alternatives considered in this study. Net savings with centralized health physics services are calculated from these results.

B.1.1 PWR DECON

Health physics staff labor requirements and costs for DECON of the reference PWR are shown in Table B.1-1. Manpower requirements from Table 10.1-2 of Reference 1 are used for decommissioning without centralized health physics; these values are modified appropriately for decommissioning with centralized health physics to account for the reduced overhead structure and the more efficient use of technicians postulated. A total of about 44 man-years, costing about $1.42 million, is required without centralized health physics as compared to about 32-1/2 man-years at a cost of about $960,000 with centralized health physics. Net savings with centralized health physics are 11-1/2 man-years and approximately $460,000.

B.1.2 PWR SAFSTOR

Health physics staff labor requirements and costs for the preparations for safe storage phase of PWR SAFSTOR are shown in Table B.1-2, based on information from Table 10.2-2 of Reference 1. Without centralized health physics services, about 19 man-years and approximately $670,000 are estimated to be required. With centralized health physics, these requirements are reduced to about 13 man-years and approximately $410,000, for net savings of 6 man-years and nearly $260,000.

Centralized health physics services are anticipated to have no significant cost effects during the continuing care phase of SAFSTOR at the reference PWR.

Deferred decontamination of the reference PWR is anticipated to require essentially the same work force as DECON (see p. H-30 of Reference 1). Therefore, the health physics staff labor requirements and costs are assumed to be the same and, thus, centralized health physics services during the deferred decontamination phase of PWR SAFSTOR are estimated to provide net savings of 11-1/2 man-years and about $460,000, as shown previously in Table B.1-1.

TABLE B.1-1. Health Physics Staff Labor Requirements and Costs for PWR DECON and ENTOMB

Position	Time Relative to Final Reactor Shutdown (year) -2	-1	1	2	3	Total Staff Labor Required (man-years)	Cost per Man-Year[a] ($ thousands)	Total Staff Labor Costs[b] ($ thousands)
	Annual Staff Labor Requirement (man-years)							
Without Centralized Health Physics[c]								
Health and Safety Supervisor	0.3	1.0	1.0	1.0	1.0	4.3	50.4	216.7
Industrial Safety Specialist	0.3	1.0	1.0	1.0	1.0	4.3	43.8	188.3
Radioactive Shipment Specialist	0	1.0	1.0	1.0	1.0	4.0	32.9	131.6
Health Physicist	0	0.5	1.0	1.0	1.0	3.5	39.4	137.9
Senior Health Physics Technician	0	1.0	2.0	2.0	1.0	6.0	32.9[d]	197.4
Health Physics Technician	0	3.0	7.0	7.0	5.0	22.0	25.1	552.2
Totals, Without Centralized Health Physics	0.6	7.5	13.0	13.0	10.0	44.1		1424.1
With Centralized Health Physics[e]								
Site Level[f]								
Health and Safety Supervisor	0.1	0.1	0.1	0.1	0.1	0.5	50.4	25.2
Industrial Safety Specialist	0.1	0.1	0.1	0.1	0.1	0.5	43.8	21.9
Clerk	0.1	0.1	0.1	0.1	0.1	0.5	20.3[g]	10.2
Group Level[h]								
Health Physics Supervisor	0	0.3	0.3	0.3	0.3	1.2	43.8[i]	52.6
Radioactive Shipment Specialist	0	0.3	0.3	0.3	0.3	1.2	32.9	39.5
Unit Level								
Health Physicist	0	0.5	1.0	1.0	1.0	3.5	39.4	137.9
Senior Health Physics Technician[j]	0	0.9	1.8	1.8	0.9	5.4	32.9[d]	177.7
Health Physics Technician[j]	0	2.7	6.3	6.3	4.5	19.8	25.1	497.0
Totals, With Centralized Health Physics	0.3	5.0	10.0	10.0	7.3	32.6		962.0
Net Savings With Centralized Health Physics	0.3	2.5	3.0	3.0	2.7	11.5		462.1

(a) Based on Table I.1-1 of Reference 1.
(b) Rounded to the nearest $100.
(c) Based on organization shown in Figure 8.3-1a; manpower requirements taken from Table 10.1-2 of Reference 1.
(d) Based on value given in Table M.1-1 of Reference 3, to provide consistency between PWR and BWR results.
(e) Based on organization shown in Figure 8.3-1b, with manpower requirements from Table 10.1-2 of Reference 1 modified appropriately; rounded to next higher 0.1 man-year.
(f) Single unit assumed to bear 10% of total site cost.
(g) From Table M.1-1 of Reference 3.
(h) Single unit assumed to bear 30% of total group cost (10% of total site cost assuming 3 groups).
(i) Study estimate.
(j) Based on an assumed 10% reduction of the manpower requirements without centralized health physics.

TABLE B.1-2. Health Physics Staff Labor Requirements and Costs for PWR Preparations for Safe Storage

Position	Time Relative to Final Reactor Shutdown (year) -2	-1	1	2	Total Staff Labor Required (man-years)	Cost per Man-Year[a] ($ thousands)	Total Staff Labor Costs[b] ($ thousands)
	Annual Staff Labor Requirements (man-years)						
Without Centralized Health Physics[c]							
Health and Safety Supervisor	0.3	1.0	1.0	0.4	2.7	50.4	136.1
Industrial Safety Specialist	0.3	1.0	1.0	0.4	2.7	43.8	118.3
Radioactive Shipment Specialist	0	1.0	1.0	0.4	2.4	32.9	79.0
Health Physicist	0	0.5	1.0	0.4	1.9	39.4	74.9
Senior Health Physics Technician	0	1.0	2.0	0.7	3.7	32.9[d]	121.7
Health Physics Technician	0	1.5	3.0	1.0	5.5	25.1	138.0
Totals, Without Centralized Health Physics	0.6	6.0	9.0	3.3	18.9		668.0
With Centralized Health Physics[e]							
Site Level[f]							
Health and Safety Supervisor	0.1	0.1	0.1	0.1	0.4	50.4	20.2
Industrial Safety Specialist	0.1	0.1	0.1	0.1	0.4	43.8	17.5
Clerk	0.1	0.1	0.1	0.1	0.4	20.3[g]	8.1
Group Level[h]							
Health Physics Supervisor	0	0.3	0.3	0.1	0.7	43.8[i]	30.7
Radioactive Shipment Specialist	0	0.3	0.3	0.1	0.7	32.9	23.0
Unit Level							
Health Physicist	0	0.5	1.0	0.4	1.9	39.4	74.9
Senior Health Physics Technician[j]	0	0.9	1.8	0.7	3.4	32.9[d]	111.9
Health Physics Technician[j]	0	1.4	2.7	0.9	5.0	25.1	125.5
Totals, With Centralized Health Physics	0.3	3.7	6.4	2.5	12.9		411.8
Net Savings With Centralized Health Physics	0.3	2.3	2.6	0.8	6.0		256.2

(a) Based on Table I.1-1 of Reference 1.
(b) Rounded to the nearest $100.
(c) Based on organization shown in Figure 8.3-1a; manpower requirements taken from Table 10.2-2 of Reference 1, rounded to next higher 0.1 man-year.
(d) Based on value given in Table M.1-1 of Reference 3, to provide consistency between PWR and BWR results.
(e) Based on organization shown in Figure 8.3-1b, with manpower requirements from Table 10.2-2 of Reference 1 modified appropriately; rounded to next higher 0.1 man-year.
(f) Single unit assumed to bear 10% of total site cost.
(g) From Table M.1-1 of Reference 3.
(h) Single unit assumed to bear 30% of total group cost (10% of total site cost assuming 3 groups).
(i) Study estimate.
(j) Based on an assumed 10% reduction of the manpower requirements without centralized health physics.

Total net savings with centralized health physics during SAFSTOR of the reference PWR are estimated to be 17-1/2 man-years and about $720,000.

B.1.3 PWR ENTOMB

The schedule of events for ENTOMB of the reference PWR is very similar to that for DECON (see p. 4-6 of Reference 2). Therefore, the manpower requirements and costs for health physics services are assumed to be the same as those shown previously in Table B.1-1. Centralized health physics services during ENTOMB are thus estimated to result in net savings of 11-1/2 man-years and about $460,000.

B.1.4 BWR DECON

Manpower requirements and costs for health physics staff during DECON of the reference BWR are shown in Table B.1-3, based on information presented in Table I.2-3 of Reference 3. A total of close to 78 man-years, costing almost $2.35 million, is required without centralized health physics as compared to almost 62 man-years, costing about $1.73 million, with centralized health physics. Net savings with centralized health physics are 16 man-years and about $620,000.

B.1.5 BWR SAFSTOR

Health physics staff labor requirements and costs for the first phase of BWR SAFSTOR, preparations for safe storage, are shown in Table B.1-4, based on information from Table J.4-1 of Reference 3. Without centralized health physics services, 49 man-years and about $1.53 million are estimated to be required. With centralized health physics, these requirements are reduced to 38 man-years and about $1.09 million, for net savings of 11 man-years and almost $440,000.

During the continuing care period of BWR SAFSTOR, centralized health physics services are anticipated to have no significant effects.

The basic work force and time required for deferred decontamination of the reference BWR are the same as for DECON (see p. J-40 of Reference 3). Therefore, the health physics staff labor requirements and costs are assumed to be the same and, thus, centralized health physics services during the deferred decontamination phase of SAFSTOR are estimated to result in net savings of 16 man-years and almost $620,000, as shown previously in Table B.1-3.

TABLE B.1-3. Health Physics Staff Labor Requirements and Costs for BWR DECON

Position	Time Relative to Final Reactor Shutdown (year) -2	-1	1	2	3	4	Total Staff Labor Required (man-years)	Cost per Man-Year[a] ($ thousands)	Total Staff Labor Costs[b] ($ thousands)
	Annual Staff Labor Requirement (man-years)								
Without Centralized Health Physics[c]									
Health and Safety Supervisor	1.0	1.0	1.0	1.0	1.0	0.8	5.8	50.4	292.3
Industrial Safety Specialist	0.3	1.0	1.0	1.0	1.0	0.5	4.8	43.8	210.2
Radioactive Shipment Specialist	0	1.0	1.0	1.0	1.0	0.4	4.4	32.9	144.8
Health Physicist	0	0.5	1.0	1.0	1.0	0.5	4.0	39.4	157.6
Senior Health Physics Technician	0	1.0	2.5	2.2	2.1	1.0	8.8	32.9	289.5
Health Physics Technician	0	3.0	14.3	14.9	14.0	3.8	50.0	25.1	1255.0
Totals, Without Centralized Health Physics	1.3	7.5	20.8	21.1	20.1	7.0	77.8		2349.4
With Centralized Health Physics[d]									
Site Level[e]									
Health and Safety Supervisor	0.1	0.1	0.1	0.1	0.1	0.1	0.6	50.4	30.2
Industrial Safety Specialist	0.1	0.1	0.1	0.1	0.1	0.1	0.6	43.8	26.3
Clerk	0.1	0.1	0.1	0.1	0.1	0.1	0.6	20.3	12.2
Group Level[f]									
Health Physics Supervisor	0	0.3	0.3	0.3	0.3	0.2	1.4	43.8[g]	61.3
Radioactive Shipment Specialist	0	0.3	0.3	0.3	0.3	0.2	1.4	32.9	46.1
Unit Level									
Health Physicist	0	0.5	1.0	1.0	1.0	0.5	4.0	39.4	157.6
Senior Health Physics Technician[h]	0	0.9	2.3	2.0	1.9	0.9	8.0	32.9	263.2
Health Physics Technician[h]	0	2.7	12.9	13.5	12.6	3.5	45.2	25.1	1134.5
Totals, With Centralized Health Physics	0.3	5.0	17.1	17.4	16.4	5.6	61.8		1731.4
Net Savings With Centralized Health Physics	1.0	2.5	3.7	3.7	3.7	1.4	16.0		618.0

(a) Based on Table M.1-1 of Reference 3.
(b) Rounded to the nearest $100.
(c) Based on organization shown in Figure 8.3-1a; manpower requirements taken from Table I.2-3 of Reference 3.
(d) Based on organization shown in Figure 8.3-1b, with manpower requirements from Table I.2-3 of Reference 3 modified appropriately; rounded to next higher 0.1 man-year.
(e) Single unit assumed to bear 10% of total site cost.
(f) Single unit assumed to bear 30% of total group cost (10% of total site cost assuming 3 groups).
(g) Study estimate.
(h) Based on an assumed 10% reduction of the manpower requirements without centralized health physics.

TABLE B.1-4. Health Physics Staff Labor Requirements and Costs for BWR Preparations for Safe Storage

Position	Time Relative to Final Reactor Shutdown (year) -2	-1	1	2	3	Total Staff Labor Required (man-years)	Cost per Man-Year[a] ($ thousands)	Total Staff Labor Costs[b] ($ thousands)
	Annual Staff Labor Requirement (man-years)							
Without Centralized Health Physics[c]								
Health and Safety Supervisor	0.5	1.0	1.0	1.0	0.8	4.3	50.4	216.7
Industrial Safety Specialist	0.2	1.0	1.0	1.0	0.5	3.7	43.8	162.1
Radioactive Shipment Specialist	0	1.0	1.0	1.0	0.4	3.4	32.9	111.9
Health Physicist	0	0.5	1.0	1.0	0.5	3.0	39.4	118.2
Senior Health Physics Technician	0	1.0	2.2	2.2	1.4	6.8	32.9	223.7
Health Physics Technician	0	3.0	13.0	9.1	2.7	27.8	25.1	697.8
Totals, Without Centralized Health Physics	0.7	7.5	19.2	15.3	6.3	49.0		1530.4
With Centralized Health Physics[d]								
Site Level[e]								
Health and Safety Supervisor	0.1	0.1	0.1	0.1	0.1	0.5	50.4	25.2
Industrial Safety Specialist	0.1	0.1	0.1	0.1	0.1	0.5	43.8	21.9
Clerk	0.1	0.1	0.1	0.1	0.1	0.5	20.3	10.2
Group Level[f]								
Health Physics Supervisor	0	0.3	0.3	0.3	0.2	1.1	43.8[g]	48.2
Radioactive Shipment Specialist	0	0.3	0.3	0.3	0.2	1.1	32.9	36.2
Unit Level								
Health Physicist	0	0.5	1.0	1.0	0.5	3.0	39.4	118.2
Senior Health Physics Technician[h]	0	0.9	2.0	2.0	1.3	6.2	32.9	204.0
Health Physics Technician[h]	0	2.7	11.7	8.2	2.5	25.1	25.1	630.0
Totals, With Centralized Health Physics	0.3	5.0	15.6	12.1	5.0	38.0		1093.9
Net Savings With Centralized Health Physics	0.4	2.5	3.6	3.2	1.3	11.0		436.5

(a) Based on Table M.1-1 of Reference 3.
(b) Rounded to the nearest $100.
(c) Based on organization shown in Figure 8.3-1a; manpower requirements taken from Table J.4-1 of Reference 3.
(d) Based on organization shown in Figure 8.3-1b, with manpower requirements from Table J.4-1 of Reference 3 modified appropriately; rounded to next higher 0.1 man-year.
(e) Single unit assumed to bear 10% of total site cost.
(f) Single unit assumed to bear 30% of total group cost (10% of total site cost assuming 3 groups).
(g) Study estimate.
(h) Based on an assumed 10% reduction of the manpower requirements without centralized health physics.

Centralized health physics services are estimated to result in total net savings for BWR SAFSTOR of 27 man-years and about $1.05 million.

