**TECHNOLOGY, SAFETY AND COSTS OF
DECOMMISSIONING A REFERENCE
PRESSURIZED WATER REACTOR
POWER STATION**

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FOREWORD
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The NRC staff is in the process of reappraising its regulatory position relative to the decommissioning of nuclear facilities.⁽¹⁾ As a part of this activity 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 will cover the technology, safety and costs of decommissioning reference nuclear facilities. Light water reactors, fuel cycle facilities and byproduct utilization facilities are included. Facilities of current design on typical sites are selected for the studies. Separate reports will be prepared as the studies of the various facilities are completed.

The first report in this series was published in FY 1977 and covered a fuel reprocessing plant;⁽²⁾ the second was published in FY 1978 and covered a pressurized water reactor;⁽³⁾ the third and fourth of the series were published in FY 1979 and deal with a small mixed oxide fuel fabrication plant⁽⁴⁾ and a low-level waste burial ground.⁽⁵⁾ This report is an Addendum to the report on the pressurized water reactor. It supplements that report by providing information on the technology, safety and costs of the entombment mode

- (1)Plan for Reevaluation of NRC Policy on Decommissioning of Nuclear Facilities. NUREG-0436, Office of Standards Development, U.S. Nuclear Regulatory Commission, March 1978.
- (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 Low-Level Waste Burial Ground. NUREG/CR-0570, Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, 1979.

and on the sensitivity of safety and costs to the power rating of the reactor. Additional topics will be reported on the tentative schedule as follows:

- FY 1979 • Boiling Water Reactor
- FY 1980 • Uranium Fabrication Plant
- Byproduct Utilization Facilities

The second series of studies covers supporting information on the decommissioning of nuclear facilities. Three reports are planned in the second series. The first consists of an annotated bibliography on the decommissioning of nuclear facilities.⁽⁶⁾ The second is a review and analysis of current decommissioning regulations.⁽⁷⁾ The third of this series covers the facilitation of the decommissioning of light water reactors.⁽⁸⁾ The major purpose is to identify modifications or design changes to facilities, equipment and procedures which will improve safety and/or reduce costs.

The information provided in this Addendum on the pressurized water reactor, including any comments, will be included in the record for consideration by the Commission in establishing criteria and new standards for decommissioning. Persons wishing to comment on this report should mail their comments to:

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Washington, DC 20555

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- (6) Decommissioning of Nuclear Facilities - An Annotated Bibliography. NUREG/CR-0130, Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, September 1978.
 - (7) Decommissioning of Nuclear Facilities - A Review and Analysis of Current Regulations. NUREG/CR-0671, Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, August 1979.
 - (8) Facilitation of Decommissioning of Light Water Reactors. NUREG/CR-0569, Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, 1979.

ABSTRACT

Additional analyses of decommissioning of the reference pressurized water reactor (PWR) power station are made that examine some parameters not covered in the initial study report (NUREG/CR-0130). The parameters examined are: 1) the effect of plant size on costs and radiation exposure for dismantlement, 2) the costs and radiation exposures associated with entombment of the reference PWR, 3) the impact on costs and radiation exposure of higher radiation dose rates throughout the facility than were assumed in the initial study, 4) the effect on costs of using individual contractors to accomplish dismantlement rather than using the utility staff as postulated in the initial study, and 5) the effect on costs of increasing disposal charges at waste disposal facilities.

Dismantlement costs in 1978 dollars for PWR plants having thermal capacities of 600, 1300, and 2500 megawatts are estimated to be \$12.05 million, \$16.54 million, and \$24.64 million, respectively, based on the estimated \$31.03 million for dismantlement of the reference (3500 megawatts thermal) PWR.

Costs and radiation exposure estimates are made for entombing the reference PWR, with and without the reactor vessel internals. These estimates are: with internals, \$20.98 million and 920 man-rem; without internals, \$24.73 million and 1025 man-rem.

The impacts on costs and radiation exposure are examined for decommissioning of the reference PWR if the radiation dose rates throughout the plant are a factor of three greater than those assumed in the initial study. It is concluded that a more extensive chemical decontamination is the most cost-effective way to cope with the higher radiation levels.

Using individual contractors for decommissioning rather than using the utility staff as postulated in the initial study is estimated to increase the cost of immediate dismantlement by about 26%.

The effect on costs is examined for increases in disposal charges at waste disposal facilities. A doubling of burial ground charges increases the total dismantlement costs by about 9%.

Placement of radioactive wastes in a deep geologic repository is estimated to cost from \$7000 to \$21,000 per cubic meter, depending on the geologic media. For the relatively small volume ($\sim 88 \text{ m}^3$) of highly activated material postulated for deep geologic disposal, a tripling of the emplacement charges increases the total disposal costs by less than 12% and increases the total dismantlement costs by less than 4%. However, if all of the radioactive wastes from immediate dismantlement ($\sim 17,900 \text{ m}^3$) were placed in a deep geologic repository at a cost of $\$7100/\text{m}^3$, the total disposal costs could exceed \$191 million. Thus, there is a strong financial incentive to minimize the volume of material that is disposed of by this method.

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1.0 INTRODUCTION

In the course of the analysis of decommissioning the reference pressurized water reactor (PWR) power station, as reported in NUREG/CR-0130,⁽¹⁾ a set of scenarios was defined and certain assumptions were made to limit the scope of the study. Because the analyses presented in that report were limited to consideration of the particular situations and bases postulated in it, a number of questions have been raised about some of the scenarios and bases excluded from it. The more important of these questions are:

- What would be the effect on the cost and radiation dose estimates if the plant size were smaller than the reference plant?
- What would be the cost and radiation dose if the reference plant were entombed?
- What would be the impact on the conclusions of the published analyses if the radiation dose rates were significantly higher than were considered in the base study?
- How sensitive are the cost estimates to the assumed structure of the decommissioning staff and to contractual arrangements?
- How sensitive are the cost estimates to charges for disposal of radioactive waste?

The purpose of this addendum report is to answer these questions, because the answers make a valuable addition to the information presented in NUREG/CR-0130 and increase its general applicability. Analyses performed to gain these answers are presented in Sections 3 through 7 and are summarized in Section 2.

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, Prepared by Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, NUREG/CR-0130, June 1978.

2.0 SUMMARY

The analyses presented in this addendum report are limited to those that answer the questions posed in the introduction. A brief description of each analysis and the conclusion reached for it is presented in the following sub-sections.

The cost estimates presented in NUREG/CR-0130 for decommissioning the reference PWR (Trojan) power station are used in this addendum as the point of reference for developing decommissioning costs for smaller-sized PWRs. For ease of reference, the estimated costs of dismantlement and of preparations for safe storage of the Trojan station are summarized in Table 2.0-1.

TABLE 2.0-1. Decommissioning Costs for the Reference PWR

<u>Cost Item</u>	<u>Immediate Dismantlement (\$ Million)(a,b)</u>	<u>Preparations for Safe Storage (\$ Million)(a,b)</u>
Equipment	1.028	0.094
Supplies	1.949	1.114
Utility Services	4.375	2.331
Activated Material Disposal	3.418	---
Contaminated Material Disposal	6.479	---
Radioactive Waste Disposal	0.866	0.680
Staff Labor	11.233	4.558
Contractor Services	0.680	0.381
Nuclear Insurance	<u>1.000</u>	<u>0.368</u>
Total	31.0	9.5
Other Potential Costs		
Fuel Shipment	3.084	3.084
Non-Radioactive Demolition	8.012	---

(a) Number of figures shown is for computational accuracy and does not imply precision to the nearest one thousand dollars.

(b) Includes a 25% contingency.

2.1 ESTIMATED COSTS AND RADIATION DOSES AS A FUNCTION OF PLANT SIZE

To obtain relative cost and radiation dose estimates for dismantlement, safe storage, and entombment, three additional PWR stations are examined by comparing their major components with the same or similar components at the Trojan station. The plants examined, Yankee-Rowe (600 MWt), R. E. Ginna (1300 MWt), and Turkey Point (2550 MWt), together with the reference plant (3500 MWt), span the range of commercial PWR power stations in service. The latter three plants are quite similar in design, differing principally in the number of coolant loops (two, three, and four, respectively). Yankee-Rowe, being one of the first commercial plants built, is quite different. Its containment building is a steel sphere rather than a reinforced concrete cylinder, and it has four small coolant loops. These and other features make Yankee-Rowe somewhat atypical compared with the latter generation designs.

For each plant, individual cost estimates for dismantlement are developed for each of the major components. These estimates are fitted with a simple algebraic expression as a function of the thermal capacity of the plant to permit interpolation to plant sizes other than those studied. A composite cost estimate is developed for each plant that is weighted over all of the major components, and these composite estimates are also fitted with a simple algebraic expression as a function of the thermal capacity of the plant in megawatts (MWt) to obtain an overall scaling factor (OSF). This latter expression is:

$$\text{OSF}(\text{MWt}) = 0.2352 + 2.173 \times 10^{-4} (\text{MWt}),$$

which is normalized to unity for the reference PWR (3500 MWt).

Similar cost analyses are made for preparations for safe storage, entombment, and deferred dismantlement. Public and occupational radiation dose estimates associated with the various decommissioning actions are also examined for their variation with plant size. In addition, the effect of plant size on demolition costs are examined. The results of these analyses are summarized in Table 2.1-1.

TABLE 2.1-1. Scaling Relationships for Decommissioning

Costs^(a)

Immediate Dismantlement	$\$31.025 \text{ M} \times \text{OSF}(\text{MWt})$
Deferred Dismantlement	
(after 30 years)	$\$28.850 \text{ M} \times \text{OSF}(\text{MWt})$
(after 50 years)	$\$22.317 \text{ M} \times \text{OSF}(\text{MWt})$
(after 100 years)	$\$22.259 \text{ M} \times \text{OSF}(\text{MWt})$
Preparations for Safe Storage	$\$9.425 \text{ M} \times \text{OSF}(\text{MWt}) + \0.107 M
Safe Storage	$\$0.079 \text{ M} \times n \text{ (years of storage)}$
Entombment w/internals	$\$20.978 \text{ M} \times \text{OSF}(\text{MWt}) + \$0.04 \text{ M} \times n \text{ (years)}$
w/o internals	$\$24.733 \text{ M} \times \text{OSF}(\text{MWt}) + \$0.04 \text{ M} \times n \text{ (years)}$
Facility Demolition ^(b)	$\$0.0348 \text{ M} (\text{MWt})^{2/3}$

Radiation Dose^(c)

Radiation Workers	Reference Worker Dose $\times$ OSF(MWt)
General Public	Reference Public Dose $\times$ OSF(MWt)

(a) Costs do not include spent-fuel disposal. Facility demolition cost is shown explicitly.

(b) This relationship is not reliable for thermal powers less than 600 MW.

(c) The reference dose is the dose estimated for a given decommissioning action at the reference PWR, as given in Section 11 of NUREG/CR-0130 and in Sections 4 and 5 of this addendum.

The relationships given in Table 2.1-1 are evaluated for the four plants considered in this addendum and the results of these evaluations are presented in Table 2.1-2. Each decommissioning step is presented separately. To determine the total cost and occupational radiation dose resulting from deferring dismantlement for 30 years, it is necessary to add the values from each step (i.e., preparations for safe storage plus safe storage for 30 years plus deferred dismantlement after 30 years). As an example, for R. E. Ginna, the total cost is: $\$4.9 \text{ M} + \$2.4 \text{ M} + \$14.9 \text{ M} = \22.2 million , and the occupational dose is: $221 + 14 + 16 = 251 \text{ man-rem}$.

TABLE 2.1-2. Estimated Costs/Occupational Radiation Doses for Decommissioning Different-Sized Plants^(a)

		Station			
		Yankee-Rowe	R. E. Ginna	Turkey Point	Trojan
Power Rating	(thermal megawatts)	600	1 300	2 550	3 500
Overall Scaling Factor	(OSF[MWt])	0.366	0.518	0.789	1.000
Immediate Dismantlement	(\$ millions)	11.3	16.1	24.5	31.0
	(man-rem)	513	727	1 108	1 404
Entombment: ^(b)					
w/internals	(\$ millions) ^(b)	7.7	10.9	16.6	21.0
	(man-rem)	329	466	710	900
w/o internals	(\$ millions)	9.1	12.8	19.5	24.7
	(man-rem)	366	518	789	1 000
Preparations for Safe Storage	(\$ millions)	3.4	4.9	7.4	9.5
	(man-rem)	156	221	336	426
Safe Storage:					
for 30 years	(\$ millions)	2.4	2.4	2.4	2.4
	(man-rem)	14	14	14	14
for 50 years	(\$ millions)	4.0	4.0	4.0	4.0
	(man-rem)	14	14	14	14
for 100 years	(\$ millions)	7.9	7.9	7.9	7.9
	(man-rem)	14	14	14	14
Deferred Dismantlement:					
after 30 years	(\$ millions)	10.5	14.9	22.8	28.9
	(man-rem)	11	16	24	30
after 50 years	(\$ millions)	8.2	11.6	17.6	22.3
	(man-rem)	0.9	1.2	1.9	2.4
after 100 years	(\$ millions)	8.2	11.6	17.6	22.3
	(man-rem)	0.4	0.6	1.0	1.2
Facility Demolition	(\$ millions)	2.5	4.1	6.5	8.0

(a) Costs do not include spent-fuel disposal.

(b) Entombment costs do not include continuing care costs (\$0.04 M/yr).

2.2 ENTOMBMENT OF THE REFERENCE PWR

The entombment scenarios considered are limited to entombment of the lower portion of the containment building, either with the reactor vessel internals removed or with the internals remaining in-place. The rest of the plant is dismantled and released for unrestricted use. The entombment structure is used as a repository for most of the contaminated material removed during the dismantlement of the balance of the plant. Factors examined in this analysis are the costs of accomplishing the work and the radiation doses to the workers and to the public resulting from the work. Table 2.2-1 summarizes and compares these parameters for the reference (Trojan) PWR with the immediate dismantlement and safe storage modes of decommissioning.

As Table 2.2-1 shows, placing the facility in passive safe storage results in the least exposure of personnel to radiation and the smallest initial expenditure of funds. The entombment approaches present the least total cost, but only if no further decommissioning actions are required at some later date. Responsibility for confinement of the residual radioactivity remains with the

TABLE 2.2-1. Initial Cost, Radiation Dose, Annual Cost, and License Status for Different Decommissioning Approaches

Category	Immediate Dismantlement(a)	Placement Into Passive Safe Storage(a)	Entombment	
			w/Internals	w/o Internals
Initial Cost (\$ millions)	31.0	9.5	21.0	24.7
Initial Occupational Radiation Dose (man-rem)	1 404	426	900	1 000
Annual Continuing Care Cost (\$ thousands)	---	80	40	40
License Status Following Initial Decommission- ing Action	terminated	maintained	maintained	maintained
Accumulated Cost at License Termination or at 100 years (\$ millions)	31.0	39.7 ^(b)	25.0 ^(c)	28.7 ^(d)

(a) From NUREG/CR-0130, excluding costs of spent-fuel shipment and demolition of non-radioactive structures.

(b) Includes deferred dismantlement.

(c) License and cost accumulations not terminated, any final disposition costs not included.

(d) License might be terminated, based on calculation of radioactive decay.

licensee until the site can be released for unrestricted use. Demonstration that an entombed structure is releasable for unrestricted use may well necessitate dismantlement of the structure, which is expected to be a rather difficult and costly undertaking.

2.3 IMPACT OF INCREASED RADIATION DOSE RATES

The radiation dose-rate data used in NUREG/CR-0130 were obtained from plants that had been operating for 6 years or less and may not be representative of conditions in plants after 30 to 40 years of operation. Thus, for this analysis, an increase of a factor of three in the radiation dose rates from deposited activated corrosion products in the various fluid systems is postulated.

If no actions were taken to reduce radiation exposure, the accumulated occupational radiation dose for decommissioning workers would be increased by a factor of two, from 1,400 man-rem to almost 2,900 man-rem for immediate dismantlement. Additional staff would have to be hired to keep the individual worker dose within allowable limits, at an additional cost of about \$2.5 million.

It is concluded that the best way to handle the problem of increased radiation dose rates from the activated corrosion products deposited throughout the various fluid systems is to increase the effectiveness of the chemical decontamination program. For the decontamination technique postulated in NUREG/CR-0130, it is estimated that increasing the circulation time of the solution about 50% would reduce the residual radioactivity by about a factor of three, thus achieving the same dose rate conditions assumed in the original analysis. The incremental cost of the extended circulation time would be about \$85,000 for additional electric power and staff labor. This approach would also be most consistent with the principles of ALARA, since the occupational radiation dose associated with extending the circulation time of the decontamination solution is relatively small.

2.4 SENSITIVITY OF DECOMMISSIONING COSTS TO CONTRACTUAL ARRANGEMENTS

The particular contractual arrangements made can affect the total cost of decommissioning the reference PWR. A likely contractual arrangement is postulated and the costs evaluated, relative to the base case evaluated in NUREG/CR-0130. The arrangement analyzed is for the utility to employ contractors to provide the bulk of the decommissioning effort, while retaining certain overview and control functions. Under this arrangement, the cost of immediate dismantlement (not including spent-fuel disposal or facility demolition) is increased by about 26%, from \$31 million to \$39 million.

2.5 SENSITIVITY OF DECOMMISSIONING COSTS TO WASTE DISPOSAL CHARGES

The impact of increases in disposal charges at a shallow-land burial ground and at a deep geologic repository on the total cost of decommissioning the reference PWR is examined. It is concluded that a doubling of the burial ground charges would result in an increase of less than 9% in the overall cost of immediate dismantlement. For the relatively small volume ($\sim 88 \text{ m}^3$) of highly activated material postulated for deep geologic disposal, a tripling of the emplacement charges (from $\$7,100/\text{m}^3$ to $\$21,000/\text{m}^3$) would increase the total disposal and dismantlement costs by less than 12% and 4%, respectively. However, if all of the radioactive waste from immediate dismantlement ($\sim 17,900 \text{ m}^3$) is placed in a deep geologic repository, the total disposal cost could exceed \$191 million. Thus, there is a strong incentive to minimize the volume of material that is disposed of by this method.

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3.0 ESTIMATION OF DECOMMISSIONING COSTS AS A FUNCTION OF PLANT POWER RATING

The purpose of this investigation is to determine a reasonable method of estimating the cost of decommissioning a pressurized water reactor (PWR) power plant as a function of its size. Three decommissioning methods are considered: immediate dismantlement, safe storage with deferred dismantlement, and entombment. Analyses of demolition costs for the non-radioactive structures and of public and occupational safety are also included.

Equations for estimating the decommissioning costs for the above decommissioning methods as a function of the thermal power ratings of the power plants are determined. The cost estimates are based on the detailed cost analyses of decommissioning the Trojan PWR power plant reported in NUREG/CR-0130 (Reference 1).

Four PWR power plants are compared, including the Trojan power plant. The power plants considered cover the range from 600 MWt to 3500 MWt. Comparisons are based on information contained in the Final Safety Analysis Reports (FSAR) of the selected plants (References 2 through 5).