B.1.6 BWR ENTOMB

Based on information presented in Table K.2-2 of Reference 3, manpower requirements and costs for health physics staff for BWR ENTOMB (reactor vessel internals removed) are shown in Table B.1-5. Totals of almost 79 man-years and about $2.41 million are required without centralized health physics as compared to 62 man-years and about $1.75 million with centralization. Centralized health physics services result in net savings of almost 17 man-years and about $650,000 for scenario 1.

B.2 SECURITY FORCES

Centralized security forces are anticipated to reduce the costs associated with security functions at a reactor sited on a multiple-reactor station during both operation and decommissioning. Two factors are postulated to account for this cost reduction:

- The overhead structure for each reactor can be reduced by sharing certain staff members between reactors.
- Off-shift coverage at a reactor being decommissioned can be reduced or eliminated after the spent fuel has been shipped (no special nuclear material at reactor) if provision is made for routine spot-checks by roving security patrolmen, reducing the overall personnel requirement.

Centralization of the security forces is not anticipated to change the occupational radiation dose for decommissioning a reactor.

The security force labor requirements and costs during decommissioning, both with and without centralized security forces, are presented here for the decommissioning of both the PWR and the BWR by all the decommissioning alternatives considered in this study. Net savings resulting from centralization of the security forces are calculated from these results.

B.2.1 PWR DECON

Security force labor requirements and costs for DECON of the reference PWR are presented in Table B.2-1, based on the schedule shown in Figure 9.1-2 of

TABLE B.1-5. Health Physics Staff Labor Requirements and Costs for BWR ENTOMB

Position	Time Relative to Final Reactor Shutdown (year): -2	-1	1	2	3	4	Total Staff Labor Required (man-years)	Cost per Man-Year[a] ($ thousands)	Total Staff Labor Costs[b] ($ thousands)
	Annual Staff Labor Requirement (man-years)								
Without Centralized Health Physics[c]									
Health and Safety Supervisor	1.0	1.0	1.0	1.0	1.0	1.2[d]	6.2	50.4	312.5
Industrial Safety Specialist	0.3	1.0	1.0	1.0	1.0	0.9	5.2	43.8	227.8
Radioactive Shipment Specialist	0	1.0	1.0	1.0	1.0	0.7	4.7	32.9	154.6
Health Physicist	0	0.5	1.0	1.0	1.0	0.8	4.3	39.4	169.4
Senior Health Physics Technician	0	1.0	2.4	2.3	2.0	2.0	9.7	32.9	319.1
Health Physics Technician	0	3.0	13.9	13.6	12.0	6.2	48.7	25.1	1222.4
Totals, Without Centralized Health Physics	1.3	7.5	20.3	19.9	18.0	11.8	78.8		2405.8
With Centralized Health Physics[e]									
Site Level[f]									
Health and Safety Supervisor	0.1	0.1	0.1	0.1	0.1	0.2	0.7	50.4	35.3
Industrial Safety Specialist	0.1	0.1	0.1	0.1	0.1	0.1	0.6	43.8	26.3
Clerk	0.1	0.1	0.1	0.1	0.1	0.1	0.6	20.3	12.2
Group Level[g]									
Health Physics Supervisor	0	0.3	0.3	0.3	0.3	0.3	1.5	43.8[h]	65.7
Radioactive Shipment Specialist	0	0.3	0.3	0.3	0.3	0.3	1.5	32.9	49.4
Unit Level									
Health Physicist	0	0.5	1.0	1.0	1.0	0.8	4.3	39.4	169.4
Senior Health Physics Technician[i]	0	0.9	2.2	2.1	1.8	1.8	8.8	32.9	289.5
Health Physics Technician[i]	0	2.7	12.6	12.3	10.8	5.6	44.0	25.1	1104.4
Totals, With Centralized Health Physics	0.3	5.0	16.7	16.3	14.5	9.2	62.0		1752.2
Net Savings With Centralized Health Physics	1.0	2.5	3.6	3.6	3.5	2.6	16.8		653.6

(a) Based on Table M.1-1 of Reference 3.
(b) Rounded to the nearest $100.
(c) Based on organization shown in Figure 8.3-1a; manpower requirements taken from Table K.2-2 of Reference 3.
(d) Includes 4 additional months following active decommissioning to complete administrative requirements; shown as part of year 4 even though it extends into year 5; from Table K.2-2 of Reference 3.
(e) Based on organization shown in Figure 8.3-1b, with manpower requirements from Table K.2-2 of Reference 3 modified appropriately; rounded to next higher 0.1 man-year.
(f) Single unit assumed to bear 10% of total site cost.
(g) Single unit assumed to bear 30% of total group cost (10% of total site cost assuming 3 groups).
(h) Study estimate.
(i) Based on an assumed 10% reduction of the manpower requirements without centralized health physics.

TABLE B.2-1. Security Force Labor Requirements and Costs for PWR DECON and ENTOMB

Postion	Time Relative to Final Reactor Shutdown (year) 1 — Annual Staff Labor Requirement (man-years)	2	3	Total Staff Labor Required (man-years)	Cost per Man-Year[a] ($ thousands)	Total Staff Labor Costs[b] ($ thousands)
Without Centralized Security Forces[c]						
Security Supervisor	1.0	1.0	1.0	3.0	32.9	98.7
Security Shift Supervisor	5.0	5.0	5.0	15.0	30.7	460.5
Security Patrolmen	39.0	21.7[d]	13.0	73.7	21.3	1569.8
Totals, Without Centralized Security Forces	45.0	27.7	19.0	91.7		2129.0
With Centralized Security Forces[e]						
Site Level[f]						
Security Supervisor	0.1	0.1	0.1	0.3	32.9	9.9
Assistant Security Supervisor	0.1	0.1	0.1	0.3	30.7[g]	9.2
Group Level[h]						
Security Shift Supervisor	1.5	1.5	1.5	4.5	30.7	138.2
Security Patrolmen	3.0	3.0	3.0	9.0	21.3	191.7
Unit Level						
Security Patrolmen[i]	39.0	17.0	6.0	62.0	21.3	1320.6
Totals, With Centralized Security Forces	43.7	21.7	10.7	76.1		1669.6
Net Savings With Centralized Security Forces	1.3	6.0	8.3	15.6		459.4

(a) Based on Table M.1-1 of Reference 3.
(b) Rounded to the nearest $100.
(c) Based on organization shown in Figure 8.3-2a, on schedule shown in Figure 9.1-2 of Reference 1 (demolition deleted), and on staffing assumptions from Reference 3 (e.g., Table I.2-3) for consistency between PWR and BWR results.
(d) Assumes spent fuel shipment completed at end of month 16, rounded to next higher 0.1 man-year.
(e) Based on organization shown in Figure 8.3-2b; rounded to the next higher 0.1 man-year.
(f) Single unit assumed to bear 10% of total site cost.
(g) Study estimate.
(h) Single unit assumed to bear 30% of total group cost (10% of total site cost assuming three groups); assumes one security shift supervisor and two security patrolmen per shift at each group.
(i) Assumes three men/shift on two-shift, 5-day-week coverage after completion of spent fuel shipment (end of month 16).

Reference 1, with demolition deleted. The requirements and costs with centralized security forces take into account both the reduced overhead structure per reactor and the elimination of continuous off-shift coverage after offsite shipment of spent fuel. A total of about 91-1/2 man-years, costing almost $2.13 million, is required without centralization as compared to about 76 man-years, costing almost $1.67 million, with centralization. Thus, centralized security forces result in net savings of about 15-1/2 man-years and almost $460,000.

B.2.2 PWR SAFSTOR

Security force labor requirements and costs for the first phase of PWR SAFSTOR, preparations for safe storage, are presented in Table B.2-2, based on the decommissioning schedule shown in Figure 9.2-5 of Reference 1. Without centralized security, 50-1/2 man-years and about $1.15 million are estimated to be required. With centralized security forces, these requirements are reduced to about 46 man-years and just over $1.00 million, for net savings of almost 4-1/2 man-years and $150,000.

Centralized security forces are anticipated to result in no significant savings during the continuing care period of SAFSTOR and, therefore, no requirements and costs are calculated for this period.

Security force labor requirements and costs for deferred decontamination (the final phase of SAFSTOR) of the reference PWR are given in Table B.2-3, based on the decommissioning schedule for DECON shown in Figure 9.1-2 of Reference 1. The results differ from the results for DECON because of the reduced requirements for security patrolmen at the reactor (both with and without centralization). These reduced requirements reflect the offsite shipment of spent reactor fuel prior to the start of deferred decontamination. Without centralized security, 57 man-years costing almost $1.39 million are estimated to be required. With centralized security forces, these totals are reduced to about 32 man-years and about $730,000, resulting in net savings of almost 25 man-years and about $660,000 with centralization.

Total net savings resulting from centralized security forces during SAFSTOR of the reference PWR are estimated to be 29 man-years and $810,000.

TABLE B.2-2. Security Force Labor Requirements and Costs for PWR Preparations for Safe Storage

Position	Time Relative to Final Reactor Shutdown (year) 1	2	Total Staff Labor Required (man-years)	Cost per Man-Year[a] ($ thousands)	Total Staff Labor Costs[b] ($ thousands)
	Annual Staff Labor Requirement (man-years)				
Without Centralized Security Forces[c]					
Security Supervisor	1.0	0.4	1.4	32.9	46.1
Security Shift Supervisor	5.0	1.7	6.7	30.7	205.7
Security Patrolmen	38.0[d]	4.4	42.4	21.3	903.1
Totals, Without Centralized Security Forces	44.0	6.5	50.5		1154.9
With Centralized Security Forces[e]					
Site Level[f]					
Security Supervisor	0.1	0.1	0.2	32.9	6.6
Assistant Security Supervisor	0.1	0.1	0.2	30.7[g]	6.1
Group Level[h]					
Security Shift Supervisor	1.5	0.5	2.0	30.7	61.4
Security Patrolmen	3.0	1.0	4.0	21.3	85.2
Unit Level					
Security Patrolmen[i]	37.7	2.0	39.7	21.3	845.6
Totals, With Centralized Security Forces	42.4	3.7	46.1		1004.9
Net Savings With Centralized Security Forces	1.6	2.8	4.4		150.0

(a) Based on Table M.1-1 of Reference 3.
(b) Rounded to the nearest $100.
(c) Based on organization shown in Figure 8.3-2a, on schedule shown in Figure 9.2-5 of Reference 1, and on staffing assumptions from Reference 3 (e.g., Table I.2-3) for consistency between PWR and BWR results; rounded to the next higher 0.1 man-year.
(d) Assumes spent fuel shipment completed after 11.5 months.
(e) Based on organization shown in Figure 8.3-2b; rounded to the next higher 0.1 man-year.
(f) Single unit assumed to bear 10% of total site cost.
(g) Study estimate.
(h) Single unit assumed to bear 30% of total group cost (10% of total site cost assuming three groups); assumes one security shift supervisor and two security patrolmen per shift at each group.
(i) Assumes three men/shift on two-shift, 5-day-week coverage after completion of spent fuel shipment (11.5 months).

TABLE B.2-3. Security Force Labor Requirements and Costs for PWR Deferred Decontamination

Postion	Time Relative to Start of Deferred Decontamination (year) 1	2	3	Total Staff Labor Required (man-years)	Cost per Man-Year[a] ($ thousands)	Total Staff Labor Costs[b] ($ thousands)
	Annual Staff Labor Requirement (man-years)					
Without Centralized Security Forces[c]						
Security Supervisor	1.0	1.0	1.0	3.0	32.9	98.7
Security Shift Supervisor	5.0	5.0	5.0	15.0	30.7	460.5
Security Patrolmen	13.0	13.0	13.0	39.0	21.3	830.7
Totals, Without Centralized Security Forces	19.0	19.0	19.0	57.0		1389.9
With Centralized Security Forces[d]						
Site Level[e]						
Security Supervisor	0.1	0.1	0.1	0.3	32.9[f]	9.9
Assistant Security Supervisor	0.1	0.1	0.1	0.3	30.7[f]	9.2
Group Level[g]						
Security Shift Supervisor	1.5	1.5	1.5	4.5	30.7	138.2
Security Patrolmen	3.0	3.0	3.0	9.0	21.3	191.7
Unit Level						
Security Patrolmen[h]	6.0	6.0	6.0	18.0	21.3	383.4
Totals, With Centralized Security Forces	10.7	10.7	10.7	32.1		732.4
Net Savings With Centralized Security Forces	8.3	8.3	8.3	24.9		657.5

(a) Based on Table M.1-1 of Reference 3.
(b) Rounded to the nearest $100.
(c) Based on organization shown in Figure 8.3-2a, on schedule shown in Figure 9.1-2 of Reference 1 (demolition and spent fuel shipment deleted) and on staffing assumptions from Reference 3 (e.g., Table I.2-3) for consistency between PWR and BWR results.
(d) Based on organization shown in Figure 8.3-2b.
(e) Single unit assumed to bear 10% of total site cost.
(f) Study estimate.
(g) Single unit assumed to bear 30% of total group cost (10% of total site cost assuming three groups); assumes one security shift supervisor and two security patrolmen per shift at each group.
(h) Assumes three men/shift on two-shift, 5-day-week coverage.

B.2.3 PWR ENTOMB

The schedule of events for entombment of the reference PWR is very similar to that for DECON, as stated previously in Section B.1.3. Therefore, the security staff requirements and costs for entombment are assumed to be the same as those given previously in Table B.2-1. Centralized security during ENTOMB is thus estimated to result in net savings of about 15-1/2 man-years and $460,000.

B.2.4 BWR DECON

Manpower requirements and costs for security personnel during DECON of the reference BWR are shown in Table B.2-4. Manpower requirements from Table I.2-3 of Reference 3 are used for decommissioning without centralized security; these values are modified appropriately for decommissioning with centralized security to account for both the reduced overhead structure and the elimination of continuous off-shift coverage after offsite shipment of spent fuel. A total of 107-1/2 man-years, costing almost $2.50 million, is required without centralized security as compared to almost 90 man-years, costing about $1.97 million, with centralization of the security forces. Net savings with centralized security are thus about 17-1/2 man-years and over $520,000.

B.2.5 BWR SAFSTOR

Security force labor requirements and costs for preparations for safe storage, the first phase of SAFSTOR, are presented in Table B.2-5, based on information from Table J.4-1 of Reference 3. Without centralized security forces, 88-1/2 man-years and about $2.03 million are estimated to be required. With centralized security, these totals are reduced to about 79 man-years and almost $1.73 million, for net savings of almost 9-1/2 man-years and about $300,000.

During the continuing care period of BWR SAFSTOR, centralized security forces are anticipated to result in no significant savings and, therefore, labor requirements and costs are not calculated for this period.