3.1 RELATIONSHIP OF DISMANTLEMENT COST TO REACTOR PLANT SIZE

The purpose of this portion of the investigation is to determine a reasonable method for estimating the cost of dismantling present-generation PWR power stations. For the purpose of this study, dismantlement is defined as the removal from the power plant site of all material that has become radioactive to levels in excess of those acceptable for unrestricted use as a result of reactor operation.

Costs of dismantling four different present-generation PWR power plants are estimated and compared by examining those components responsible for the major portion of the dismantlement cost. The four power plants used for comparison in this study are:

- Yankee-Rowe 600 MW Thermal 185 MWe
- R. E. Ginna 1300 MW Thermal 420 MWe

- Turkey Point 2550 MW Thermal 728 MWe
- Trojan 3500 MW Thermal 1175 MWe

Scaling factors for the principal components are determined by comparing the pertinent characteristics of the individual components with those of similar components in the Trojan power plant.

A detailed analysis of the dismantlement cost of the Trojan power plant is contained in Reference 1. All cost estimates in this study are derived by comparing the dimensions and characteristics of the individual power plants with the corresponding features of the Trojan power plant. A ratio, or scaling factor, is then determined as a result of this comparison. The estimated dismantlement cost for each component is determined by multiplying the estimated cost of dismantling the similar component in the Trojan power plant by the scaling factor.

Determination of individual scaling factors for the major components, using these to determine individual component dismantlement costs, and then summing the individual costs, provides a weighted total; that is, the more expensive of the dismantling procedures will provide correspondingly greater contributions to the total. By comparing the total costs for dismantling a set of major components of the power plant being analyzed with the total costs of dismantling the same set of major components in the Trojan power plant, a weighted overall scaling factor is obtained. This overall scaling factor is then applied to the total estimated cost of dismantling the Trojan power plant to obtain an estimate of the cost of dismantling the subject power plant. By using the weighted scaling factor times the total dismantlement cost, proper consideration is allotted to the costs of power, supplies, staff labor, insurance, and miscellaneous costs.

The above method of estimating cost applies to the basic dismantlement cost of a PWR power plant (i.e., the cost of dismantlement without the inclusion of the cost of disposing of the spent fuel). The major costs of disposal of the spent fuel are the cost of cask rental and the transportation costs. Only a short time is required to load a cask, so the miscellaneous and overhead

costs associated with the disposal of the spent fuel are sufficiently small, relatively speaking, that they will have no important effect on the cost of dismantling the power plant. On the other hand, if the basic cost of disposing of the spent fuel is allotted the same proportion of overhead and miscellaneous costs as the other portions of the dismantlement process, then the estimated cost of disposing of the spent fuel will be disproportionately high, and the total dismantlement cost will also be distorted on the high side. Thus, to maintain a proper balance, the estimated cost of dismantling a PWR power plant, including the cost of disposing of the spent fuel, is obtained by estimating the spent fuel disposal cost separately and adding this to the cost of dismantling a power plant derived using the weighted scaling factor.

3.1.1 Study Approach

It is assumed that all of the equipment on the primary side of the power-generation cycle will contain small amounts of residual radioactivity. All such equipment must, therefore, be removed and shipped to permanent storage in a nuclear waste disposal facility. Such equipment includes the following:

1. the reactor pressure vessel.
2. reactor pressure vessel internals.
3. primary coolant pumps and piping.
4. steam generators.
5. pressurizer.
6. containment building. This includes the steel liner of the reactor cavity, the biological shield and the refueling pool, the fuel transfer tube, and the surfaces of any concrete shielding walls which may have become radioactively contaminated (estimated 63.5 mm thick layer of exposed surface). The biological shield walls will have been subjected to neutron irradiation and will have become radioactive. These surfaces will have to be removed to a depth of about 1 m.
7. the final core. It is assumed that all previously discharged spent fuel has been disposed of prior to dismantlement. There is some question,

however, as to whether the cost of disposal of the final core should be charged to the decommissioning activity or to reactor operations, so estimated dismantlement costs are determined for both cases--cost of disposition of final core included and cost of fuel disposition not included.

Scaling factors and estimates of the dismantlement costs of the listed components are determined and tabulated in the following sections for each of the subject PWR power plants. Basic dismantlement cost data, as well as scaling factor bases common to all three cases, are developed in Section 3.6.

3.1.2 Methods of Determining Individual Scaling Factors

The methods of determining the individual scaling factors for the different components are discussed in the following sections.

In general, the cost of dismantling metal components is in almost direct proportion to their masses. Scaling factors for dismantling costs of metal components (vessels, pumps, piping, liners, etc.) are thus taken as equal to the ratio of the mass of component divided by the mass of the comparable Trojan power plant component.

The cost of dismantling a concrete component is composed of two factors: the cost of removing the surface layer of concrete (see Section 3.6.2.2) and the cost of disposing of that material. In the case of concrete, the cost of removing the surface layer is an appreciable portion of the cost of disposal, so it cannot be ignored.

The base dismantlement costs are determined by summing the costs of removing and sectioning the components and then disposing of the activated/contaminated material.

The estimated disposal costs for the different components in the Trojan power plant are listed in Table G.4-3 (page G-27) and Table G.4-4 (page G-31) of NUREG/CR-0130. The estimated disposal costs for the corresponding components of the other power plants are obtained by multiplying the listed Trojan costs by the appropriate scaling factors. The disposal costs for the material from the containment building are calculated individually.

The base segmenting/disposal cost estimates for the components in the Trojan power plant are given in Figure G.2-2 (page G-10) of NUREG/CR-0130. However, the costs given in the figure are only the direct costs and do not include the indirect, or overhead costs. The ratio of indirect to direct costs can be determined with the aid of Tables 10.1-1 and 10.1-2 (pages 10-2 and 10-5) of NUREG/CR-0130, assuming that the indirect costs are shared equally by the different in-plant dismantlement operations.

Table 10.1-1 contains a tabulation of all of the costs that would be included in the dismantlement of the Trojan power plant. There are 13 cost categories included in the table. Of these, the first five deal with nuclear waste disposal. The disposal costs are derived and listed elsewhere (Tables G.4-3, G.4-4, and G.4-5 of NUREG/CR-0130). These are separate costs and consist principally of container, transportation, and handling (at the burial site) costs. They would not contribute meaningfully to the overhead or indirect costs.

The sixth item, staff labor, is made up of both direct and indirect costs. The proportion of each can be determined with the aid of Figure G.2-2 (page G-10) and Table 10.1-2 (page 10-5) of NUREG/CR-0130. The direct labor charge categories for the dismantlement operations are defined in Figure G.2-2. The total of these defined costs during the dismantlement operations equals \$4,873,000 from the data in Table 10.1-2. The non-defined, overhead costs, over the life of the project sum to \$4,113,000. The sum of these two categories equals the staff labor cost of \$8,986,000 listed in Table 10.1-1.

The costs of electrical power, special equipment, miscellaneous supplies, specialty contractors, nuclear insurance, and environmental surveillance would all be incurred during the dismantlement portion of the decommissioning/dismantlement operation as explained in the text of NUREG/CR-0130. The different costs allocable to the dismantlement portion of the operation are listed in Table 3.1-1.

TABLE 3.1-1. Estimated Direct and Indirect Costs for Dismantling the Trojan Power Plant

<u>Category</u>	<u>Estimated Dismantling Cost 1978 megadollars(a)</u>
Staff labor, direct	4.873
indirect	4.113
Electric Power	3.500
Special Equipment	0.822
Miscellaneous Supplies	1.559
Specialty Contractors	0.390
Nuclear Insurance	0.800
Environmental Surveillance	0.154
Total Direct Costs	4.873
Total Indirect Costs	11.338

(a) Number of figures shown is for computational accuracy and does not imply the degree of precision indicated.

From the data in Table 3.1-1 it can be seen that for each dollar of direct labor cost there would be an additional cost of \$2.327 for supporting services, overhead, etc.

3.1.2.1 Determination of Reactor Vessel Scaling Factors

The reactor pressure vessels in the four power plants considered in this study, as well as in other PWR power plants, are all of the same general design. The vessels consist of cylindrical bodies with hemispherical bottoms and approximately hemispherical closure heads. The closure heads are bolted to the bodies by means of flanges on the heads and bodies. The bottom heads are welded to the cylindrical bodies. In addition, the temperatures, pressures, and code requirements are also all very similar.

Since the configurations, pressures, and stresses are all basically the same, it would appear that the masses of the different reactor vessels could be compared with reasonable accuracy by comparing their dimensions -- diameter and height. The masses of the nozzles, penetrations, flanges, etc., should

be in approximately the same proportion as the major contributors to the total mass of a vessel (cylindrical body and heads). Such a relationship is derived in Section 3.6.3.1.

The mass ratio as determined from the theoretical relationships derived in Section 3.6.3.1 is compared in each case with that determined using the actual dimensions of the vessel when such are given in the FSAR. The two values are compared and the most likely one is selected as the reactor vessel scaling factor.

3.1.2.2 Determination of Scaling Factors for Reactor Pressure Vessel Internals

The vessel internals are compared on the basis of mass, since the disposal costs and the dismantling costs are roughly proportional to the masses of the internals.

The vessel internals include, in general, the following components: core support assembly, support columns, grid plates, guide tubes, shroud, core barrel(s), thermal shield(s), lower core forging, and miscellaneous internals. However, the design and composition of the vessel internals are different for each of the four reactors considered. This is especially true for the thermal shields. The masses of the thermal shields for the four reactors equal 17.7, 31.0, 31.2, and 10.4 tonnes for the Yankee-Rowe, Ginna, Turkey Point, and Trojan reactors, respectively. The greatest variation is shown by the Trojan reactor thermal shield. While the Trojan reactor has the greatest power rating of the four, the thermal shield has the smallest mass by a considerable amount. (The reduced mass of the Trojan thermal shield is the result of a different design.) In addition, the masses of the thermal shields for the Ginna and Turkey Point reactors are very nearly the same even though the ratio of the power output of these two reactors is almost 2:1.

Another variation is noted in the case of the Yankee-Rowe reactor. The masses of the vessel internals for this reactor are given in the FSAR as 34.43 tonnes of which the thermal shield constitutes 51%. However, the thermal shield contributes only 25% of the estimated total mass of internals for the

Ginna reactor and only 19% for the Turkey Point reactor. There is, thus, no satisfactory method of estimating the masses of the vessel internals by comparing the power ratings of the reactors.

The masses of the reactor vessel internals are estimated, for the Ginna and Turkey Point reactors in the following manner:

1. The masses of the thermal shield and the core barrel are calculated from the dimensions given in the FSAR.
2. The masses of the remaining internal components are approximated comparing core sizes. The fuel assemblies are roughly the same length, so the sizes of the cores will be proportional to the cross-sectional areas of the cores, or the squares of the diameters of the core barrels. The masses of the internals that are not described in the FSARs are estimated by multiplying the masses of the corresponding components in the Trojan reactors by the square of the ratio of the core diameters.

The masses of the thermal shield and of the other vessel internals in the Yankee-Rowe reactor are given in the FSAR.

3.1.2.3 Determination of Scaling Factors for Primary Coolant Pumps and Coolant Piping

The coolant motor-pump assemblies all consist of a constant-speed, induction motor direct connected to a single-stage centrifugal pump. The Yankee-Rowe motor is of the canned-rotor type. The other three motors are standard induction type motors. The canned-rotor type motor is less efficient than a standard induction motor, so the Yankee-Rowe motor-pump assembly would have a greater mass than a non-canned-rotor motor-pump assembly with the same output.

As discussed previously, the decommissioning cost for the coolant motor-pump assemblies would be very nearly proportional to the mass. The scaling factors are thus based on mass ratios.

Pump manufacturers' data indicate that the mass ratios for pumps of the same style, of approximately the same size and similar specific speeds, are roughly equal to the cube root of the ratio of the pump outputs, as discussed in Section 3.6.3.2.

A review of data obtained from different electric motor manufacturers indicates that the mass of a large ac induction motor may be approximated by the relationship:

$$\text{Mass (kg)} = 3800 + 3.3 \times \text{Power (in kW)}$$

as discussed in Section 3.6.3.3. The masses of the various coolant motor-pump combinations are estimated with the aid of the above relationships.

As with the other metal components, the cost of dismantling the coolant piping depends primarily on the mass of the piping. The mass of the piping is estimated from the dimensions and the length of the piping. The dismantlement costs are then calculated from the mass of steel to be disposed of.

3.1.2.4 Determination of Scaling Factors for Steam Generators

The steam generators are shell and tube type heat exchangers. The greatest proportion of the mass of the steam generators is in the cylindrical shell. The mass of the shell is a function of the height, diameter, and wall thickness. The relative masses of the shells can be determined by the relationship derived in Section 3.6.3.1. The masses of the internals (primarily the tubes) are assumed to be in the same ratio as the masses of the shells. As with the other metal components, the dismantlement cost is primarily a function of the mass, so the scaling factor equals the mass ratio.

3.1.2.5 Determination of Scaling Factors for Pressurizers

The pressurizer vessels are cylindrical with hemispherical ends. The shells constitute the bulk of the mass, so the mass ratios can be calculated with reasonable accuracy using the relationship derived in Section 3.6.3.1. The dismantlement cost is primarily a function of the mass, so the scaling factor equals the mass ratio.

3.1.2.6 Determination of Scaling Factors for Containment Buildings

The costs of dismantling the containment buildings are estimated by calculating the amounts of concrete and steel liner plate that must be removed. The surface areas of the walls subject to contamination and/or neutron activation are determined and the volume of the concrete to be removed is calculated.

The removal and disposal costs are determined on the basis of the volume of material. Similarly, the area and mass of liner plate to be disposed of are calculated. The disposal cost of the liner plate is determined from the mass. The cost of sectioning and disposing of the fuel transfer tube is added to the concrete and liner dismantlement costs.

3.1.2.7 Determination of the Estimated Cost of Disposing of Spent Fuel

The cost of disposing of the spent fuel that is considered here includes just the cost of transporting it to an approved fuel storage facility. This cost includes cask rental, loading the fuel assemblies into casks, transporting the casks and fuel assemblies to the fuel disposal facility, unloading the fuel assemblies, and returning the empty casks to the power plant where they can be loaded with additional fuel assemblies. The cost of ultimate disposal of the spent fuel bundles at a disposal facility is not included.

The casks used for transporting fuel assemblies can hold seven of the Trojan fuel assemblies at a time. The fuel assemblies for the other three reactors considered in this study have cross-sectional dimensions that are sufficiently similar to those of the Trojan reactor fuel assemblies, so that only seven of them could be transported in a single cask at a time. Thus, the cost of disposing of spent fuel for a given reactor will be roughly proportional to the number of fuel assemblies contained in that reactor's core. As noted previously, the miscellaneous costs (overhead, supplies, etc.) associated with the shipment of the spent fuel are very small in proportion to the costs of cask rental and transportation. In addition, there is no way of accurately estimating the proportion of such overhead costs that should be applied to the shipment of the spent fuel. Thus, since these overhead costs would not have any appreciable effect on the total estimated dismantlement costs, they are not included here.

3.1.3 Yankee-Rowe Power Plant Analysis

The Yankee-Rowe power plant is the smallest of the four power plants considered, rated at 600 MWt and 185 MWe, and is different in many respects from the other three plants examined in this study.

Small though it is, relatively speaking, the Yankee-Rowe power plant contains four complete coolant loops. It also contains an external fuel transfer chute that is much longer and more massive than the fuel transfer tubes in the other three power plants. Another difference is that the Yankee-Rowe power plant contains a neutron shield tank 914 mm thick that surrounds the reactor. The containment building is also different, being a spherical steel structure while the other three containment buildings are cylindrical concrete structures with hemispherical heads.

The individual scaling factors and estimated costs of dismantlement are determined in the following sections. The dismantlement costs are summarized in Table 3.1-2.

TABLE 3.1-2. Comparison of Estimated Dismantlement Costs for Yankee-Rowe and Trojan PWR Power Plants

Major Components	Dismantlement Cost (1978 dollars)(a)		Scaling Factor
	Trojan	Yankee-Rowe	
Reactor Vessel	\$ 2 606 239	\$ 893 940	0.343
Vessel Internals	3 301 060	594 191	0.180
Primary Coolant Pumps and Piping	1 027 279	561 922	0.547
Steam Generators	767 798	221 894	0.289
Pressurizer	527 427	90 717	0.172
Containment Building	<u>2 361 481</u>	<u>685 694</u>	<u>0.290</u>
Total of Listed Decommissioning Costs	\$10 591 284	\$3 048 358	0.288

(a)The number of figures shown is for computational accuracy and does not imply precision to that many significant figures.

The total estimated cost of dismantling the Yankee-Rowe power plant, including supplies, power, staff labor, etc., plus a 25% contingency factor, but not including the cost of disposing of the spent fuel, equals:

$$0.288 \times \$31,028,000 = \$8,936,064$$

The total dismantlement cost for the Yankee-Rowe PWR power plant, including the cost of disposing of the spent fuel is:

$$\$8,936,064 + (1.25 \times \$969,531)^{(a)} = \$10,147,978$$

The corresponding cost for the Trojan power plant is \$34,112,000. These costs give a scaling factor of $10,147,978/34,112,000 = 0.297$ for the dismantlement cost of the Yankee-Rowe power plant, including the cost of disposing of the spent fuel.

3.1.3.1 Development of the Scaling Factor for the Sectioning and Disposal of the Yankee-Rowe Reactor Pressure Vessel

As noted previously in Section 3.1.2, the dismantlement cost of the reactor pressure vessel will be nearly proportional to its mass. The vessel mass can be estimated from the basic dimensions. The pertinent dimensions of the Yankee-Rowe reactor vessel are tabulated in Table 3.1-3.

TABLE 3.1-3. Dimensions of Yankee-Rowe Reactor Vessel

<u>Feature</u>	<u>Dimension</u>	<u>Trojan Reactor Vessel Dimension</u>
Overall Height	10.05 m (32.99 ft)	13.34 m
Height Excluding Closure Head	8.17 m (26.80 ft)	10.59 m
O.D. of Shell at Nozzles	3.27 m (10.73 ft)	
Shell Thickness at Nozzles Including Cladding	251 mm (9.88 in.)	4.84 m
O.D. of Shell Below Nozzles	3.17 m (10.41 ft)	4.84 m
Shell Thickness Including Cladding	203 mm (7.98 in.)	244 mm

The mass ratio of the two vessels can be calculated by the method given in Section 3.6.3.1, as follows:

(a) From Section 3.1.3.7, includes 25% contingency.

$$\frac{M_2}{M_1} = \left(\frac{3.17}{4.84}\right)^2 \times \frac{(10.05 - 1.58)}{(13.34 - 2.42)} = 0.333$$

Then, 397.12 tonnes x 0.333 = 132.13 tonnes,

where 397.12 is the mass of the Trojan reactor vessel in tonnes. The estimated mass of 132.13 tonnes compares favorably with the Yankee-Rowe vessel mass of 136.08 tonnes given in the FSAR. The actual mass is 3% greater than the estimated mass.

The mass given in the FSAR is considered to be more accurate than the estimated mass. The preferred scaling factor for the Yankee-Rowe reactor vessel then equals 136.08/397.12 = 0.343, and the estimated dismantlement cost is 0.343 x \$2,606,239 = \$893,940.