Security force labor requirements and costs for deferred decontamination of the reference BWR are presented in Table B.2-6. The requirements are based

TABLE B.2-4. Security Force Labor Requirements and Costs for BWR DECON

Position	Time Relative to Final Reactor Shutdown (year) 1	2	3	4	Total Staff Labor Required (man-years)	Cost per Man-Year[a] ($ thousands)	Total Staff Labor Costs[b] ($ thousands)
	Annual Staff Labor Requirements (man-years)						
Without Centralized Security Forces[c]							
Security Supervisor	1.0	1.0	1.0	0.5	3.5	32.9	115.2
Security Shift Supervisor	5.0	5.0	5.0	2.5	17.5	30.7	537.3
Security Patrolmen	39.0	28.0	13.0	6.5	86.5	21.3	1842.5
Totals, Without Centralized Security Forces	45.0	34.0	19.0	9.5	107.5		2495.0
With Centralized Security Forces[d]							
Site Level[e]							
Security Supervisor	0.1	0.1	0.1	0.1	0.4	32.9	13.2
Assistant Security Supervisor	0.1	0.1	0.1	0.1	0.4	30.7[f]	12.3
Group Level[g]							
Security Shift Supervisor	1.5	1.5	1.5	0.8	5.3	30.7	162.7
Security Patrolmen	3.0	3.0	3.0	1.5	10.5	21.3	223.7
Unit Level							
Security Patrolmen[h]	39.0	25.3	6.0	3.0	73.3	21.3	1561.3
Totals, With Centralized Security Forces	43.7	30.0	10.7	5.5	89.9		1973.2
Net Savings With Centralized Security Forces	1.3	4.0	8.3	4.0	17.6		521.8

(a) Based on Table M.1-1 of Reference 3.
(b) Rounded to the nearest $100.
(c) Based on organization shown in Figure 8.3-2a; manpower requirements taken from Table I.2-3 of Reference 3.
(d) Based on organization shown in Figure 8.3-2b; rounded to the next higher 0.1 man-year.
(e) Single unit assumed to bear 10% of total site cost.
(f) Study estimate.
(g) Single unit assumed to bear 30% of total group cost (10% of total site cost assuming three groups); assumes one security shift supervisor and two security patrolmen per shift at each group.
(h) Assumes three men/shift on two-shift, 5-day-week coverage after completion of spent fuel shipment (end of month 19).

TABLE B.2-5. Security Force Labor Requirements and Costs for BWR Preparations for Safe Storage

Postion	Time Relative to Final Reactor Shutdown (year) 1	2	3	Total Staff Labor Required (man-years)	Cost per Man-Year[a] ($ thousands)	Total Staff Labor Costs[b] ($ thousands)
	Annual Staff Labor Requirement (man-years)					
Without Centralized Security Forces[c]						
Security Supervisor	1.0	1.0	0.5	2.5	32.9	82.3
Security Shift Supervisor	5.0	5.0	2.5	12.5	30.7	383.8
Security Patrolmen	39.0	28.0	6.5	73.5	21.3	1565.6
Totals, Without Centralized Security Forces	45.0	34.0	9.5	88.5		2031.7
With Centralized Security Forces[d]						
Site Level[e]						
Security Supervisor	0.1	0.1	0.1	0.3	32.9	9.9
Assistant Security Supervisor	0.1	0.1	0.1	0.3	30.7[f]	9.2
Group Level[g]						
Security Shift Supervisor	1.5	1.5	0.8	3.8	30.7	116.7
Security Patrolmen	3.0	3.0	1.5	7.5	21.3	159.8
Unit Level						
Security Patrolmen[h]	39.0	25.3	3.0	67.3	21.3	1433.5
Totals, With Centralized Security Forces	43.7	30.0	5.5	79.2		1729.1
Net Savings With Centralized Security Forces	1.3	4.0	4.0	9.3		302.6

(a) Based on Table M.1-1 of Reference 3.
(b) Rounded to the nearest $100.
(c) Based on organization shown in Figure 8.3-2a; manpower requirements taken from Table J.4-1 of Reference 3.
(d) Based on organization shown in Figure 8.3-2b; rounded to the next higher 0.1 man-year.
(e) Single site assumed to bear 10% of total site cost.
(f) Study estimate.
(g) Single unit assumed to bear 30% of total group cost (10% of total site cost assuming three groups); assumes one security shift supervisor and two security patrolmen per shift at each group.
(h) Assumes three men/shift on two-shift, 5-day-week coverage after completion of spent fuel shipment (end of month 19).

TABLE B.2-6. Security Force Labor Requirements and Costs for BWR Deferred Decontamination

Position	Time Relative to Start of Deferred Decontamination (year) 1	2		3	Total Staff Labor Required (man-years)	Cost per Man-Year[a] ($ thousands)	Total Staff Labor Costs[b] ($ thousands)
	Annual Staff Labor Requirement (man-years)						
Without Centralized Security Forces[c]							
Security Supervisor	1.0	1.0	1.0	0.5	3.5	32.9	115.2
Security Shift Supervisor	5.0	5.0	5.0	2.5	17.5	30.7	537.3
Security Patrolmen	13.0	13.0	13.0	6.5	45.5	21.3	969.2
Totals, Without Centralized Security Forces	19.0	19.0	19.0	9.5	66.5		1621.7
With Centralized Security Forces[d]							
Site Level[e]							
Security Supervisor	0.1	0.1	0.1	0.1	0.4	32.9[f]	13.2
Assistant Security Supervisor	0.1	0.1	0.1	0.1	0.4	30.7[f]	12.3
Group Level[g]							
Security Shift Supervisor	1.5	1.5	1.5	0.8	5.3	30.7	162.7
Security Patrolmen	3.0	3.0	3.0	1.5	10.5	21.3	223.7
Unit Level							
Security Patrolmen[h]	6.0	6.0	6.0	3.0	21.0	21.3	447.3
Totals, With Centralized Security Forces	10.7	10.7	10.7	5.5	37.6		859.2
Net Savings With Centralized Security Forces	8.3	8.3	8.3	4.0	28.9		762.5

(a) Based on Table M.1-1 of Reference 3.
(b) Rounded to the nearest $100.
(c) Based on organization shown in Figure B.3-2a and on manpower requirements from Table I.2-3 of Reference 3; modified for deletion of spent fuel shipment.
(d) Based on organization shown in Figure B.3-2b; rounded to the next higher 0.1 man-year.
(e) Single unit assumed to bear 10% of total site cost.
(f) Study estimate.
(g) Single unit assumed to bear 30% of total group cost (10% of total site cost assuming three groups); assumes one security shift supervisor and two security patrolmen per shift at each group.
(h) Assumes three men/shift on two-shift, 5-day-week coverage.

on information from Table I.2-3 of Reference 3 for DECON of the plant, modified to reflect the offsite shipment of the spent reactor fuel prior to deferred decontamination. Without centralized security, 66-1/2 man-years and about $1.62 million are estimated to be required. With centralized security, these totals are reduced to about 37-1/2 man-years and almost $860,000, resulting in net savings of almost 29 man-years and approximately $760,000.

Total net savings with centralized security forces for BWR SAFSTOR are estimated to be about 38 man-years and almost $1.07 million.

B.2.6 BWR ENTOMB

Based on information presented in Table K.2-2 of Reference 3, manpower requirements and costs for security personnel for BWR ENTOMB are given in Table B.2-7. Totals of about 114-1/2 man-years and approximately $2.67 million are required without centralized security as compared to 94 man-years and almost $2.07 million with centralization. Centralized security forces thus result in net savings of over 20-1/2 man-years and $600,000.

B.3 SOLID WASTE PROCESSING

Centralized solid waste processing facilities at a multiple-reactor site can provide significant savings in waste disposal costs, during both the operating and the decommissioning phases of reactor life, by reducing the volume of wastes requiring shipment and disposal. Reductions in radiation exposures, both to workers and to the public, can also result because of the reduced handling and shipping requirements.

This analysis assumes a central waste incineration facility capable of handling 1) all dry combustible wastes generated by the 10 operating reactors onsite as well as 2) the dry combustible wastes resulting from the onsite decommissioning activities (when they commence). The results for this case (with incineration) are compared to those of the base case, given in References 1 through 3, in which these wastes are assumed to be compacted for shipment offsite.

Compaction of dry combustible wastes is assumed to reduce the waste volume by an average of 5:1. This is the same factor used in estimating disposal

TABLE B.2-7. Security Force Labor Requirements and Costs for BWR ENTOMB

Position	Time Relative to Final Reactor Shutdown (year) 1	2	3	4	Total Staff Labor Required (man-years)	Cost per Man-Year[a] ($ thousands)	Total Staff Labor Costs[b] ($ thousands)
	Annual Staff Labor Requirements (man-years)						
Without Centralized Security Forces[c]							
Security Supervisor	1.0	1.0	1.0	0.9	3.9	32.9	128.3
Security Shift Supervisor	5.0	5.0	5.0	4.4	19.4	30.7	595.6
Security Patrolmen	39.0	28.0	13.0	11.4	91.4	21.3	1946.8
Totals, Without Centralized Security Forces	45.0	34.0	19.0	16.7	114.7		2670.7
With Centralized Security Forces[d]							
Site Level[e]							
Security Supervisor	0.1	0.1	0.1	0.1	0.4	32.9	13.2
Assistant Security Supervisor	0.1	0.1	0.1	0.1	0.4	30.7[f]	12.3
Group Level[g]							
Security Shift Supervisor	1.5	1.5	1.5	1.4	5.9	30.7	181.1
Security Patrolmen	3.0	3.0	3.0	2.7	11.7	21.3	249.2
Unit Level							
Security Patrolmen[h]	39.0	25.3	6.0	5.3	75.6	21.3	1610.3
Totals, With Centralized Security Forces	43.7	30.0	10.7	9.6	94.0		2066.1
Net Savings With Centralized Security Forces	1.3	4.0	8.3	7.1	20.7		604.6

(a) Based on Table M.1-1 of Reference 3.
(b) Rounded to the nearest $100.
(c) Based on organization shown in Figure 8.3-2a; manpower requirements from Table K.2-2 of Reference 3.
(d) Based on organization shown in Figure 8.3-2b; rounded to the next higher 0.1 man-year.
(e) Single unit assumed to bear 10% of total site cost.
(f) Study estimate.
(g) Single unit assumed to bear 30% of total group cost (10% of total site assuming three groups); assumes one security shift supervisor and two security patrolmen per shift at each group.
(h) Assumes three men/shift on two-shift, 5-day-week coverage after completion of spent fuel shipment (end of month 19).

requirements in the reference decommissioning studies (see, for example, page G-33 of Reference 1 and page I-41 of Reference 3) and agrees with that reported in another analysis of incineration versus compaction (see page 10-1 of Reference 4). Incineration is assumed to reduce the volume an additional factor of 5:1, for an overall volume reduction of 25:1 for incineration.[4] The volume reduction factor for incineration depends on the type of waste involved and on the incinerator used. The factor used here falls in the center of the range reported in the literature, from an overall volume reduction (from uncompacted wastes) of about 10:1[5,6] to a reduction of about 35 or 40:1.[7,8]

The effects of incineration of the dry combustible wastes on both costs and radiation doses are presented here for the various combinations of reactor types and decommissioning alternatives considered in this study.

B.3.1 Cost Effects

A large LWR averages about 142 m^3 of compacted trash annually, with an 85 to 100% combustible content (see page 10-2 of Reference 4). Thus, for a site with 10 operating reactors, the average annual production of compacted combustible trash is about 1420 m^3. To maximize the cost savings of onsite incineration, the central incinerator must be sized to process all of this waste. Assuming two-shift/day, 5-day/week operation of the facility (48% availability), the nominal rated (instantaneous) capacity of the facility is about 2980 m^3 per year of compacted waste.

From page 10-3 of Reference 4, an incinerator servicing a twin-reactor site involves a capital cost of about $2 million. Again, assuming an annual production of 142 m^3 of compacted combustible waste per reactor, this incinerator is sized to process 284 m^3/year of waste, under normal operating conditions. Assuming the need for incineration at a twin-reactor site to be somewhat variable and discontinuous, it is postulated that the incinerator operates 5 to 6 shifts/week (one shift/day for a 5-day week or two consecutive shifts 3 days a week). This results in the unit being operated 24 to 29% of the time, giving the unit a nominal rated (instantaneous) capacity of between 980 and 1180 m^3 per year.

Based on the above information, the incinerator for the twin-reactor site must be scaled up by a factor of between 2.5 and 3.0 to be properly sized for the 10-reactor site. For the subsequent calculations, the latter number is used to ensure the conservatism of the cost estimate.

Equipment size and capital cost correlate fairly well by the logarithmic relationship known as the "six-tenths factor," shown by:[9]

$$C_h = r^{0.6}\, C \tag{B.1}$$

where:

C_h = the capital cost of the new plant

C = the capital cost of the previous plant

r = the ratio of new to previous capacity.

Thus, for the incinerator at the 10-reactor site:

$$C_h = (3.0)^{0.6} \cdot \$2{,}000{,}000. \tag{B.2}$$

This yields a capital cost of about \$3.9 million for the postulated incinerator, or \$390,000 per reactor at the site.

Assuming annual operating and maintenance costs to be 5% of the original capital cost, maintenance and operation of the incinerator are estimated to cost \$195,000/year, or \$19,500/year per reactor. With 142 m^3 of compacted waste processed for each reactor, this yields a unit cost for operation and maintenance of $\sim$\$137/m^3 of compacted waste (or \$685/m^3 of incinerated product, assuming the 5:1 volume-reduction factor given previously).

Assuming 40 years of operation for each reactor (see page 7-16 of Reference 1), each reactor generates about 5680 m^3 of compacted combustible waste during its operating lifetime. During decommissioning, up to 284 m^3 of compacted combustible waste are generated at a PWR (page G-33 of Reference 1) and up to 678 m^3 at a BWR (page I-41 of Reference 3). Thus, on average, decommissioning accounts for less than 10% of the combustible wastes generated at a reactor and, consequently, less than 10% of the waste processed through the incinerator. Therefore, because the incinerator mainly benefits the operations phase of each reactor, it is assumed here that all capital costs are borne by reactor operations.

B.3.1.1 Cost Savings During Reactor Operations

As stated previously, ~142 m^3 of compacted combustible wastes are generated annually at a large LWR. This volume of waste fills about 675 steel drums, 0.21-m^3-capacity.

From the previous discussion, the capital cost of the incinerator for the 10-reactor site is $3.9 million, or $390,000 per reactor. Operation and maintenance costs are $19,500/year per reactor. Decommissioning costs for the incinerator are $39,000 per reactor. Assuming a 40-year operating life for a reactor, the combined annual costs for capital, for operation and maintenance, and for decommissioning are $30,225 for each reactor.

Table B.3-1 summarizes the annual costs for disposal of dry combustible wastes, either with compaction or with incineration, during the operating lifetime of an LWR at a 10-reactor site. Annual net savings with incineration are also shown. As evidenced by the table, the postulated incinerator results in annual savings of about $35,000 for each reactor, or $351,000 for the entire 10-reactor site. The total net savings associated with incineration during the 40-year operating lifetimes of the 10 reactors is estimated to be ~$14 million. Thus, it can be seen that the incinerator facility represents significant cost savings during operations.

B.3.1.2 Cost Savings During Reactor Decommissioning

As stated previously in Section B.3.1, the capital costs of the incinerator are assumed to be borne solely by the reactor operations. Therefore, the costs of using the facility to process decommissioning wastes are only the additional incremental costs of operating and maintaining the facility during incineration of these wastes. This additional cost, also derived in Section B.3.1, is $137/$m^3$ of compacted combustible waste fed into the facility. (It is assumed that, in order to handle the decommissioning waste, a third shift is added to the facility operating schedule as needed.)