There is also an appreciable mass of studs, nuts, and washers. However, the mass of these components is on the order of 8% or less of the vessel mass, and it is assumed that their mass is proportional to the mass of the vessel. Thus, the omission of the treatment of these components as a separate entity would have no effect upon the calculation of the reactor vessel scaling factor.

3.1.3.2 Development of the Scaling Factor for the Sectioning and Disposal of the Yankee-Rowe Reactor Vessel Internals

As noted in Section 3.1.1, the cost of dismantling the reactor vessel internals is essentially proportional to their mass.

The mass of the internals of the Yankee-Rowe reactor vessel is given in the FSAR as 34.43 tonnes (75,900 lb).

The mass of the internals in the Trojan reactor is 191.00 tonnes (421,100 lb). These masses give a scaling factor of 34.43/191.00 = 0.180. The estimated decommissioning cost for the Yankee-Rowe reactor vessel internals is 0.180 x \$3,301,060 = \$594,191.

3.1.3.3 Development of the Scaling Factor for the Sectioning and Disposal of the Yankee-Rowe Primary Coolant Pumps and Piping

The Yankee-Rowe PWR power plant contains four loops and each loop contains a coolant motor-pump assembly. The four motor-pump assemblies are identical.

The scaling factor and the dismantlement cost for the coolant motor-pump assemblies will, as for the other metal components, depend on the mass. The mass of an assembly can be estimated from the characteristics of that assembly. The characteristic data for a Yankee-Rowe coolant motor-pump assembly are listed in Table 3.1-4, where they are compared with the corresponding data for a Trojan coolant pump assembly.

TABLE 3.1-4. Characteristic Data for Yankee-Rowe and Trojan Coolant Motor-Pump Assemblies

Feature	Station	
	Trojan	Yankee-Rowe
Developed Head, "H", m (ft)	84.43 (277)	69.64 (228.5)
Flow Rate, "Q", m ³ /sec (gpm)	5.583 (88 500)	1.615 (25 600)
Discharge Nozzle I.D., mm (in.)	699 (27.5)	610 (24)
Suction Nozzle I.D., mm (in.)	787 (31)	610 (24)
Overall Unit Height, m (ft)	8.702 (28.55)	(a)
Mass Dry, tonnes (wt., tons)	85.366 (94.1)	(a)
Motor Rated Power, kW (hp)	4 476 (6 000)	1 069 (1 433 est.)
Q x H, m ⁴ /sec	471.37	112.47

(a)Data unavailable.

A study of a group of commercial pumps over a range of sizes, presented in Section 3.6.3.2, indicates that the mass of a centrifugal pump is roughly proportional to the cube root of its power output for similar types of pumps. The power output of a centrifugal pump is proportional to the flow rate times the head added to the liquid by the pump, or Q x H.

Details of the Trojan coolant pump-motor assembly are listed in Table 3.1-5.

TABLE 3.1-5. Design Data of Trojan Reactor Coolant Pump

<u>Factor</u>	
Overall Length (height), m	8.7 (342 in.)
Motor, Mass (weight), tonnes	38.4 (86 800 lb)
Motor Support, Mass (weight), tonnes	4.9 (10 800 lb)
Pump Stator, Mass (weight), tonnes	21.1 (46 400 lb)
Pump Rotor, Mass (weight), tonnes	2.9 (6 500 lb)
Casing, Mass (weight), tonnes	<u>17.0 (37 500 lb)</u>
Total Mass (weight), Pump Motor, and Structure, tonnes	85.3 (188 000 lb)

Both pumps are large-volume, high-specific speed pumps, so their efficiencies would be very nearly the same. The motor horsepower requirement for the Yankee-Rowe pumps can thus be estimated with reasonable accuracy by multiplying the ratio of the pump outputs ($Q \times H$) by the power requirement for the Trojan coolant pump.

From data supplied by electric motor manufacturers for 3-phase induction motors, given in Section 3.6.3.3, the mass of a 1,119-kW (1,500-hp) squirrel cage induction motor would equal approximately 5,900 kg (13,000/lb), while the mass of a 4,476-kW (6,000-hp) motor of the same type would be approximately 16,700 kg (36,800 lb). These figures imply a Yankee-Rowe/Trojan motor mass ratio of 0.353. From Table 3.1-5, the mass of the Trojan motor plus motor support is 44.3 tonnes. Thus, the estimated mass of coolant pump motor plus motor support for the Yankee-Rowe power plant would equal 0.353×44.3 , or 15.6 tonnes (34,500 lb).

The ratio of pump capacities from Table 3.1-4 equals $112.47/471.37 = 0.239$, and the mass of the Trojan coolant pump from Table 3.1-5 is 41.0 tonnes. Thus, the estimated mass of a Yankee-Rowe pump equals $0.239^{1/3} \times 41.0 = 25.4$ tonnes (56,000 lb), and the total estimated mass of the Yankee-Rowe coolant motor-pump assembly is 41.0 tonnes (90,400 lb). However a canned-rotor motor is less efficient than a standard squirrel cage induction type motor. To allow

for the lower efficiency and resulting larger motor required by the canned-rotor design, increase the mass of the motor-pump assembly by 10% to give a corrected estimated mass of 45.1 tonnes (99,400 lb).

There are four coolant loops in parallel in the Yankee-Rowe power plant. These four loops contain the following amounts of pipe:

62.2 m (204 ft) of 50.8 mm (20 in.) I.D. x 49 mm (1.94 in.) wall
unit mass = 677.8 kg/m (37.92 lb/in.)

Mass of pipe = $62.2 \times 677.8 = 42,159 \text{ kg} = 42.16 \text{ tonnes}$

20.7 (68 ft) of 610 mm (24-in.) I.D. x 56 mm (2.19 in.) wall
unit mass 913.5 kg/m (51.11 lb/in.). Mass = 18.91 tonnes

The total mass of coolant piping = 61.07 tonnes (67.3 tons) compared with a total mass of 100.70 tonnes for the Trojan power plant.

This pipe is only a little smaller than the coolant piping in the Trojan power plant. The segmenting and disposal costs can be considered as being proportional to the mass of the pipe with small error.

There are four cooling loops in the Yankee-Rowe plant, so there will be four motor-pump assemblies. The total estimated mass of the coolant pumps and coolant piping thus equals:

$$4 \times 45.10 + 61.07 = 241.47 \text{ tonnes}$$

This compares with a total estimated mass of $4 \times 85.28 + 100.7 = 441.8 \text{ tonnes}$ for the coolant pumps and piping in the Trojan power plant.

The scaling factor for the coolant pumps and piping for the Yankee-Rowe power plant thus equals $241.5/441.8 = 0.547$ and the estimated decommissioning cost is $0.547 \times \$1,027,279 = \$561,922$.

3.1.3.4 Development of the Scaling Factor for the Sectioning and Disposal of the Yankee-Rowe Steam Generators

The Yankee-Rowe steam generator is similar to the Trojan steam generator in design and configuration. A reasonable estimate for the cost of sectioning

and disposing of the Yankee-Rowe steam generator can thus be obtained by determining a suitable scaling factor and applying that factor to the cost of sectioning the Trojan steam generator, as developed in Reference 1. As with other metal components, the dismantlement cost will be proportional to the mass. Thus, the scaling factor will equal the ratio of the mass of the Yankee-Rowe steam generators to the Trojan steam generators.

The mass ratio is estimated by the method derived in Section 3.6.3.1 and discussed in Section 3.1.2.4.

The overall heights of the two steam generators are:

Trojan 20.603 m (67.6 ft), Yankee-Rowe 17.068 m (56 ft)

The diameters of the lower portions are:

Trojan 3.398 m (11.15 ft), Yankee-Rowe 1.981 m (6.5 ft)

The Trojan steam generator mass, given in NUREG/CR-0130, is 312 tonnes

The estimated mass ratio (and scaling factor) are:

$$M_2/M_1 = (D_2/D_1)^2 (H_2 - D_2/2)/(H_1 - D_1/2)$$

$$M_2/M_1 = (1.981/3.398)^2 (17.068 - 0.990)/(20.603 - 1.699) = 0.289$$

Since there are four steam generators in each of the two power plants, the scaling factor for the steam generator portion of the Yankee-Rowe power plant is 0.289.

The estimated disposal cost of the Yankee-Rowe steam generators is $0.289 \times \$767,798 = \$221,894$.

3.1.3.5 Development of the Scaling Factor for the Sectioning and Disposal of the Yankee-Rowe Pressurizer

The Yankee-Rowe pressurizer is similar in shape and design to the Trojan pressurizer. The sectioning cost will be relatively small in proportion to the disposal cost. In addition, the ratio of the sectioning cost of the Yankee-Rowe pressurizer compared with the sectioning cost of the Trojan pressurizer will be roughly the same as the ratio of the masses. The scaling factor is thus taken as equal to the mass ratio.

The internals constitute a relatively small proportion of the total mass of the pressurizer and it is assumed that the mass of the internals will be proportional to the mass of the shell. The masses can be compared by the method given in Section 3.6.3.1.

The Yankee-Rowe pressurizer is 1.22 m (4.0 ft) in diameter and 10.06 m (33 ft) long. The corresponding dimensions of the Trojan pressurizer are 2.34 m (7.67 ft) diameter by 16.10 m (52.83 ft), and its mass is 88.45 tonnes. The estimated mass ratio (and scaling factor) then equals:

$$\frac{M_2}{M_1} = \left(\frac{1.22}{2.34}\right)^2 \times \frac{(10.06 - 0.61)}{(16.10 - 1.17)} = 0.172$$

The estimated disposal cost is $0.172 \times \$527,427 = \$90,717$.