Costs for disposal of incinerated combustible wastes from decommissioning, based on the previous assumptions, are presented in Table B.3-2 for the various combinations of reactor types and decommissioning alternatives considered in this study. Also presented are the net savings associated with incineration as

TABLE B.3-1. Annual Costs for Disposal of Dry Combustible Wastes for an Operating LWR

Waste Form	Number of Disposable Containers	Container Costs($)[a]	Estimated No. Requiring Shielding[b]	Cask Rental Costs($)[c]	Number of Shipments Shielded[d]/Unshielded	Transportation Costs($)[e]	Handling Costs($)[f]	Burial Volume(m^3)[g]	Burial Costs($)[h]	Total Facility Operation and Maintenance Costs($)[i]	Total Disposal Costs($)[j]
Compacted Combustible Wastes	675[k]	13 500	210	15 000	15/3	34 560	6 000	142	13 810	0	82 870
Incinerated Combustible Wastes	135[m]	2 700	42	3 000	3/1	7 680	1 200	29	2 920	30 225	47 725
Annual Net Savings With Incineration	540	10 800	168	12 000	12/2	26 880	4 800	113	10 890	(29 250)[n]	35 145

(a) Assumes $20/container, based on Table I.2-1 of Reference 1 and Table M.2-1 of Reference 3.
(b) Assumed to be the same percentage of material as during decommissioning (31%), as calculated from Table I.3-5 of Reference 3.
(c) Based on $500/cask/shipment, maximum seven containers/cask, from Table I.3-1 of Reference 1 and Table M.3-1 of Reference 3.
(d) Assumes two casks per shipment.
(e) Assumes $1,920 per shipment, based on Table M.4-4 of Reference 3 for overweight shipments.
(f) Assumes $200 per cask, based on Table I.5-1 of Reference 1 and Table M.5-1 of Reference 3.
(g) Assumes 0.21 m^3 per container including the disposable container; rounded to the next whole m^3.
(h) Based on Table M.5-1 of Reference 3; surface dose rates assumed to be <0.20 R/hr for unshielded drums, 0.21 to 1.00 R/hr for shielded drums of compacted wastes, and 1.01 to 2.00 R/hr for shielded drums of incinerated wastes; rounded to the next higher $10.
(i) Based on annual changes of $9 750/reactor to offset capital costs and $19,500/reactor for routine operation and maintenance costs for the incinerator facility; compaction facility assumed to be included in costs of normal reactor operation.
(k) Calculated based on 142 m^3 of compacted combustible wastes as reported on page 10-2 of Reference 4.
(m) Based on a 5:1 reduction of the estimated volume of compacted combustible wastes.
(n) Parentheses indicate a negative net saving, or a net costs.

TABLE B.3-2. Costs for Disposal of Incinerated Combustible Wastes from Decommissioning

Decommissioning Alternative	Number of Disposable Containers[a]	Container Costs($)[b]	Estimated No. Requiring Shielding[c]	Cask Rental Costs($)[d]	Number of Shipments Shielded[e]/Unshielded	Transportation Costs($)[f]	Handling Costs($)[g]	Burial Volume(m^3)[h]	Burial Costs($)[i]	Facility Operation and Maintenance Costs($)[j]	Total Disposal Costs($)[k] With Incineration	Total Disposal Costs($)[k] Without Incineration	Net Cost Savings With Incineration($)[k]
PWR													
DECON/ENTOMB[m]	270	5 400	84	6 000	6/2	15 360	2 400	57	5 840	38 840	73 840	207 430	133 590
SAFSTOR:													
Preparations for Safe Storage[n]	54	1 080	27	2 000	2/1	5 760	800	12	1 240	7 770	18 650	59 250	40 600
Deferred Decontamination After 30 Years[o]	220	4 400	0	0	0/2	3 840	0	47	4 330	31 650	44 220	148 100[p]	103 880
Deferred Decontamination After 50 Years[o]	143	2 860	0	0	0/1	1 920	0	31	2 810	20 570	28 160	96 300[p]	68 140
Deferred Decontamination After 100 Years[o]	96	1 920	0	0	0/1	1 920	0	21	1 890	13 810	19 540	64 600[p]	45 060
Total, w/30-Year Deferred Decontamination	274	5 480	27	2 000	2/3	9 600	800	59	5 570	39 420	62 870	207 350	144 480
Total, w/50-Year Deferred Decontamination	197	3 940	27	2 000	2/2	7 680	800	43	4 050	28 340	46 810	155 550	108 740
Total, w/100-Year Deferred Decontamination	150	3 000	27	2 000	2/2	7 680	800	33	3 130	21 580	38 190	123 850	85 660
BWR													
DECON/ENTOMB[q]	645	12 900	200	14 500	15/3	34 560	5 800	136	13 940	92 780	174 480	395 650	221 170
SAFSTOR:													
Preparations for Safe Storage[r]	228	4 560	71	5 500	6/1	13 440	2 200	48	4 930	32 800	63 430	142 670	79 240
Deferred Decontamination After 30 Years[s]	417	8 340	0	0	0/3	5 760	0	88	8 200	59 990	82 290	255 000[t]	172 710
Deferred Decontamination After 50 Years[s]	334	6 680	0	0	0/2	3 840	0	71	6 570	48 050	65 140	204 000[t]	138 860
Deferred Decontamination After 100 Years[s]	229	4 580	0	0	0/2	3 840	0	49	4 500	32 940	45 860	140 000[t]	94 140
Total, w/30-Year Deferred Decontamination	645	12 900	71	5 500	6/4	19 200	2 200	136	13 130	92 790	145 720	397 670	251 950
Total, w/50-Year Deferred Decontamination	562	11 240	71	5 500	6/3	17 280	2 200	119	11 500	80 850	128 570	346 670	218 100
Total, w/100-Year Deferred Decontamination	457	9 140	71	5 500	6/3	17 280	2 200	97	9 430	65 740	109 290	282 670	173 380

(a) Based on a 5:1 reduction of estimated volumes of compacted combustible dry wastes from References 1 and 3, rounded to the next higher whole container.
(b) Assumes $20/container, based on Table I.2-1 of Reference 1 and Table M.2-1 of Reference 3.
(c) For DECON, ENTOMB, and preparations for safe storage the same percentage of incinerated material is assumed to require shielding as was assumed for compacted combustible wastes in References 1 and 3; no shielding assumed to be required for deferred decontamination.
(d) Based on $500/cask/shipment, maximum seven containers/cask, from Table I.3-1 of Reference 1 and Table M.3-1 of Reference 3.
(e) Assumes two casks per shipment.
(f) Assumes $1920 per shipment, based on Table M.4-4 of Reference 3 for overweight shipment.
(g) Assumes $200 per cask, based on Table I.5-1 of Reference 1 and Table M.5-1 of Reference 3.
(h) Assumes 0.21 m^3 per container including the disposable container; rounded to the next whole m^3.
(i) Based on Table M.5-1 of Reference 3; surface dose rates assumed to be 1.01 to 2.00 R/hr for shielded drums, <0.20 R/hr for all others; rounded to the next higher $10.
(j) Based on $137/$m^3$ of compacted waste fed into the facility, rounded to the nearest $10.
(k) The number of figures shown is for computational completeness and does not imply accuracy to that many significant figures.
(m) Based on information from Table G.4-6 and page G-33 of Reference 1; requirements for ENTOMB assumed the same as for DECON based on cost presented in Table 4.5-1 of Reference 2.
(n) Based on information from Table H.3-2 and pages H-14 through H-16 of Reference 1.
(o) Calculated from burial volumes presented in Table H.5-1 of Reference 1.
(p) Calculated by multiplying the disposal cost for DECON by the ratio of the waste volumes for deferred decontamination and DECON.
(q) Based on information from Table I.3-5 of Reference 3; requirements for ENTOMB assumed the same as for DECON based on discussion of radioactive wastes presented on page K-27 of Reference 3.
(r) Based on information from Table J.5-3 of Reference 3.
(s) Calculated from burial volumes presented in Table J.7-1 of Reference 3.
(t) From Table J.7-2 of Reference 3.

TABLE B.3-2. Costs for Disposal of Incinerated Combustible Wastes from Decommissioning

compared to disposal of the compacted combustible wastes. The savings are small compared to the total costs of waste management for decommissioning but represent a significant fraction of the disposal costs for compacted combustible wastes without incineration.

B.3.2 Radiation Dose Effects

Reduction of the volume of waste handled could lead to potential radiation dose reductions for:

1. plant workers who prepare and package the waste for shipment
2. transportation workers involved in the shipment of the waste
3. members of the public along the waste transport route.

Dose reductions are calculated here only for waste disposal activities during decommissioning, and not for activities during the operating lifetime of the plant, even though such dose reductions would occur during both operations and decommissioning.

B.3.2.1 Waste Packaging Workers

After the combustible wastes are compacted at the individual reactor site, they are transported to the incinerator and burned. The resulting ash is then packaged in burial drums for transportation to and disposal at a low-level waste burial ground. The actual volume of waste packaged and shipped offsite is reduced by a factor of 5 from the compacted volume, thus reducing both the time required for packaging and the associated occupational radiation dose. However, the extra step of transporting the compacted waste to the incinerator and processing it there involves some radiation dose to the workers involved. For this analysis, this extra dose is assumed to offset the dose reduction resulting from reduced packaging time. Therefore, no significant net dose reduction is anticipated for the waste packaging workers.

B.3.2.2 Waste Transportation Workers

The radiation dose estimates presented for transport workers in the PWR and the BWR decommissioning studies are based on the maximum allowable dose rates for each shipment in exclusive-use trucks. (See pages 11-27 and 11-28 of Reference 1 and pages N-74 and N-75 of Reference 3.) The dose factors from the

BWR study are used here for consistency. The estimated radiation doses to transport workers from routine waste transportation activities, as shown in Table 11.4-2 of Reference 1, are:

Transport Workers	Radiation Dose Per Shipment (man-rem)
Truck Drivers	7.0×10^{-2}
Garagemen	3.3×10^{-3}
Total	7.3×10^{-2}

Thus, the total transport worker dose is 7.3×10^{-2} man-rem/shipment, based on one-way trips of 800-km each. Based on this unit dose per shipment value and on the reduction in the total number of shipments required, the radiation dose reductions for transport workers resulting from incineration of the combustible wastes are presented in Table B.3-3.

B.3.2.3 Members of the Public

The radiation dose estimates for members of the public along the waste transport routes are again based on the maximum allowable dose rates for each shipment, as they were for transport workers (see Section B.3.3.2). Again, the dose factors from the PWR study are used here for consistency. The estimated radiation doses to members of the public from routine waste transportation activities, as given in Table 11.4-2 of Reference 1, are:

Members of the Public	Radiation Dose Per Shipment (man-rem)
Onlookers	5.0×10^{-3}
General Public	1.0×10^{-2}
Total	1.5×10^{-2}

Thus, the total public dose is 1.5×10^{-2} man-rem per shipment. Based on this unit dose per shipment and on the number of shipments saved by incineration, the radiation dose reductions for members of the public are given in Table B.3-3.

TABLE B.3-3. Radiation Dose Reductions Resulting from Incineration of Dry Combustible Wastes from Decommissioning

Decommissioning Alternative	Number of Shipments: Required for Compacted Wastes	Number of Shipments: Required for Incinerated Wastes[a]	Number of Shipments: Saved by Incineration	Radiation Dose Reductions (man-rem): To Transport Workers[b]	Radiation Dose Reductions (man-rem): To Members of The Public[c]	Radiation Dose Reductions (man-rem): Total[d]
PWR						
DECON/ENTOMB	60[e]	8	52	3.8	0.78	4.6
SAFSTOR:						
Preparations for Safe Storage	19[f]	3	16	1.2	0.24	1.4
Deferred Decontamination After 30 Years	7[g]	2	5	0.4	0.08	0.5
Deferred Decontamination After 50 Years	5[g]	1	4	0.3	0.06	0.4
Deferred Decontamination After 100 Years	3[g]	1	2	0.1	0.03	0.2
Total, w/30-Year Deferred Decontamination	26	5	21	1.6	0.32	1.9
Total, w/50-Year Deferred Decontamination	24	4	20	1.5	0.30	1.8
Total, w/100-Year Deferred Decontamination	22	4	18	1.3	0.27	1.6
BWR						
DECON/ENTOMB	86[h]	18	68	5.0	1.02	6.0
SAFSTOR:						
Preparations for Safe Storage	32[i]	7	25	1.8	0.38	2.2
Deferred Decontamination After 30 Years	13[j]	3	10	0.7	0.15	0.9
Deferred Decontamination After 50 Years	10[j]	2	8	0.6	0.12	0.7
Deferred Decontamination After 100 Years	7[j]	2	5	0.4	0.08	0.5
Total, w/30-Year Deferred Decontamination	45	10	35	2.5	0.53	3.0
Total, w/50-Year Deferred Decontamination	42	9	33	2.4	0.50	2.9
Total, w/100-Year Deferred Decontamination	39	9	30	2.2	0.46	2.7

(a) From Table B.3-2.
(b) Based on a reduction of 7.3×10^{-2} man-rem per shipment saved, rounded to the nearest 0.1 man-rem.
(c) Based on a reduction of 1.5×10^{-2} man-rem per shipment saved, rounded to the nearest 0.01 man-rem.
(d) Rounded on the nearest 0.1 man-rem.
(e) From Table G.4-6 of Reference 1.
(f) From Table H.3-2 of Reference 1.
(g) Calculated from waste volumes presented in Table H.5-1 of Reference 1, assuming no shielding of container required.
(h) From Table I.3-5 of Reference 3.
(i) From Table J.5-3 of Reference 3.
(j) Calculated from waste volumes presented in Table J.7-1 of Reference 3, assuming no shielding of containers required.

B.3.3 Summary

The net cost savings and radiation dose reductions during the decommissioning of an LWR at a multiple-reactor site, resulting from incineration of dry combustible wastes, are presented in Table B.3-4.

Cost savings resulting from the incineration facility are in the range of 65 to 70% of the disposal costs of the compacted combustible wastes for the PWR and 55 to 70% for the BWR. However, the dollar value savings are higher for the BWR than for the PWR because of the larger volume of waste requiring disposal at the BWR.

The radiation dose reductions are directly proportional to the number of waste shipments saved by incineration and, therefore, represent about 80% reductions in the doses to transport workers and to the public from shipment of these wastes. However, these dose reductions are relatively small when compared to the overall radiation doses resulting from decommissioning. Dose reductions are larger for the BWR than for the PWR because more waste requires disposal from the BWR and, consequently, more waste shipments can be eliminated by incineration.

B.4 EQUIPMENT DECONTAMINATION SERVICES

Equipment decontamination services (and associated facilities) can be more fully utilized at a multi-reactor station than at a single- or twin-unit station, thereby increasing the economy of these services and the economic incentive to provide improved services and facilities at a multi-reactor station. Several types of equipment decontamination services are considered here for inclusion in the centralized services available at a multi-reactor station:

- decontamination of special tools and equipment used for decommissioning, allowing maintenance and reuse of these items
- mobile decontamination systems for in-situ chemical decontamination of piping and components
- central electropolishing and chemical decontamination facilities for improved decontamination of pipe sections and components.

TABLE B.3-4. Summary of Net Cost Savings and Radiation Dose Reductions for Incineration of Dry Combustible Wastes from LWR Decommissioning

Decommissioning Alternative	Total Disposal Costs ($ thousands)[a]		Net Cost Savings With Incineration ($ thousands)[a]	Radiation Dose Reductions (man-rem)[b]		
	Compacted Combustible Wastes	Incinerated Wastes		To Transport Workers	To Members of the Public	Total
PWR						
DECON/ENTOMB	207.4	73.8	133.6	3.8	0.78	4.6
SAFSTOR:						
Preparations for Safe Storage	59.3	18.7	40.6	1.2	0.24	1.4
Deferred Decontamination After 30 Years	148.1	44.2	103.9	0.4	0.08	0.5
Deferred Decontamination After 50 Years	96.3	28.2	68.1	0.3	0.06	0.4
Deferred Decontamination After 100 Years	64.6	19.5	45.1	0.1	0.03	0.2
Totals, w/30-Year Deferred Decontamination	207.4	62.9	144.5	1.6	0.32	1.9
Totals, w/50-Year Deferred Decontamination	155.6	46.8	108.7	1.5	0.30	1.8
Totals, w/100-Year Deferred Decontamination	123.9	38.2	85.7	1.3	0.27	1.6
BWR						
DECON/ENTOMB	395.7	174.5	221.2	5.0	1.02	6.0
SAFSTOR:						
Preparations for Safe Storage	142.7	63.4	79.2	1.8	0.38	2.2
Deferred Decontamination After 30 Years	255.0	82.3	172.7	0.7	0.15	0.9
Deferred Decontamination After 50 Years	204.0	65.1	138.9	0.6	0.12	0.7
Deferred Decontamination After 100 Years	140.0	45.9	94.1	0.4	0.08	0.5
Totals, w/30-Year Deferred Decontamination	397.7	145.7	252.0	2.5	0.53	3.0
Totals, w/50-Year Deferred Decontamination	346.7	128.6	218.1	2.4	0.50	2.9
Totals, w/100-Year Deferred Decontamination	282.7	109.3	173.4	2.2	0.46	2.7

(a) From Table B.3-2; rounded to the nearest $100.
(b) From Table B.3-3.