3.1.3.6 Development of the Scaling Factor for the Removal and Disposal of Contaminated Material in the Yankee-Rowe Containment Building

The Yankee-Rowe containment building is a spherical steel structure 38.1 m (125 ft) in diameter made of 22.2 mm (7/8-in.) thick steel plate. It is supported by 16 columns. Inside the spherical shell are a reactor cavity, biological shields, and other wall structures made of concrete. Parts of the internal wall structures are lined with steel plate.

It is assumed that some of the plate may become radioactive from irradiation. It is also assumed that the liners may leak, and that water containing radioactive substances may penetrate the concrete behind the liners to a depth of 63.5 mm. It is also assumed that the concrete walls that shield the coolant pumps and the steam generator may become contaminated with radioactive substances to a depth of 63.5 mm (2.5 in.).

Dismantlement of the containment building consists of removing all radioactive material, which includes the steel liner plates plus a 63.5 mm (2.5-in.) thick surface layer of the concrete behind the liner plate plus a similar layer from the walls and floors of the compartments that house the primary coolant components.

The wall areas in the containment building that could conceivably become contaminated are listed in Table 3.1-6.

TABLE 3.1-6. Contaminated Wall Areas in Yankee-Rowe Containment Building

Wall Description	Area	
	m ²	ft ²
Primary shielding below RV head	168	1 180
Base of upper portion, floor area	35	373
Surface area, inside of upper section	263	2 828
Base area secondary shielding	365	3 926
Inside area, concrete missile and biological shield	962	10 356
Outer surface of upper section	334	3 592
Outer surface of reactor shielding	218	2 346
Surface area of six partitions	<u>959</u>	<u>10 320</u>
	3 304	35 551

It should be noted here that the reactor cavity walls are shielded against intensive irradiation from the reactor core by neutron shield tanks. This tank occupies the annular space between the reactor vessel and the reactor cavity wall. It interposes a layer of water 0.91 m (3 ft) thick between the reactor and the surface of the concrete wall. This water shield prevents the reactor cavity wall from becoming highly activated. It is probable, however, that the surface layer of the concrete would become contaminated.

$$\begin{array}{l} \text{Remove 63.5 mm (2.5 in.) from the surface} \\ 0.0635 \times 3,304 = 209.8 \text{ m}^3 \text{ (7409 ft}^3\text{) or 503.9 tonnes (555.5 tons)} \end{array}$$

The fuel transfer chute can also be considered as a part of the containment building. It can be considered as being contaminated, and would probably all have to be disposed of as contaminated waste.

The fuel transfer chute is 24.4 m (80 ft) long and contains 220 m³ (288 yd³) of concrete. Part of the concrete is in the form of concrete blocks, but there

is also some lead shielding. The concrete blocks can be removed easily. It would be more trouble to remove the lead shielding. For the purpose of estimating the cost of dismantlement, assume that the concrete has to be broken up by balling and blasting, and neglect the cost of removing the relatively small amount of lead shielding. The major portion of the fuel transfer chute is in the open and is readily accessible for balling or to a mounted impulse breaker. This concrete would be much easier to break up and dispose of than would the concrete inside containment. The direct costs of blasting, loading, and hauling are estimated at $\$80/\text{m}^3$ (Section 3.6.2.3). The estimated direct labor costs for dismantling the fuel transfer chute would thus equal $220 \text{ m}^3 \times \$80/\text{m}^3 = \$17,600$. To this would have to be added indirect costs in the amount of $2.327 \times 17,600 = \$40,955$. Disposal cost @ $\$265/\text{tonne}$ would equal:

$$\$265/\text{tonne} \times 220 \text{ m}^3 \times 2.403 \text{ tonnes}/\text{m}^3 = \$140,095$$

The estimated cost for dismantling the fuel transfer chute equals $\$17,600 + \$40,955 + \$140,095 = \$198,650$.

The estimated cost of removing and disposing of the concrete, liners, etc., from inside the containment building equals:

$$503.9 \text{ tonnes} \times \$966.55/\text{tonne} = \$487,045 \text{ (Section 3.6.1.6)}$$

The total estimated cost of dismantling the Yankee-Rowe containment building equals $\$685,694$, and the scaling factor is $685,694/2,361,481 = 0.290$.

3.1.3.7 Development of the Scaling Factor for Disposing of the Yankee-Rowe Spent Fuel

The cost of disposing of the spent fuel is essentially the cost of cask rental and of transporting the fuel to an approved fuel storage facility. This cost includes loading the fuel assemblies into casks and transporting them to the waste storage facility, unloading the fuel assemblies, and returning the casks to the power plant where they can be loaded with additional fuel assemblies.

The fuel assemblies in the Yankee-Rower power plant are 193 mm x 193 mm x 2.83 m long (7.61 in. x 7.61 in. x 9.29 ft). These are shorter than the fuel assemblies in the Trojan power plant, but the cross-sectional dimensions are similar, so a fuel cask would hold the same number of Yankee-Rowe fuel assemblies as Trojan fuel assemblies. The fuel disposal costs would be in approximately the same ratio as the number of fuel cask loadings.

There are 193 fuel assemblies in the Trojan power plant reactor and 76 fuel assemblies in the Yankee-Rowe power plant reactor. Since the casks used for transporting fuel assemblies hold seven assemblies at a time:

$$193/7 = 27.6 \text{ or } 28 \text{ fuel cask loads}$$

$$76/7 = 10.9 \text{ or } 11 \text{ fuel cask loads}$$

$$11/28 = 0.393, \text{ which is the most probable disposal cost ratio}$$

The estimated cost for disposing of the Trojan fuel is \$2,464,000 (Reference 1).

The estimated cost for disposing of the Yankee-Rowe spent fuel is $0.393 \times \$2,467,000 = \$969,500$.

3.1.4 R. E. Ginna Power Plant Analysis

The Robert Emmett Ginna power plant is rated at 1300 MWt and 420 MWe. It contains two heat transfer loops, each of which includes a coolant pump and a steam generator. The design of the Ginna power plant, including the containment building and all major components, is similar to the design of the Trojan power plant.

The characteristics of the principal components of the Ginna power plant are compared with those of the corresponding components of the Trojan power plant. Scaling factors are determined and applied to the Trojan costs (Reference 1) to obtain estimates of the sectioning and disposal costs of the major components in the Ginna power plant. The comparative sectioning/disposal costs are listed in Table 3.1-7. The individual costs are then summed for the Ginna and Trojan power plants and the ratio of the sums provides a weighted, overall, power plant scaling factor.

TABLE 3.1-7. Comparison of Estimated Dismantlement Costs for
Ginna and Trojan PWR Power Plants

Major Component	Dismantlement Costs (1978 dollars)(a)		Scaling Factor
	Trojan	Ginna	
Reactor Vessel	\$ 2 606 239	\$1 428 219	0.548
Vessel Internals	3 301 060	2 195 205	0.665
Primary Coolant Pumps and Piping	1 027 279	506 449	0.493
Steam Generators	767 798	325 546	0.424
Pressurizer	527 798	166 667	0.316
Containment Building	<u>2 361 481</u>	<u>895 471</u>	<u>0.379</u>
Total of Listed Dismantlement Costs	\$10 591 284	\$5 517 557	0.521

(a)The number of figures shown is for computational accuracy and does not imply precision to that many significant figures.

The total estimated cost of dismantling the Ginna power plant, including supplies, power, staff labor, etc., plus a 25% contingency factor, but not including the cost of disposing of the spent fuel, is:

$$0.521 \times \$31,026,000 = \$16,164,546$$

The total estimated dismantlement cost for the Ginna power plant, including the cost of disposing of the spent fuel, is:

$$\$16,164,546 + (1.25 \times \$1,586,280)^{(a)} = \$18,147,396$$

The corresponding cost for the Trojan power plant is \$34,110,000. These costs give a scaling factor of $18,147,396/34,110,000 = 0.532$ for the dismantlement cost of the Ginna power plant, including the cost of disposing of the spent fuel.

Detailed analyses are given in the following sections.

(a) From Section 3.1.4.7, includes a 25% contingency.

3.1.4.1 Development of the Scaling Factor for the Sectioning and Disposal of the Ginna Reactor Vessel

The Ginna Reactor vessel is composed of a cylindrical body with two hemispherical ends. The pertinent dimensions are listed in Table 3.1-8.

TABLE 3.1-8. Dimensions of Ginna Reactor Vessel

Total Height Overall, m	11.92 (39.1 ft)
I.D. of Shell, m	3.353 (132 in.)
I.D. of Closure Head, m	3.086 (121.5 in.)
Lower Head Thickness, mm	104.8 (4.125 in.)
Closure Head Thickness, mm	136.5 (5.375 in.)
Vessel Belt Line Thickness, mm	165.1 (6.50 in.)
Clad Thickness, mm	3.96 (0.156 in.)

From the listed data, the overall height is 11.92 m and the O.D. of the shell equals $3.353 + 2 \times 0.165 = 3.673$ m. The corresponding dimensions of the Trojan reactor vessel are:

height = 13.34 m and O.D. of shell below nozzle = 4.84 m.

The mass ratio of the two vessels can be calculated by the method given in Section 3.6.3.1:

$$M_2/M_1 = \left(\frac{3.673}{4.84}\right)^2 \times \frac{(11.92 - 1.84)}{(13.34 - 2.42)} = 0.532$$

Based on the analysis of Yankee-Rowe (see Section 3.1.3.1), this value should be increased by about 3% to include structural variations from the simple model calculated, to obtain a scaling factor of 0.548.

The estimated scaling factor can be checked by calculating the masses of the three main portions of the reactor vessel; the closure head, the cylindrical section, and the lower head; and comparing them with the masses of the corresponding portions of the Trojan reactor vessel.

Closure Head

$$\text{Mean diameter} = 3.086 + 0.1365 + 0.0040 = 3.2265 \text{ m}$$

$$\text{Wall thickness} = 136.5 + 3.96 = 140.46 \text{ mm}$$

$$\text{Vol. of metal} \approx \left(\pi \frac{D^2}{2} \right) \times t = 2.297 \text{ m}^3 \text{ (approx.)}$$

$$\text{Mass of metal} = 2.297 \times 7.861 = 18.06 \text{ tonnes (19.90 tons)}$$

$$\begin{aligned} \text{Mass of flange} &= \rho \pi (R_o^2 - R_i^2) h \\ &= (7.861 \text{ tonnes/m}^3) \pi [(2.210 \text{ m})^2 - (1.768 \text{ m})^2] (0.381 \text{ m}) \\ &= 16.55 \text{ tonnes} \end{aligned}$$

$$\begin{aligned} \text{Total mass of} \\ \text{closure head} &= 18.06 \text{ tonne} + 16.55 \text{ tonne} = 34.61 \text{ tonne} \end{aligned}$$

Cylindrical section

$$\text{Length} = 11.92 - (3.353 + 3.086)/2 - 0.105 - 0.137 = 8.46 \text{ m (27.76 ft)}$$

$$\text{Mean diameter, including clad} = 3.353 + 0.165 + 0.004 = 3.522 \text{ m (11.556 ft)}$$

$$\text{Wall thickness, including clad} = 169 \text{ mm}$$

$$\text{Volume of steel} = \pi \times D \times t \times L = \pi \times 3.522 \times 0.169 \times 8.46 = 15.82 \text{ m}^3$$

$$\text{Mass of steel} = 15.82 \times 7.861 = 124.35 \text{ tonnes (137.08 tons)}$$

Add mass of flange, assume flange of roughly same mass as flange of closure head

$$\begin{aligned} \text{Total mass of cylindrical section} &= 124.36 + 16.55 = 140.91 \text{ tonnes} \\ &= 155.32 \text{ tons} \end{aligned}$$

Vessel Bottom, or Lower Head

$$\text{Mean diameter} = 3.353 + 0.1048 + 0.00396 = 3.462 \text{ m (11.36 ft)}$$

$$\text{Wall thickness} = 104.8 + 3.96 = 108.76 \text{ mm (4.282 in.)}$$

$$\text{Vol. of steel} \approx \left(\pi \frac{D^2}{2} \right) \times t = 2.048 \text{ m}^3 \text{ (72.31 ft}^3\text{) (approx.)}$$

$$\text{Mass of steel} = 2.048 \times 7.861 = 16.10 \text{ tonnes (17.75 tons)}$$

The masses of the different components are tabulated in Table 3.1-9. For comparison, the masses of the corresponding Trojan components are also listed in the same table.

TABLE 3.1-9. Comparison of the Masses of the Major Portions of the Trojan and Ginna Reactor Vessels

<u>Portion</u>	<u>Mass, tonnes</u>	
	<u>Trojan</u>	<u>Ginna</u>
Closure Head	88.45	38.14
Cylindrical Section	269.80	140.91
Lower Head	<u>38.87</u>	<u>16.10</u>
Total Mass	397.12	195.15

The ratio of the total masses equals 0.491, which is reasonably close to the previously calculated value of 0.548. The effect of nozzles, penetrations, etc., implies that the 0.548 mass ratio is the better of the two values and thus is selected as the reactor vessel scaling factor.

The estimated cost of sectioning and disposing of the Ginna reactor vessel is:

$$0.548 \times \$2,606,239 = \$1,428,219$$

3.1.4.2 Development of the Scaling Factor for the Sectioning and Disposal of the Ginna Reactor Vessel Internals

The masses of the reactor vessel internals are compared by calculating the masses of the components in the Ginna vessel for which the dimensions can be estimated (thermal shield and core barrel) and estimating the mass of the other internals by comparing the core volumes.

Thermal shield 3.111 m O.D. x 2.929 m I.D. x 4.572 m long
(122.5 in. x 115.3 in. x 180 in.)

$$\text{Volume of steel} = \frac{\pi}{4} (3.111^2 - 2.929^2) \times 4.572 = 3.947 \text{ m}^3 (139.40 \text{ ft}^3)$$

$$\text{Mass of steel} = 3.947 \text{ m}^3 \times 7.861 \text{ tonnes/m}^3 = 31.03 \text{ tonnes (34.20 tons)}$$

Core barrel 2.858 m O.D. x 2.769 m I.D. x 7.722 m long
(112.5 in. x 109.0 in. x 304 in.)

$$\text{Volume of steel} = \frac{\pi}{4} (2.858^2 - 2.769^2) \times 7.722 = 3.037 \text{ m}^3 (107.26 \text{ ft}^3)$$

$$\text{Mass of steel} = 3.037 \text{ m}^3 \times 7.861 \text{ tonne/m}^3 = 23.874 \text{ tonnes (26.316 tons)}$$

The remainder of the internal components are not specified in sufficient detail in the FSAR to enable the masses to be calculated accurately. However, their masses can be estimated by comparing them with the masses of the internals in the Trojan reactor.

The cross-sectional areas of the cores can also be compared by comparing the squares of the I.D.s of the thermal shields $(2.929 \text{ m}/4.013 \text{ m})^2 = 0.533$. This is also a volume ratio since the heights of the two cores are similar.

The ratio of the masses of the thermal shields is not meaningful, since the thermal shields for the two reactors are so different. The thermal shield for the Ginna reactor is a steel tube 4.572 m long, with a wall thickness of 91 mm and a mass of 31.03 tonnes. The thermal shield in the Trojan reactor consists of four plates attached to the O.D. of the core barrel, with a total mass of 10.43 tonnes. It is assumed that the other internal components will have mass ratios equal to the mass ratio of the core barrels and the area ratio of the two cores. The estimated masses are tabulated in Table 3.1-10.

The scaling factor for the vessel internals, therefore, is 0.665. The estimated cost for dismantling and disposing of the Ginna reactor vessel internals is:

$$0.665 \times \$3,301,060 = \$2,195,205$$

TABLE 3.1-10. Comparison of Masses of Internal Components of Trojan and Ginna Reactor Vessels

Component	Mass, tonnes		Ratio
	Trojan	Ginna	
Thermal Shield	10.43	31.03	2.97
Core Barrel(s)	45.36	23.86	0.526
Upper Core Support Assembly	12.02	6.41	(0.533) ^(a)
Upper Support Columns	11.11	5.92	(0.533)
Upper Core Grid Plate	4.63	2.47	(0.533)
Guide Tubes	15.10	8.05	(0.533)
Core Shroud	12.29	6.55	(0.533)
Lower Grid Plate	3.95	2.11	(0.533)
Lower Support Columns	3.36	1.79	(0.533)
Lower Core Forging	36.47	19.44	(0.533)
Misc. Internals	<u>36.29</u>	<u>19.34</u>	<u>(0.533)</u>
Total	191.01	126.97	0.665

(a) Ratios assumed equal to ratio of cross-sectional areas of cores.

3.1.4.3 Development of the Scaling Factor for the Sectioning and Disposal of the Ginna Primary Coolant Pumps and Piping

The Ginna and Trojan power plant coolant pumps are similar in nature. Both are single-stage, vertical units direct-coupled to an ac-induction motor. Both have vertical suction nozzles at the bottom and horizontal discharge nozzles. The pertinent features of the two coolant pumps, Ginna and Trojan, are listed in Table 3.1-11.

The rated output of the Ginna coolant pump is slightly less than that of the rated output of the Trojan coolant pump, in the ratio of $(Q \times H)/(Q \times H) = 436.1/471.5 = 0.925$. However, this could easily be the result of different pump efficiencies or a higher safety factor. It is not considered to have a noticeable effect on the mass of the motor-pump assembly.

TABLE 3.1-11. Comparison of Ginna and Trojan Power Plant Coolant Pumps

Feature	Trojan	Ginna
Developed Head, "H", m (ft)	84.43 (277)	76.81 (252)
Flow Rate, "Q", m ³ /sec (gpm)	5.584 (88 500)	5.678 (90 000)
Discharge Nozzle I.D., mm (in.)	699 (27.5)	699 (27.5)
Suction Nozzle I.D., mm (in.)	787 (31.0)	787 (31.0)
Overall Unit Height, m (ft)	8.702 (28.55)	8.601 (28.22)
Mass, Dry, tonnes (wt, tons)	85.366 (94.1)	(a)
Motor Rated Power, kW (hp)	4 476 (6 000)	4 476 (6 000)
Q x H, m ⁴ /sec	471.5	436.1

(a)Data not available.

On the other hand, the dimensions of the two motor-pump assemblies are very nearly the same and the motor power ratings are identical. The cost of decommissioning a Ginna coolant pump would be the same as the cost of decommissioning a Trojan coolant pump. There are two coolant pumps in the Ginna power plant and four in the Trojan power plant, so the coolant pump scaling factor would equal 0.500.

The mass of the four Trojan coolant pumps is 341.10 tonnes (752,000 lb), so the estimated mass of the Ginna coolant pumps is 170.55 tonnes (376,000 lb).

The mass of the coolant piping can be estimated by first estimating the lengths of run. The coolant flow is out of the reactor vessel, through the steam generator, to the pump suction, and out of the pump back into the reactor vessel. The sizes and estimated lengths of run are listed in Table 3.1-12.

The piping from the coolant loop to the pressurizer is 3.05 m (10.0 ft) long, and is made of 10-in. schedule 140 pipe, 222.3 mm O.D. x 25.4 mm wall thickness (8.750-in. O.D. x 1.00-in. wall). The mass of this piece of pipe is 474 kg (1044 lb).

The total mass of coolant piping equals $2 \times 23.32 + 0.474 = 47.11$ tonnes for the two coolant loops and one pressurizer in the Ginna PWR power plant.