These services would provide significant benefits during both operation and decommissioning of a reactor. The resulting benefits during decommissioning are analyzed here.

B.4.1 Decontamination of Special Tools and Equipment

The special tools and equipment required to decommission an LWR represent a sizable cost investment. In the reference studies,[1-3] these items are not assumed to be salvaged after decommissioning and, thus, the full cost of these items is assumed to be borne by a single decommissioning. However, most of these items could be reused if proper decontamination and maintenance were performed on them, reducing the net cost of decommissioning a reactor.

For the following analysis, it is assumed that the special decommissioning tools and equipment are decontaminated, maintained, and reused where possible. An estimated useful lifetime (in terms of the number of decommissioning projects) is assigned to each item, and the capital costs for the item are assumed to be shared equally by that number of projects. Decontamination and maintenance costs are assumed to be 10% per year of the total capital cost of the item. However, each item is assumed to be used for only half of the total decommissioning period and, thus, the effective cost of decontamination and maintenance is assumed to be 5% per year over the total length of the decommissioning schedule. Items with a useful lifetime of only one decommissioning project are not assumed to require any substantial decontamination or maintenance. The total costs with reuse (the costs for capital and for decontamination and maintenance) are compared to those costs without reuse to calculate the net savings resulting from decontamination, maintenance, and reuse of the special tools and equipment.

B.4.1.1 PWR DECON

The costs for special tools and equipment for PWR DECON at a 10-reactor station, both with and without decontamination and reuse, are presented in Table B.4-1, together with net cost savings per decommissioning project with reuse. A total of over $820,000 is required without reuse while only about $495,000 is required with reuse. Net savings from decontamination and reuse of the tools and equipment are about $326,000, about 40% of the total capital cost of the items.

TABLE B.4-1. Costs for Special Tools and Equipment for PWR DECON and ENTOMB

Item	Estimated Number Required[a]	Estimated Total Costs ($ thousands)[a]	Estimated Useful Lifetime (Number of Decommissionings)[b]	Cost/Decommissioning With Reuse ($ thousands)[c]: Capital	Decontamination and Maintenance[d]	Total	Net Cost Savings/ Decommissioning with Reuse ($ thousands)[c]
Underwater Manipulator	1	300.0	1[e]	300.0	--	300.0	--
Underwater Plasma Cutting Torch	2	40.0	5	8.0	6.0	14.0	26.0
Underwater Oxyacetylene Torch	2	10.0	2	5.0	1.5	6.5	3.5
Portable Plasma Cutting Torch	4	80.0	5	16.0	12.0	28.0	52.0
Arc Saw	1	100.0	5	20.0	15.0	35.0	65.0
Guillotine Pipe Saw	9	36.0	5	7.2	5.4	12.6	23.4
Closed-Circuit, High-Resolution Television System	2	--[f]	1	--	--	--	--
Shielded Vehicle With Manipulators, Exchangeable Tools, Scooploader, etc.	1	50.0	5	10.0	7.5	17.5	32.5
Underwater Lights and Viewing Windows	as required	5.0	5	1.0	0.8	1.8	3.2
Submersible Pump With Disposable Filter Cartridges	5	7.5	2	3.8	1.1	4.9	2.6
Assorted Underwater Tools	as required	25.0	1	25.0	--	25.0	--
Hydraulic Concrete-Surface Spalling Device	4	20.0	2	10.0	3.0	13.0	7.0
Concrete Drill, Electric/Pneumatic Hammer	4	2.0	2	1.0	0.3	1.3	0.7
Portable Filtered Ventilation Enclosure	4	6.0	1	6.0	--	6.0	--
Supplied-Air Bubble Suit	200	10.0	1	10.0	--	10.0	--
Safety Nets	5	25.0	2	12.5	3.8	16.3	8.7
Blasting Mats	10	5.0	2	2.5	0.8	3.3	1.7
Electropolishing Decontamination Unit	1	100.0	--[g]	--	--	--	100.0
Totals		821.5		438.0	57.2	495.2	326.3

(a) Based on information presented in Table 10.1-7 of Reference 1.
(b) Assumes adequate maintenance and decontamination.
(c) Rounded to the nearest $100.
(d) Based on an assumed effective rate of 5% of total capital cost per year over the 3-year decommissioning schedule.
(e) Modification of existing plant equipment, not reusable at other reactors.
(f) Existing plant equipment.
(g) Assumed to be included in centralized decontamination services, see Section B.4.3.

B.4.1.2 PWR SAFSTOR

The costs for special tools and equipment for the first phase of SAFSTOR (preparations for safe storage) at a PWR are presented in Table B.4-2. Shown are costs both with and without decontamination and reuse, and net savings with reuse are also included. About $27,000 is required without reuse as compared to only about $13,000 with reuse, resulting in net savings per decommissioning cycle (with reuse) of about $14,000, or almost 52% of the total capital cost of the items.

No significant expenditures for tools and equipment are required during the continuing care period and, therefore, no significant cost savings are anticipated and no calculations are performed here.

The cost for special tools and equipment for deferred decontamination is $60,000 less than that for DECON ($75,000 less with 25% contingency included, see Table H.5-2 of Reference 1); thus, the total cost is $761,500. However, no details are given concerning the specific items involved. Assuming the special tools and equipment required for deferred decontamination are essentially the same as those required for DECON, the same percentage savings should apply to both cases. Using the 40% savings derived in Section B.4.1.1, the total cost per decommissioning project is estimated to be about $457,000 and the resulting net savings are nearly $305,000.

Overall costs for special tools and equipment during PWR SAFSTOR are thus nearly $790,000 without reuse as compared to about $470,000 with reuse, resulting in net savings of almost $320,000 with decontamination, maintenance, and reuse of these items.

B.4.1.3 PWR ENTOMB

Table 4.5-1 of Reference 2 shows the costs for special tools and equipment during PWR entombment to be the same as those during DECON. Thus, the results for ENTOMB are assumed to be the same as those presented previously in Table B.4-1, based on the assumption that the actual items involved in the two cases are essentially the same.

TABLE B.4-2. Costs for Special Tools and Equipment for PWR Preparations for Safe Storage

Item	Estimated Number Required[a]	Estimated Total Costs ($ thousands)[a]	Estimated Useful Lifetime (Number of Decommissionings)[b]	Cost/Decommissioning With Reuse ($ thousands)[c] Capital	Decontamination and Maintenance[d]	Total	Net Cost Savings/Decommissioning with Reuse ($ thousands)[c]
Portable Oxyacetylene Cutting Torch	2	2.0	2	1.0	0.1	1.1	0.9
Guillotine Pipe Saw	2	8.0	5	1.6	0.5	2.1	5.9
Closed-Circuit, High-Resolution Television System	2	--[e]	1	--	--	--	--
Submersible Pump With Disposable Filter Cartridges	2	3.0	2	1.5	0.2	1.7	1.3
Hydraulic Concrete-Surface Spalling Device	1	5.0	2	2.5	0.3	2.8	2.2
Concrete Drill, Electric/Pneumatic Hammer	1	0.5	2	0.3	<0.1	0.3	0.2
Portable Filtered Ventilation Enclosure	1	1.5	1	1.5	--	1.5	--
Supplied-Air Bubble Suit	50	2.5	1	2.5	--	2.5	--
Safety Nets	1	5.0	5[f]	1.0	0.3	1.3	3.7
Totals		27.5		11.9	1.4	13.3	14.2

(a) Based on information presented in Table 10.2-6 of Reference 1.
(b) Assumes adequate maintenance and decontamination.
(c) Rounded to the nearest $100.
(d) Based on the assumed effective rate of 5% of total capital cost per year over the 16-month decommissioning schedule.
(e) Existing plant equipment.
(f) Revised upward to reflect short time of use for this decommissioning alternative.

B.4.1.4 BWR DECON

For BWR DECON at a 10-reactor station, the costs for special tools and equipment, both with and without decontamination and reuse, are presented in Table B.4-3. Also included in the table are the net cost savings resulting from decontamination and reuse of these items. The total cost of the items is ∿$2.02 million without reuse as compared to ∿$850,000 with reuse. Thus, reuse results in net savings of nearly $1.17 million per decommissioning project, or about 58% of the total capital cost.

B.4.1.5 BWR SAFSTOR

At a BWR, the costs for special tools and equipment for preparations for safe storage, the initial phase of SAFSTOR, are presented in Table B.4-4. Costs both with and without decontamination and reuse are included, as are net savings resulting from reuse. About $350,000 is required without reuse as compared to about $150,000 with reuse. Net savings per decommissioning project with reuse are almost $200,000, or about 56% of the total capital cost.

As discussed previously for PWR SAFSTOR, no significant expenditures for tools and equipment are required for continuing care and, thus, no estimates of savings are calculated here.

The costs for special tools and equipment for deferred decontamination, from Table J.7-2 of Reference 3, are $1.728 million. Again, as for deferred decontamination of the PWR, no specifics are provided on the items involved. Assuming the items required are essentially the same as those for DECON, the same percentage savings (58%, see Section B.4.1.4) should apply. Thus, the costs for special equipment and materials with reuse are about $730,000 and the net savings are about $1.00 million.

Overall costs for special tools and equipment during BWR SAFSTOR are thus almost $2.08 million without reuse as compared to less than $880,000 with reuse, resulting in net savings of nearly $1.20 million with decontamination, maintenance, and reuse of these items.

TABLE B.4-3. Costs for Special Tools and Equipment for BWR DECON and ENTOMB

Item	Estimated Number Required[a]	Estimated Total Costs ($ thousands)[a]	Estimated Useful Lifetime (Number of Decommissionings)[b]	Cost/Decommissioning With Reuse ($ thousands)[c] Capital	Decontamination and Maintentance[d]	Total	Net Cost Savings/ Decommissioning with Reuse ($ thousands)[c]
Underwater Manipulator	1	1000	5	200.0	175.0	375.0	625.0
Underwater Plasma-Arc Torch	2	40	5	8.0	7.0	15.0	25.0
Underwater Oxyacetylene Torch	2	10	2	5.0	1.8	6.8	3.2
Arc Saw	1	100	5	20.0	17.5	37.5	62.5
Portable Plasma-Arc Torch	2	40	5	8.0	7.0	15.0	25.0
Portable Oxyacetylene Torch	10	10	2	5.0	1.8	6.8	3.2
Remote-Controlled Oxyacetylene Torch	4	20	2	10.0	3.5	13.5	6.5
Guillotine Pipe Saw	10	40	5	8.0	7.0	15.0	25.0
Power-Operated Reciprocating Hacksaw	10	5	5	1.0	0.9	1.9	3.1
Closed-Circuit, High-Resolution Television	2	15	1[e]	15.0	--	15.0	--
Underwater Lights and Periscopes	as required	5	5	1.0	0.9	1.9	3.1
Underwater Tools	as required	25	1	25.0	--	25.0	--
Submersible Pump With Disposable Filter	5	5	2	2.5	0.9	3.4	1.6
High-Pressure Water Jet	2	40	2	20.0	7.0	27.0	13.0
Pipe Jumper	4	3	1[f]	3.0	--	3.0	--
Mobile Chemical Decontamination Unit	5	100	5	20.0	17.5	37.5	62.5
Mobile Chemical Mixing and Heating Unit	4	10	5	2.0	1.8	3.8	6.2
Scaffolding	200	10	5	2.0	1.8	3.8	6.2
Safety Nets	as required	25	2	12.5	4.4	16.9	8.1
Power-Operated, Mobile, Scissors-Type Manlift	6	192	5	38.4	33.6	72.0	120.0
Power-Operated, Mobile, Articulated-Arm Manlift	3	27	5	5.4	4.7	10.1	16.9
9100-kg Mobile Hydraulic Crane	3	60	5	12.0	10.5	22.5	37.5
9100-kg Forklift	6	80	5	16.0	14.0	30.0	50.0
Rigging Materials (e.g., Chokers, Grapples, Winches)	as required	25	2	12.5	4.4	16.9	8.1
Concrete Drill With HEPA-Filtered Dust Collecting System	4	8	2	4.0	1.4	5.4	2.6
Concrete Surface Spaller	4	20	2	10.0	3.5	13.5	6.5
Front-End Loader (Highly Maneuverable, Light-Duty)	3	30	5	6.0	5.3	11.3	18.7
Vacuum Cleaner (HEPA-Filtered)	3	15	5	3.0	2.6	5.6	9.4
Portable Ventilation Enclosure	10	15	1	15.0	--	15.0	--
Supplied-Air Plastic Suit	250	15	1	15.0	--	15.0	--
Filtered-Exhaust Fan Unit	4	16	5	3.2	2.8	6.0	10.0
Polyurethane Foam Generator	2	10	5	2.0	1.8	3.8	6.2
Totals		2016		510.5	340.4	850.9	1165.1

(a) Based on information presented in Table I.3-9 of Reference 3.
(b) Assumes adequate maintenance and decontamination.
(c) Rounded to the nearest $100.
(d) Based on an assumed effective rate of 5% of total capital cost per year over the 3-1/2-year decommissioning schedule.
(e) Modification of existing plant equipment, not reusable at other reactors.
(f) Designed specifically for individual plant, not reusable.

TABLE B.4-4. Costs for Special Tools and Equipment for BWR Preparations for Safe Storage

Item	Estimated Number Required[a]	Estimated Total Costs ($ thousands)[a]	Estimated Useful Lifetime (Number of Decommissionings)[b]	Cost/Decommissioning With Reuse ($ thousands)[c]			Net Cost Savings/Decommissioning with Reuse ($ thousands)[c]
				Capital	Decontamination and Maintentance[d]	Total	
Portable Oxyacetylene Torch	2	1.0	2	0.5	0.1	0.6	0.4
Guillotine Pipe Saw	2	8.0	5	1.6	1.0	2.6	5.4
Power-Operated Reciprocating Hacksaw	2	1.0	5	0.2	0.1	0.3	0.7
Closed-Circuit, High-Resolution Television	1	7.5	1[e]	7.5	--	7.5	--
Submersible Pump with Disposable Filter	5	5.0	2	2.5	0.6	3.1	1.9
High-Pressure Water Jet	2	40.0	2	20.0	5.0	25.0	15.0
Low-Pressure Water Jet	1	15.0	2	7.5	1.9	9.4	5.6
Pipe Jumper	4	3.0	1[f]	3.0	--	3.0	--
Mobile Chemical Decontamination Unit	5	100.0	5	20.0	12.5	32.5	67.5
Mobile Chemical Mixing and Heating Unit	4	10.0	5	2.0	1.3	3.3	6.7
Scaffolding	50	2.5	5	0.5	0.3	0.8	1.7
Safety Nets	as required	10.0	2	5.0	1.3	6.3	3.7
Power-Operated, Mobile, Scissors-Type Manlift	2	64.0	5	12.8	8.0	20.8	43.2
Power-Operated, Mobile, Articulated-Arm Manlift	1	9.0	5	1.8	1.1	2.9	6.1
9100-kg-Capacity Forklift	1	13.3	5	2.7	1.7	4.4	8.9
Rigging Materials (e.g., Chockers, Grapples, Winches)	as required	5.0	2	2.5	0.6	3.1	1.9
Concrete Drill with HEPA-Filtered Dust Collecting System	1	2.0	2	1.0	0.3	1.3	0.7
Concrete Surface Spaller	1	5.0	2	2.5	0.6	3.1	1.9
Front-end Loader (Highly Maneuverable, Light-Duty)	1	10.0	5	2.0	1.3	3.3	6.7
Vacuum Cleaner (HEPA-Filtered)	3	15.0	5	3.0	1.9	4.9	10.1
Portable Ventilation Enclosure	3	4.5	1	4.5	--	4.5	--
Supplied-Air Plastic Suit	100	6.0	1	6.0	--	6.0	--
Polyurethane Foam Generator	2	10.0	5	2.0	1.3	3.3	6.7
Paint Sprayer	4	4.0	5	0.8	0.5	1.3	2.7
Totals		350.8		111.9	41.4	153.3	197.5

(a) Based on information presented in Table J.5-6 of Reference 3.
(b) Assumes adequate maintenance and decontamination.
(c) Rounded to the nearest $100.
(d) Based on an assumed effective rate of 5% of total capital cost per year over the 2-1/2-year decommissioning schedule.
(e) Modification of existing plant equipment, not reusable at other reactors.
(f) Designed specifically for individual plant, not reusable.

B.4.1.6 BWR ENTOMB

For BWR entombment with the reactor vessel internals removed, the special tools and equipment required are assumed to be the same as for DECON, as stated on p. K-29 of Reference 3. Thus, the results for ENTOMB are the same as those presented previously in Table B.4-3.

B.4.2 Mobile Chemical Decontamination Equipment

Mobile chemical decontamination equipment is postulated in the BWR study[3] to be used for in-situ decontamination of piping and components during decommissioning by any of the three alternatives. However, such equipment is not discussed in the PWR study.[1] The costs of using such equipment for PWR decommissioning are estimated here 1) to provide a common basis between PWR and BWR decontamination activities and 2) because such equipment is judged to provide additional benefits in terms of ease of decontamination, better control of the process, and more consistent conditions and, consequently, more consistent results.

For the BWR study, five mobile chemical decontamination units, estimated to cost $20,000 each, are assumed to be used. In addition, four mobile chemical mixing and heating units, costing $2,500, are postulated to be required. (See Tables I.3-9 and J.5-6 of Reference 3.) It is assumed here that the same number of units would be used for PWR decontamination work.

Assuming proper maintenance and decontamination of the units, the costs of the units would not have to be borne by a single reactor. In Tables B.4-3 and B.4-4 presented previously, it is assumed that such units will last for the decommissioning of five reactors. Applying the same assumptions to PWR decommissioning, the estimated costs of these units are presented in Table B.4-5. The total costs with reuse are $38,500 for DECON or ENTOMB and $29,300 for preparations for safe storage. It should be noted that, although these are additional costs not included in the PWR study, the incremental cost is relatively small and reuse of the units results in large (65 to 75%) savings over one-time use at a single reactor.

B.4.3 Central Electropolishing and Chemical Decontamination Facility

A central electropolishing and chemical decontamination facility could be used to reclaim piping, valves, and other plant components for reuse or salvage,

TABLE B.4-5. Costs for Mobile Chemical Decontamination Equipment for PWR Decommissioning

Decommissioning Alternative	Estimated Total Capital Cost ($ thousands)[a]	Estimated Useful Lifetime (No. of Decommissionings)[b]	Cost/Decommissioning with Reuse ($ thousands)[c] Capital	Maintenance[d]	Total	Savings/ Decommissioning ($ thousands)
DECON/ENTOMB	110.0	5	22.0	16.5	38.5	71.5
SAFSTOR[e]	110.0	5	22.0	7.3	29.3	80.7

(a) From Table I.3-9 and Table J.5-6 of Reference 3.
(b) Assumes adequate maintenance.
(c) Rounded to the nearest $100.
(d) Based on assumed average rate of 5% of capital cost per year; assumes a 3-year decommissioning schedule for DECON or ENTOMB and a 16-month schedule for preparations for safe storage.
(e) Chemical decontamination equipment used only during preparations for safe storage.

reducing both the net cost of decommissioning and the volume of waste requiring disposal. Electropolishing could also be used during construction to polish component surfaces before installation to reduce the subsequent rate of contamination buildup, thus reducing occupational radiation doses and costs for both operations and decommissioning.[10]

An electropolishing facility sized to provide adequate capacity to handle construction, operation, and decommissioning of a single-unit reactor station is described in Section 11 of Reference 4. The information in the reference is used as a basis for the analysis presented in this study; major differences are:

- The facility size is increased somewhat in this analysis to allow for occasional increased demands for the facility services from the 10 reactors onsite.
- Chemical decontamination facilities are included here to provide more complete capability.
- Portable electropolishing equipment is also postulated to be included here for in-situ decontamination of plant components.

The costs and potential savings associated with a central electropolishing and chemical decontamination facility are estimated here.

B.4.3.1 Facility Costs

For this study, it is assumed that the central electropolishing and chemical decontamination facility is housed in a building measuring about 27 m by 37 m in plan, with $\sim$1000 m^2 of space. Using an assumed cost of $\$1080/m^2$ as given on page 11-3 of Reference 4, the structure's capital cost is $1.08 million. A permanently installed electropolishing unit (polishing and rinsing tanks, electrical supply equipment, and controls) capable of handling components up to about 6 m long and 2 m in diameter is estimated to cost an additional $500,000. Chemical decontamination facilities and a portable electropolishing unit for in-situ work are assumed to add $250,000 and $50,000, respectively, to bring the total capital cost of the facility to $1.88 million.

It is anticipated that all of the electropolishing required during the decommissioning of a single reactor could be performed in 1 year of actual facility operation. Using an assumed rate of 10% of total capital cost per year, maintenance and operation of the facility are estimated to cost $188,000 per decommissioning cycle.

The total facility cost per decommissioning cycle is the capital cost attributable to decommissioning plus the operation and maintenance cost. For this analysis, it is assumed that the facility is used both during reactor construction and operation as well as during decommissioning. Thus, it is assumed that decommissioning bears 25% of the capital cost. The capital cost per decommissioning cycle at a 10-reactor site is therefore $47,000 and the total facility cost per decommissioning is $235,000.

B.4.3.2 Potential Cost Savings

Significant cost savings would result from cleaning contaminated (but nonactivated) stainless steel components to unrestricted release levels, thus permitting either salvage as scrap or refurbishment and eventual reuse of components.

The savings resulting from electropolishing and salvage of stainless steel are two-fold. The material does not require disposal as radioactive waste, eliminating the costs for packaging, shipping, and burial. In addition, the metal can be sold as scrap for further savings. On page 10-3 of Reference 1, the eliminated cost of disposal and the salvage value are estimated at ∿74¢/kg and ∿60¢/kg F.O.B. at the site, respectively, yielding total savings of $1.34/kg of stainless steel electropolished to unrestricted release levels.

For the PWR decommissioning, it is estimated that there is over 0.91 million kg of potentially salvageable stainless steel removed from the facility (see p.10-3 of Reference 1). Assuming that 20% of this material is of complex geometry and would be extremely difficult to survey for release, a total of 80% of the material (∿0.73 million kg) is anticipated to be salvaged. At $1.34/kg, this yields a savings of ∿$975,000. Subtracting the costs for retirement of capital and for facility operation and maintenance ($235,000, from Section B.4.3.1), the net savings for PWR decommissioning are $740,000.

A BWR contains much less stainless steel than a PWR and, consequently, the potential for salvage is considerably lower. Table B.4-6 shows the contaminated stainless steel equipment outside the primary containment vessel of the reference BWR. The total mass of this equipment is about 115,000 kg. In addition, the pool liners are potentially salvageable. Only the spent fuel storage pool and the dryer and separator pool are included in this analysis; not considered are the reactor well pool cavity liner, because of its relatively small area and higher contamination levels, and the spent fuel storage racks, because their composite structure would make salvage very difficult. The spent fuel storage pool has two cavities, the main cavity and the shipping cask storage area. The dimensions of these two cavities (from Figure C.3-5 of Reference 3 and Figure 3.8-34 of Reference 11) are:

- main cavity - 12.2 m by 10.4 m by 11.8 m deep
- shipping cask storage area - 3.0 m by 3.0 m by 4.5 m deep.

Based on these dimensions, the liner floor area and the lined wall area of the spent fuel storage pool are 126.9 m^2 and 587.4 m^2, respectively, for a total liner surface area in the pool of 714.3 m^2. The dryer and separator pool has dimensions (from Figure 3.8-35 of Reference 11) of 12.6 m by 12.2 m by 7.6 m deep. Thus, the lined floor and wall areas of the dryer and separator pool are

TABLE B.4-6. Mass of Contaminated Stainless Steel Equipment Outside Primary Containment Vessel of the Reference BWR

EKN[a]	Equipment Item/Quantity	Mass, Each (kg)	Total Mass (kg)	Reference
--	Piping, Reactor Building	--	25 368	(b)
--	Piping, Turbine Generator Building	--	7 895	(b)
--	Piping, Radwaste and Control Building	--	16 667	(b)
308	Chemical Waste Tank/2	5 030	10 060	(c)
309	Distillate Tank/2	5 030	10 060	(c)
331	Concentrator Feed Pump/2	254	508	(c)
332	Chemical Waste Pump/2	479	958	(c)
333	Distillate Tank Pump/2	231	462	(c)
334	Detergent Drain Pump/2	175	350	(c)
386	Decontamination Solution Concentrator/2	3 409	6 818	(c)
435	Decon. Solution Conc. Bottoms Recycle Pump/2	844	1 688	(c)
302	Condensate Phase Separator Tank/2	3 182	6 364	(d)
304	Condensate Backwash Receiver Tank/1	6 920	6 920	(d)
320	Condensate Sludge Discharge Mixing Pump/1	420	420	(d)
321	Condensate Decant. Pump/1	420	420	(d)
322	Condensate Backwash Transfer Pump/1	420	420	(d)
305	Spent Resin Tank/1	658	658	(d)
327	Spent Resin Pump/1	102	102	(d)
306	Waste Sludge Phase Separator Tank/1	5 497	5 497	(d)
328	Waste Decant Pump/1	102	102	(d)
330	Waste Sludge Discharge Mixing Pump/1	288	288	(d)
311	Decon. Solution Conc. Waste Tank/2	712	1 424	(d)
335	Decon. Solution Conc. Waste Pump/1	254	254	(d)
408	Concentrator Waste Measuring Tank/1	386	386	(d)
379	Hopper Mixer/2	2 727	5 454	(d)
380	Waste Processing Pump/1	136	136	(d)
409	Centrifuge/2	454	908	(d)
307	Cleanup Phase Separator Tank/2	2 041	4 082	(d)
329	Cleanup Decant Pump/1	102	102	(d)
337	Cleanup Sludge Discharge Mixing Pump/1	284	284	(d)
	Total		115 055	

(a) EKN = Equipment Key Number.
(b) Table C.3-11 of Reference 3.
(c) Table C.5-1 and Table C.3-6 of Reference 3.
(d) Table C.5-3 and Table C.3-6 of Reference 3.

153.7 m^2 and 377.0 m^2, respectively, for a total liner area in this pool of 530.7 m^2. For the two pools, the lined area is 1245.0 m^2 and, at a thickness of 0.0064 m (see p. C-62 of Reference 3), the total solid volume of the liners is 7.97 m^3. At a density of $\sim$8030 kg/m^3 (0.29 lb/in^3, from p. 23-39 of Reference 12), the total mass of stainless steel in the two pool liners is about 64,000 kg. Thus, the total salvageable stainless steel in the BWR is estimated to be about 179,000 kg. Assuming as before, for the PWR, that 80% of the material is recovered at a savings of $1.34/kg, savings are estimated at $\sim$$192,000.

The large quantities of carbon steel in equipment, piping, and valves in the BWR have a low salvage value, $\sim$5.5¢/kg; however, the elimination of disposal costs of $\sim$74¢/kg makes it cost effective to decontaminate this material, giving a savings of 79.5¢/kg. In Table C.3-11 of Reference 3, the mass of contaminated carbon steel piping and valves is given as 435,000 kg. Assuming that 80% of the carbon steel is salvaged at a savings of 79.5¢/kg, the savings are estimated to be $\sim$$280,000.

Total savings from salvaging the stainless and carbon steel are $472,000, which results in a net savings of $237,000 per BWR decommissioning.

The estimated costs and potential cost savings resulting from use of the central electropolishing facility during decommissioning are summarized in Table B.4-7. It should be noted that the estimates presented do not include savings that would result from recovery and refurbishment of components for eventual reuse. However, such recovery and refurbishment is desirable where appropriate and is likely to result in incremental cost savings. The recovery of even a small percentage of the stainless steel valves in the plant being decommissioned would yield considerable additional savings, even assuming that refurbishment of these valves would cost an average of 50% of their replacement costs. (Valve reconditioning typically costs less than 50% of new-valve cost.)[13]

TABLE B.4-7. Estimated Costs and Potential Cost Savings Associated with Use of a Central Electropolishing Facility During Decommissioning

Type of Reactor	Facility Costs/Decommissioning ($ thousands)[a] Capital[b]	Operation and Maintenance[c]	Total	Net Recovery Value of Stainless Steel ($ thousands)[a,d]	Net Cost Savings/ Decommissioning ($ thousands)[a]
PWR	47	188	235	975[e]	740
BWR	47	188	235	472[f]	237

(a) Rounded to the nearest $1000.
(b) Based on a facility cost of $1,880,000, 25% of which is assumed to be charged to decommissioning, with 10 reactors at the site.
(c) Assumed to be 10% of total capital cost/year; electropolishing associated with decommissioning estimated to be completed in 1 year.
(d) Based on $0.60/kg salvage value for stainless steel and $0.74/kg disposal cost, for a net recovery value of $1.34/kg (see p. 10-3 of Reference 1). Carbon steel has a salvage value of $0.055/kg to give a net recovery value of $0.795/kg.
(e) Based on 80% recovery of 910,000 kg potentially recoverable stainless steel.
(f) Based on 80% recovery of 179,000 kg potentially recoverable stainless steel and 435,000 kg of potentially recoverable carbon steel.

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APPENDIX C

OCCUPATIONAL DOSES FROM INTERIM ONSITE NUCLEAR WASTE STORAGE

The purpose of this appendix is to estimate the occupational doses associated with the placement of decommissioning wastes in and the retrieval of decommissioning wastes from an onsite interim waste storage facility. It is assumed that such a facility will be designed to: minimize occupational doses, provide safe and secure storage for up to 100 years, and permit safe retrieval of radioactive materials for relocation offsite. Doses are estimated for the highly radioactive neutron-activated reactor components and the combined contaminated and radwaste materials removed from both a reference PWR and a reference BWR. This analysis is not intended to result in an "exact" solution; however, the resulting doses are intended to be an estimate (based on key assumptions) that will be useful in the comparative analysis. Much of the occupational dose analysis discussed here is based on the results of previous studies in this series.[1-3]

C.1 NEUTRON-ACTIVATED REACTOR COMPONENTS

A list of the number of waste containers required for neutron-activated reactor components from the PWR and the BWR is given in Table C.1-1. This table shows the number of waste containers required for DECON, SAFSTOR, and ENTOMB, as well as the average radioactivity per container.

Occupational doses from waste burial are estimated using the work descriptions and dose rates discussed in Reference 3. Table C.1-2 contains the estimated occupational doses and data per canister of waste for burial of 1-year-old neutron-activated (slit trench) waste. The dose rates in this table are based on 5000 Ci per waste container, and are reduced by an order of magnitude as an assumed facility design shielding factor. This is not an unreasonable assumption since a simple calculation indicates that less than 0.4 m of concrete will reduce the dose rate of 1.0-MeV gamma rays by an order of magnitude.

For the BWR, values from Table C.1-1 indicate that each canister contains about four times more radioactivity than the 5000 Ci assumed in Table C.1-2. Using the dose versus contamination level relationship shown in Figure E.2-4 of

TABLE C.1-1. Waste Containers Required for Neutron-Activated Reactor Components

	Number of Containers Required					Average Radioactivity per Container (Ci/Container)
		SAFSTOR Deferred Decontamination				
Reactor	DECON	30 Yr	50 Yr	100 Yr	ENTOMB	
	Containers to Interim Storage					
BWR	311	311	311	311	275	2.1×10^4
PWR	365	365	365	365	88	1.3×10^4
	Containers to Offsite Disposal					
BWR	311	311	311	311	275	2.1×10^4
PWR	365	365	365	365	88	1.3×10^4

Reference 2, increasing radioactivity content by a factor of 4 increases the surface dose rate by a factor of about 2.6. This lower increase in the dose than the increase in radioactivity content is due to self-shielding of the material involved. For the PWR, a similar analysis indicates that the dose rate will increase by a factor of about 1.7. If these dose rate correction factors are applied to the dose per canister value from Table C.1-2 and if the resulting corrected dose rate is multiplied by the number of containers of waste handled for each decommissioning option, the total occupational doses are estimated. The time dependence of the burial doses for neutron-activated components is shown in Figure C.1-1 for the PWR and in Figure C.1-2 for the BWR. The shapes of these curves are based on the dose rate curves shown for the PWR in Figure 7.4-1 of Reference 1 (p. 7-39) and for the BWR in Figure E.1-6 of Reference 2 (p. E-23).

Occupational doses from neutron-activated component waste retrieval operations are estimated in a manner similar to that used for waste burial. Table C.1-3 gives the estimated occupational doses per container of waste for the relocation of 30-year-old neutron-activated (slit trench) waste. The dose rates and data shown are directly from Reference 3 (Table I.2-1, p. I-32) without the inclusion of a facility design shielding factor. If the same self-shielding dose correction factor developed for PWR and BWR waste burial is used along with the canister requirements, occupational waste retrieval doses can be calculated. The time dependence of the neutron-activated component

TABLE C.1-2. Occupational Doses and Data per Container for Slit Trench Waste Disposal - 1-Year-Old Waste[a]

Operation	Personnel/Number	Personnel Location	Exposure Time per Container (hr)	Dose Rate at Location (rem/hr)	Dose at Location per Worker (rem)	Total Dose per Worker (rem)	Total Dose per Category (man-rem)
Waste Unloading and Disposal	Foreman (1)	4 m (Skyshine)	1	4.0×10^{-5}	4.0×10^{-5}	4.0×10^{-5}	4.0×10^{-5}
	Laborers (2)	0.3 m from Cask	0.25	2.0×10^{-1}	5.0×10^{-2}		
		1 m from Cask	0.25	1.0×10^{-2}	2.5×10^{-3}		
		4.m (Skyshine)	1	4.0×10^{-5}	4.0×10^{-5}	5.2×10^{-2}	1.0×10^{-1}
	Equipment Operator (2)	10 m from Container plus 0.4 m Concrete	0.25	8.2×10^{-2}	2.0×10^{-2}		
		4 m (Skyshine)	1	4.0×10^{-5}	4.0×10^{-5}	2.0×10^{-2}	4.0×10^{-2}
	Health Physics Tech. (1)	4 m (Skyshine)	1	4.0×10^{-5}	4.0×10^{-5}		
		5 m from Container plus 0.4 m Concrete	0.083	3.3×10^{-1}	2.7×10^{-2}	2.7×10^{-2}	2.7×10^{-2}
Cover and Overburden Placement	Equipment Operator (1)	2 m above Trench plus 80 mm Steel	18[b]	2.0×10^{-6}[b]	--[c]	--	--
	Health Physics Tech. (1)	1 m over Trench	4.5[b]	2.0×10^{-5}[b]	--	--	--
Total for all Operations	8						1.7×10^{-1}[d]

(a) Based on Table I.2-1 from Reference 3, with dose rates corrected to 1 year of radioactive decay, for burial of 1 container of waste. Note: 40 cm of concrete is assumed to reduce the dose rate by at least a factor of 10.
(b) Cover and overburden placement is assumed to take 3 days. The hours and dose rates (in rem/hr) shown are for the entire operation, and are not on a per container basis.
(c) These doses are for the total operation and are less than 1×10^{-4}; thus they are not considered further.
(d) The average dose to one of eight workers is about 21 millirem per container.

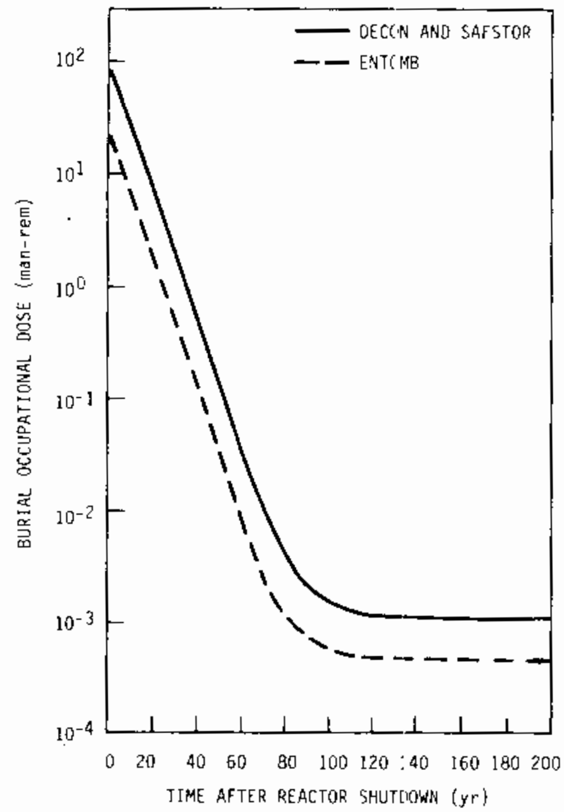

FIGURE C.1-1. Time Dependence of Occupational Dose for Burial of Neutron-Activated PWR Components

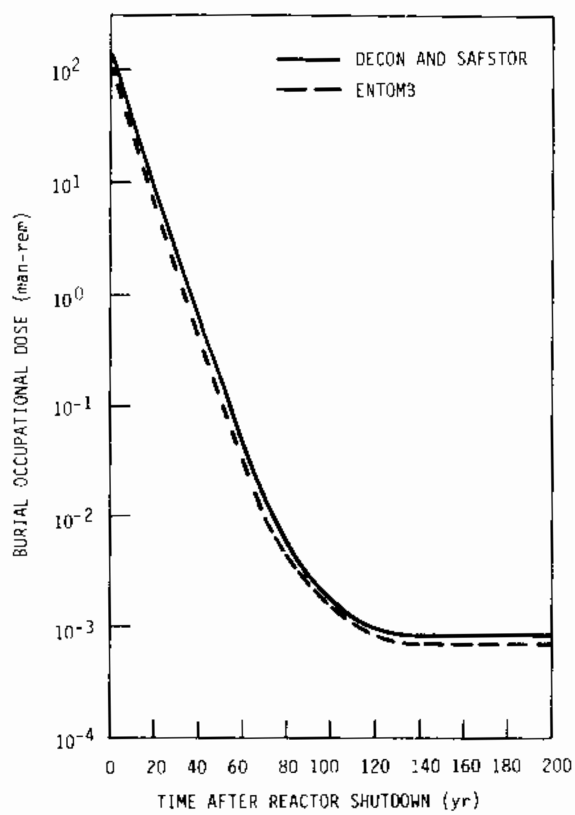

FIGURE C.1-2. Time Dependence of Occupational Dose for Burial of Neutron-Activated BWR Components

TABLE C.1-3. Occupational Doses and Data per Container for Slit Trench Waste Relocation after 30 Years[(a)]

Operation	Personnel/Number	Personnel Location	Exposure Time per Container (hr)	Dose Rate at Location (rem/hr)	Dose at Location per Worker (rem)	Total Dose per Worker (rem)	Total Dose per Category (man-rem)
Overburden and Cover Removal	Equipment Operator (1)	2 m above Trench plus 80 mm Steel	18[(b)]	2.0×10^{-6}[(b)]	--[(c)]	--	--
	Health Physics Tech. (1)	1 m over Trench	4.5[(b)]	2.0×10^{-5}[(b)]	--	--	--
Waste Exhumation and Loading	Foreman (1)	4 m (Skyshine)	1	2.1×10^{-5}	2.1×10^{-5}	2.1×10^{-5}	2.1×10^{-5}
	Equipment Operator (2)	10 m from Canister	0.25	1.8×10^{-2}	4.5×10^{-3}		
		4 m (Skyshine)	1	2.1×10^{-5}	2.1×10^{-5}	4.5×10^{-3}	9.0×10^{-3}
	Laborers (2)	0.3 m from Cask	0.25	4.0×10^{-3}	1.0×10^{-3}		
		1 m from Cask	0.25	2.0×10^{-4}	5.0×10^{-5}		
		4 m (Skyshine)	1	2.1×10^{-5}	2.1×10^{-5}	1.0×10^{-3}	2.0×10^{-3}
	Health Physics Tech. (1)	4 m (Skyshine)	1	2.1×10^{-5}	2.1×10^{-5}		
		5 m from Canister	0.083	7.1×10^{-2}	5.9×10^{-3}	6.0×10^{-3}	6.0×10^{-3}
Total for all Operation	8						1.7×10^{-2}[(d)]

(a) Based on Table I.2-1, Reference 3, with dose rates corrected to 30 years of radioactive decay, for relocation of 1 container of waste.
(b) Overburden and cover removal is assumed to take 3 days. The hours and dose rates (in rem/hr) shown here are for the entire operation, and are not on a per container basis.
(c) These doses are for the total operation and are less than 1×10^{-4}; thus they are not considered further.
(d) The average dose to one of eight workers is about 2 millirem per container.

waste retrieval doses is shown in Figure C.1-3 for the PWR and in Figure C.1-4 for the BWR. Again, the shapes of these curves are based on the dose rate curves shown for the PWR in Figure 7.4-1 of Reference 1 and for the BWR in Figure E.1-6 of Reference 2.

C.2 CONTAMINATED AND RADWASTE MATERIALS

A list of the number of waste containers required for contaminated and radwaste materials from the PWR and BWR for each decommissioning alternative is given in Table C.2-1. Deferred decontamination is assumed to occur at either 30, 50, or 100 years after reactor shutdown, and the wastes are assumed to be held in onsite interim storage for 30, 50, or 100 years. The data show the amount of waste that is estimated to be shipped offsite for each alternative and interim storage period. All of the occupational doses estimated in this section are based on the number of containers required for the DECON and ENTOMB alternatives. All dose rates are based on an average amount of radioactivity per container, corrected for radioactive decay and shielding considerations. No attempt is made to estimate the dose rates from the containers required for all of the SAFSTOR options. Rather, it is assumed that the same quantity of material is involved at an average concentration and that the dose may be obtained from the DECON or ENTOMB time-dependent curves. This assumption simplifies the efforts, and should not result in answers that grossly misrepresent the occupational dose. The doses obtained in this manner are not "exact" solutions, but they are useful in this comparative analysis.

Occupational doses from waste burial are estimated using the work descriptions and dose rates discussed in Reference 3. It is difficult to determine the occupational dose per container; thus the doses are calculated based on the time it takes to bury all the waste associated with the BWR. Doses for the PWR are found by direct ratio of the waste volumes involved for the two types of reactors.

Table C.2-2 contains the estimated occupational doses and data for burial of 1-year-old BWR wastes. The BWR waste will fill about 1.5 reference trenches (defined in Reference 3); thus the exposure times shown have been increased by a factor of 1.5. The dose rates from Table I.2-3 of Reference 3 have been

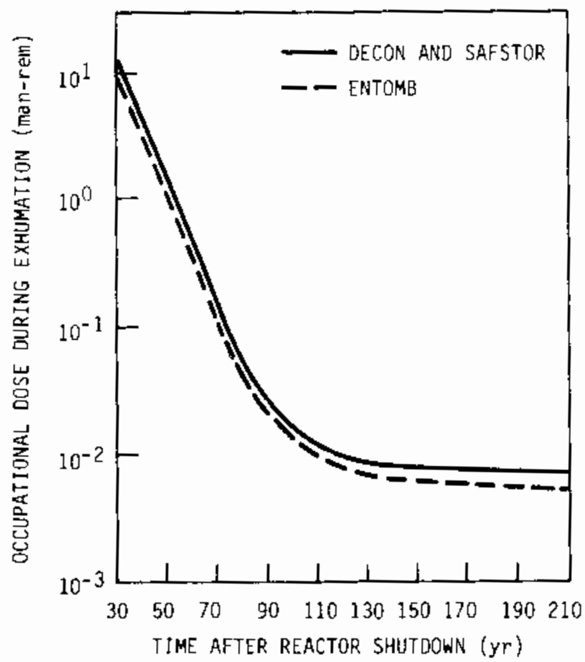

FIGURE C.1-3. Time Dependence of Occupational Dose for Retrieval of Neutron-Activated PWR Components

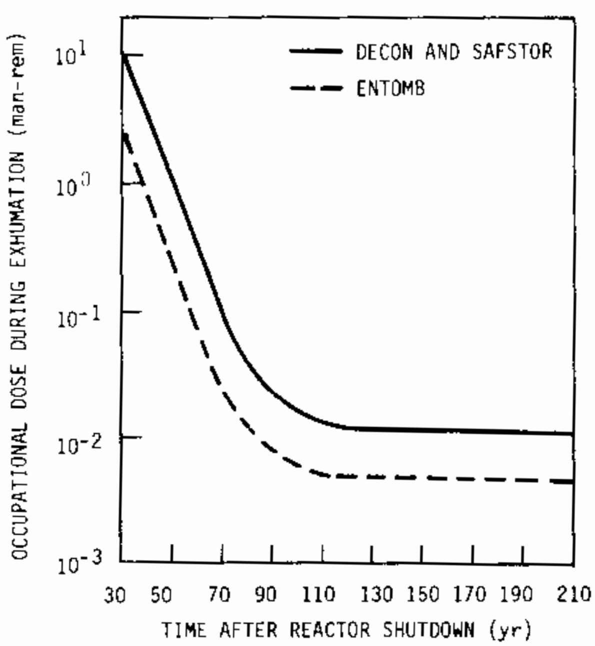

FIGURE C.1-4. Time Dependence of Occupational Dose for Retrieval of Neutron-Activated BWR Components

TABLE C.2-1. Waste Container Requirements for Contaminated and Radwaste Materials

Reactor/Age	Number of Containers Required				
		SAFSTOR			
		Deferred Decontamination			
	DECON	30 Yr	50 Yr	100 Yr	ENTOMB
	Containers to Interim Storage				
BWR	7.4×10^3	7.4×10^3	1.7×10^3	1.2×10^3	4.8×10^3
PWR	5.7×10^2	5.7×10^3	7.4×10^2	5.1×10^2	2.0×10^3
	Containers to Offsite Disposal				
BWR					
30 Yr	6.4×10^3	2.5×10^3	1.4×10^3	1.0×10^3	3.7×10^3
50 Yr	1.5×10^3	1.4×10^3	1.2×10^3	9.2×10^2	1.5×10^3
100 Yr	1.0×10^3	1.0×10^3	9.2×10^2	7.8×10^2	9.7×10^2
PWR					
30 Yr	5.5×10^3	7.4×10^2	5.1×10^2	3.8×10^2	1.8×10^3
50 Yr	4.2×10^2	5.1×10^2	5.1×10^2	3.1×10^2	4.0×10^2
100 Yr	1.9×10^2	3.8×10^2	3.0×10^2	2.5×10^2	1.6×10^2

reduced by a factor of 10 as an assumed facility design shielding factor, the same factor used for the neutron-activated reactor component waste disposal analysis. The average waste container radioactivity concentrations for both the PWR and BWR are found to be between 2 and 3 Ci/m^3 for 1-year-old waste. These concentrations are assumed to be equal to the 2.9 Ci/m^3 concentration used for 30-year-old waste in Reference 3. The resulting occupational doses for contaminated and radwaste material burial are shown in Table C.2-2, and the time dependence is shown in Figure C.2-1. The time dependence of the burial occupational doses for the PWR is found by ratio and is shown in Figure C.2-2. The shapes of these curves are based on the total dose curve in Figure E.2-1 of Reference 2.

Occupational doses for waste retrieval are found in a manner similar to that used for waste burial. Table C.2-3 contains occupational doses and data for retrieval of 30-year-old BWR waste. The dose rates and data shown are from Table I.2-3 of Reference 3, corrected for radioactive decay without a facility design shielding factor. Again, the exposure times are increased by a factor of 1.5 since BWR waste will fill 1.5 reference trenches. The time dependence of the occupational doses for retrieving BWR waste is shown by the curves in Figure C.2-3. Similar doses for retrieving PWR wastes are found by ratio of the waste volumes, and are shown in Figure C.2-4. The shapes of these curves are based on the total dose curve in Figure E.2-1 of Reference 2.

TABLE C.2-2. Occupational Doses and Data per BWR for Waste Disposal - 1-Year-Old Waste[(a)]

Operation	Personnel/Number	Personnel Location	Exposure Time per Container (hr)[(b)]	Dose Rate at Location (rem/hr)[(c)]	Dose at Location per Worker (rem)	Total Dose per Worker (rem)	Total Dose per Category (man-rem)
Waste Unloading and Disposal	Foremen (2)	1 m above Ground Surface	189	1.0×10^{-3}	1.9×10^{-1}		
		10 m from Waste Face	189	4.8×10^{-3}	9.1×10^{-1}	1.1×10^{0}	2.2×10^{-0}
	Equipment Operators (8)	1 m above Ground Surface	189	1.0×10^{-3}	1.9×10^{-1}		
		3 m from Waste Face	9.5	2.1×10^{-2}	2.0×10^{-1}		
		5 m from Waste Face	29	1.3×10^{-2}	3.8×10^{-1}		
		10 m from Waste Face	150	4.8×10^{-3}	7.2×10^{-1}	1.5×10^{0}	1.2×10^{1}
	Laborers (8)	1 m above Ground Surface	189	1.0×10^{-3}	1.9×10^{-1}		
		1 m from Waste Face	9.5	3.6×10^{-2}	3.4×10^{-1}		
		2 m from Waste Face	9.5	2.8×10^{-2}	2.7×10^{-1}		
		3 m from Waste Face	20	2.1×10^{-2}	4.2×10^{-1}		
		5 m from Waste Face	57	1.3×10^{-2}	7.4×10^{-1}		
		10 m from Waste Face	94	4.8×10^{-3}	4.5×10^{-1}	2.4×10^{0}	1.9×10^{1}
	Truck Drivers (2)	1 m above Ground	378	1.0×10^{-3}	3.8×10^{-1}	3.8×10^{-1}	7.6×10^{-1}
	Health Physics Tech. (2)	1 m above Ground Surface	189	1.0×10^{-3}	1.9×10^{-1}		
		3 m from Waste Face	20	2.1×10^{-2}	4.2×10^{-1}		
		5 m from Waste Face	20	1.3×10^{-2}	2.6×10^{-1}		
		10 m from Waste Face	94	4.8×10^{-3}	4.5×10^{-1}		
		20 m from Waste Face	57	1.4×10^{-3}	8.0×10^{-2}	1.4×10^{0}	2.8×10^{0}
Overburden/Cover Placement	Equipment Operator (2)	2 m above Trench	27	1.0×10^{-4}	2.7×10^{-3}	2.7×10^{-3}	5.4×10^{-3}
	Health Physics Tech. (1)	1 m above Overburden	4.5	1.0×10^{-3}	4.5×10^{-3}	4.5×10^{-3}	4.5×10^{-3}
Total for all Operations	25						3.7×10^{1}[(d)]

(a) Based on Table I.2-3 of Reference 3 with corrected dose rates and exposure times.
(b) Waste from the BWR fills 1.5 trenches; thus all times from Table I.2-3 are multiplied by 1.5.
(c) Dose rates are reduced by a factor of 10 from those reported in Table I.2-3, assuming dose reduction is achieved through facility design.
(d) The average dose to one of 25 workers is about 1.5 rem.

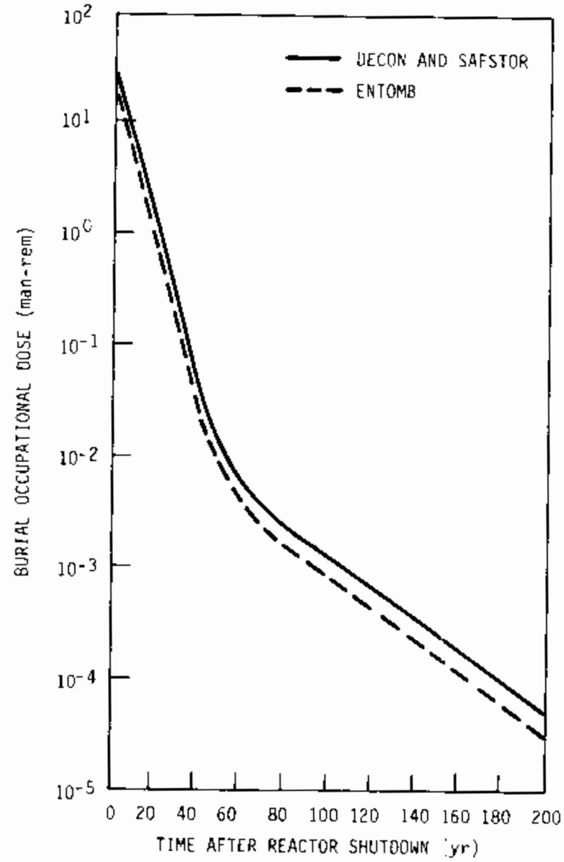

FIGURE C.2-1. Time Dependence of Occupational Dose for Burial of BWR Contaminated Material and Radwaste

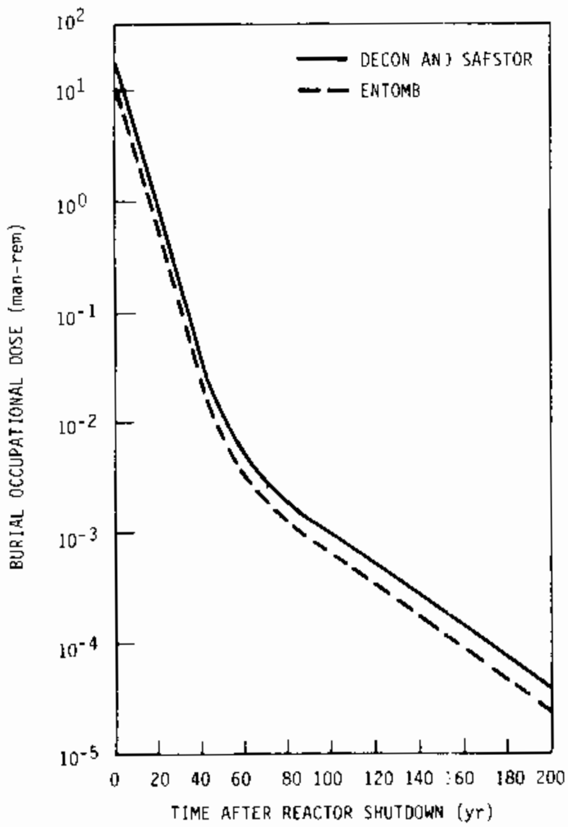

FIGURE C.2-2. Time Dependence of Occupational Dose for Burial of PWR Contaminated Material and Radwaste

TABLE C.2-3. Occupational Doses and Data per BWR for Waste Retrieval - 30-Year-Old Waste[a]

Operation	Personnel/Number	Personnel Location	Exposure Time per Container (hr)[b]	Dose Rate at Location (rem/hr)[c]	Dose at Location per Worker (rem)	Total Dose per Worker (rem)	Total Dose per Category (man-rem)
Overburden/Cover Removal	Equipment Operators (2)	2 m above Trench plus 80 mm of Steel	27	2.0×10^{-5}	5.4×10^{-4}	5.4×10^{-4}	5.4×10^{-4}
	Health Physics Tech. (1)	1 m above Overburden	4.5	2.0×10^{-4}	9.0×10^{-4}	9.0×10^{-4}	9.0×10^{-4}
Waste Retrieval and Loading	Foremen (2)	1 m above Ground Surface	189	2.0×10^{-4}	3.8×10^{-2}		
		10 m from Waste Face	189	9.6×10^{-4}	1.8×10^{-1}	2.2×10^{-1}	4.4×10^{-1}
	Equipment Operators (8)	1 m above Ground Surface	189	2.2×10^{-4}	3.8×10^{-2}		
		3 m from Waste Face	9.5	4.2×10^{-3}	4.0×10^{-2}		
		5 m from Waste Face	29	2.6×10^{-3}	7.5×10^{-2}		
		10 m from Waste Face	150	9.6×10^{-4}	1.4×10^{-1}	2.9×10^{-1}	2.3×10^{0}
	Laborers (8)	1 m above Ground Surface	189	2.0×10^{-4}	3.8×10^{-2}		
		1 m from Waste Face	9.5	7.2×10^{-3}	6.8×10^{-2}		
		2 m from Waste Face	9.5	5.6×10^{-3}	5.3×10^{-2}		
		3 m from Waste Face	20	4.2×10^{-3}	8.4×10^{-2}		
		5 m from Waste Face	57	2.6×10^{-3}	1.5×10^{-1}		
		10 m from Waste Face	94	9.6×10^{-4}	9.0×10^{-2}	4.8×10^{-1}	3.9×10^{0}
	Truck Drivers (2)	1 m above Ground Surface	378	2.0×10^{-4}	7.6×10^{-2}	1.5×10^{-1}	1.5×10^{-1}
	Health Physics Tech. (2)	1 m above Ground Surface	189	2.0×10^{-4}	3.8×10^{-2}		
		3 m from Waste Face	20	4.2×10^{-3}	8.4×10^{-2}		
		5 m from Waste Face	20	2.6×10^{-3}	5.2×10^{-2}		
		10 m from Waste Face	94	9.6×10^{-4}	9.0×10^{-2}		
		20 m from Waste Face	57	2.8×10^{-4}	1.6×10^{-2}	2.8×10^{-1}	5.6×10^{-1}
Total for all Operations	25						7.4×10^{0}[d]

(a) Based on Table I.2-3 of Reference 3 with corrected dose rates and exposure times.
(b) Waste from the BWR fills 1.5 trenches; thus all times from Table I.2-3 are multiplied by 1.5.
(c) Dose rates are reduced by a factor of 50 for 30 years of radioactive decay, from Table E.2-1 of Reference 2.
(d) The average dose to one of 25 workers is about 300 millirem.

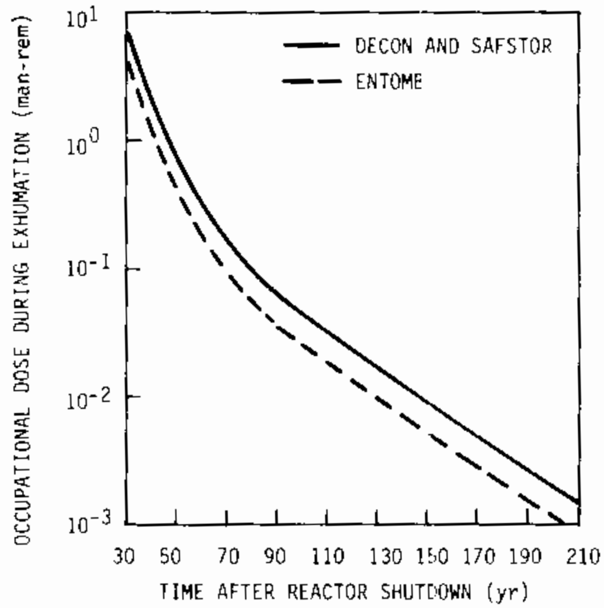

FIGURE C.2-3. Time Dependence of Occupational Dose for Retrieval of BWR Contaminated Material and Radwaste

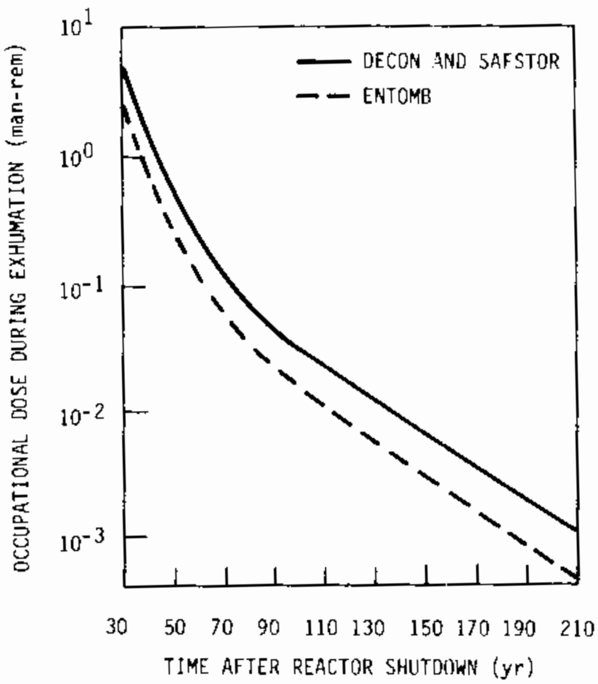

FIGURE C.2-4. Time Dependence of Occupational Dose for Retrieval of PWR Contaminated Material and Radwaste

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Safety and cost information is developed for the conceptual decommissioning of large (1175-MWe) pressurized water reactors (PWR) and large (1155-MWe) boiling water reactors (BWR) at multiple-reactor stations. Three decommissioning alternatives are studied: DECON (immediate decontamination), SAFSTOR (safe storage followed by deferred decontamination), and ENTOMB (entombment). Safety and costs of decommissioning are estimated by determining the impact of probable features of multiple-reactor-station operation that are considered to be unavailable at a single-reactor station, and applying these estimated impacts to the decommissioning costs and radiation doses estimated in previous PWR and BWR decommissioning studies. The multiple-reactor-station features analyzed are: the use of interim onsite nuclear waste storage with later removal to an offsite waste disposal facility, the use of permanent onsite nuclear waste disposal, the dedication of the site to nuclear power generation, and the provision of centralized services.

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