TABLE 3.1-12. Sizes, Lengths of Run, and Masses of Coolant Piping per Loop in Ginna Power Plant

Function	Diameter/Wall Thickness		Length,		Mass,	wt,
	mm/mm	in./in.	m	ft	tonnes	tons
Vessel to Steam Generator	737/63.5	29/22.5	5.36	17.6	6.73	7.42
Steam Generator to Pump	787/66.7	31/2.625	7.92	26.0	11.15	12.29
Pump to Vessel	699/60.3	27.5/2.375	4.82	15.8	<u>5.44</u>	<u>6.00</u>
Total Mass (weight) for One Loop					23.32	25.71

The total estimated mass of the Ginna coolant pumps and piping is $170.55 + 47.11 = 217.66$ tonnes. This compares with the total estimated mass of 441.80 tonnes for the Trojan power plant coolant pumps and piping, to give a scaling factor of $217.66/441.80 = 0.493$.

The estimated cost of dismantling and disposing of the Ginna power plant coolant pumps and piping is:

$$0.493 \times \$1,027,279 = \$506,449$$

3.1.4.4 Development of the Scaling Factor for Sectioning and Disposal of the Ginna Steam Generator

The Ginna steam generators are two in number and are similar in design to the four Trojan steam generators. A comparison of the pertinent features of the individual steam generators is given in Table 3.1-13.

TABLE 3.1-13. Comparison of Ginna and Trojan Steam Generators

Feature	Trojan	Ginna	Ratio
Overall Height, m (ft)	20.60 (67.6)	19.24 (63.1)	0.934
Diameter, Lower Section, m (ft)	3.40 (11.15)	3.24 (10.63)	0.953
Heat Transfer Rating, MW	875	650	0.743
Estimated Volume, m ³ (ft ³)	230.2 (8130)	195.1 (6890)	0.848

The steam generators are similar in configuration. They are both in the shape of long circular cylinders, with the top third of the cylinder being roughly 30% greater in diameter than the bottom two-thirds. The upper and lower portions are continuous and concentric. The diameters of the lower sections are known. It is assumed that the diameters of the upper portions are proportional to the diameters of the lower sections.

The masses of the internal components are small compared with the masses of the shells. In addition, it is assumed that the masses of the internals will be proportional to the volumes of the vessels. The scaling factor for a Ginna steam generator can thus be calculated by the method given in Section 3.6.3.1:

$$M_2/M_1 = \left(\frac{3.24}{3.40}\right)^2 \times \frac{(19.24 - 1.62)}{(20.60 - 1.70)} = 0.847$$

There are two Ginna steam generators and four Trojan steam generators, so the scaling factor for the steam generator portion of the Ginna power plant is:

$$(2/4) \times 0.847 = 0.424$$

The estimated cost of dismantling and disposing of the Ginna steam generators is:

$$0.424 \times \$767,798 = \$325,546$$

3.1.4.5 Development of the Scaling Factor for the Sectioning and Disposal of the Ginna Pressurizer

The Ginna pressurizer is a carbon steel, stainless steel lined, cylindrical vessel. It is similar in design and configuration to the Trojan pressurizer. The scaling factor can thus be determined by the method described in Section 3.6.3.1.

The height and diameter of the Ginna and Trojan steam pressurizers are:

Ginna: height = 7.73 m (25.4 ft), O.D. = 1.92 m (6.3 ft)
Trojan: height = 16.1 m (52.8 ft), O.D. = 2.3 (7.6 ft)

$$M_2/M_1 = \left(\frac{1.92}{2.3}\right)^2 \times \frac{(7.73 - 0.96)}{(16.1 - 1.15)} = 0.316$$

The estimated cost of sectioning and disposing of the Ginna pressurizer is $0.316 \times \$527,427 = \$166,667$.

3.1.4.6 Development of the Scaling Factor for the Removal and Disposal of Contaminated Material in the Ginna Containment Building

The Ginna containment building is a reinforced-concrete, vertical right-circular cylinder with a reinforced concrete hemispherical dome on top. The inside surface of the concrete of both cylinder and dome is lined with welded steel plate 9.5 mm (0.375 in.) thick. The cylindrical section is 30.17 m (99 ft) high and has an inside diameter of 32.0 m (105 ft). The cylindrical concrete wall is 1.067 m (3.5 ft) thick and the concrete dome is 762 mm (2.5 ft) thick. The concrete base slab is 610 mm thick (2.0 ft) and is covered with a welded steel plate 6.35 mm (0.250 in.) thick. An additional layer of concrete 610 mm (2.0 ft) thick is laid over the steel liner.

There is a cavity at the bottom of the containment building to hold the reactor. The cavity is in the shape of a right circular cylinder 4.27 m (14 ft) in diameter by 13.11 m (43 ft) deep. It is lined with 6.35-mm (0.250-in.) thick steel plate.

There is also a refueling pool and a fuel transfer tube. These are also lined with 6.35-mm (0.250-in.) thick steel plate. In addition, there are compartments in which the coolant pumps, the steam generators and the pressurizer are located. The walls of these compartments are made of concrete and are not lined.

It is assumed that any residual radioactive material that may have adhered to the walls of the containment building or dome will be removed by cleaning and washdown. It is also assumed that the steel liners in the reactor cavity and the refueling pool will be contaminated. The liner plate will have to be

removed and shipped to an approved nuclear waste disposal facility. It is quite possible that the liner plates may have developed leaks at some points, so the surface of the concrete behind the liners will have to be removed to a depth of 63.5 mm (2.5 in.) and shipped to a disposal facility.

The reactor cavity wall will be activated in the region surrounding the reactor core. The surface of the concrete to a depth of 1 m (3.28 ft) will be removed and shipped to a disposal facility. The bottom of the reactor cavity will not have been subjected to the same intensity of irradiation, so the surface of the concrete on the bottom of the cavity will only have to be removed to a depth of 100 mm (3.94 in.). The fuel transport tube will be removed in its entirety and shipped to a disposal facility.

The refueling pool has a linear length of wall 54.3 m (178 ft) long. The height of the wall of the pool (depth of the pool) varies from 7.9 m (25.8 ft) to 12.4 m (40.7 ft). Assume an average height of 10.7 m (35 ft). The wall area then equals 581 m^2 (6254 ft^2). The floor area equals 107.8 m^2 (1161 ft^2).

The volume of concrete to be removed from the surface of the walls and floor equals $688.8 \text{ m}^2 \times 0.0635 \text{ m} = 43.74 \text{ m}^3$ (1544.8 ft^3). The mass of the concrete to be removed equals $43.74 \text{ m}^3 \times 2.403 \text{ tonne/m}^3 = 105.11 \text{ tonnes}$ (115.9 tons).

The walls of the compartments in which the coolant pumps, the steam generators, and the pressurizer are located are approximately 12.2 m (40 ft) high. The linear length of wall equals 31.7 m (104.1 ft) for one compartment plus 46.4 m (152.4 ft) for the other, for a total length of 78.1 m (256.3 ft). The total compartment wall area equals $78.1 \times 12.2 = 952.8 \text{ m}^2$ ($10,257 \text{ ft}^2$). The floor area of one compartment equals 61.3 m^2 (660 ft^2) and the floor area of the other compartment is 94.4 m^2 (1016 ft^2).

The total area of concrete to be removed from the surfaces of the walls, ceilings, and floors of the two compartments then equals (assuming ceiling area equal to floor area):

$$952.8 \text{ m}^2 + 2(61.3 \text{ m}^2 + 94.4 \text{ m}^2) = 1,264.2 \text{ m}^2 \text{ (13,610 ft}^2\text{)}$$

The volume of concrete to be removed and disposed of is:

$$1,264.2 \text{ m}^2 \times 0.0635 \text{ m} = 80.28 \text{ m}^3 (2,835 \text{ ft}^3)$$

The mass of the concrete is $80.28 \times 2.403 = 192.9$ tonnes (212.6 tons).

The volume of concrete to be removed from the wall of the reactor cavity would equal the volume of a tube of concrete 1 m thick.

$$V = \pi/4 (6.27^2 - 4.27^2) \text{ m}^2 \times 13.11 \text{ m} = 217.05 \text{ m}^3$$

To this would be added the bottom section, 100 mm thick.

$V = \pi/4 \times 4.27^2 \text{ m}^2 \times 0.10 \text{ m} = 1.43 \text{ m}^3$, which gives a total volume of 218.48 m^3 of concrete to be removed from the reactor cavity, a mass of 525.0 tonnes.

The fuel transfer tube would be similar to the fuel transfer tube in the Turkey Point power plant. The estimated mass of the concrete in that fuel transfer tube is 103.45 tonnes (see Section 3.1.5.6). The same mass is estimated for the Ginna power plant.

The total of the costs for decommissioning the Ginna containment building are listed in Table 3.1-14.

3.1.4.7 Development of the Scaling Factor for Disposing of the Ginna Spent Fuel

The Ginna reactor contains 121 fuel assemblies with cross-sectional dimensions of 197 mm x 197 mm (7.763 x 7.763 in.). The spent fuel assemblies are transported in fuel casks. Each cask holds seven fuel assemblies. The cost of disposing of the spent fuel is proportional to the number of casks used to transport the spent fuel assemblies.

The Trojan reactor contains 193 fuel assemblies. These constitute 28 fuel cask loads. The Ginna core of 121 fuel assemblies would provide 18 fuel cask loads.

TABLE 3.1-14. Estimated Costs of Removing and Disposing of the Contaminated Material in the Ginna Containment Building

<u>Feature</u>	<u>Mass of Concrete to be Removed tonnes</u>	<u>Cost of Removal and Disposal 1978 dollars(a)</u>
Reactor Cavity	525.0 ^(b)	\$507 439
Refueling Pool	105.11	101 594
Pump/Steam Generator Shielding Walls	192.9	186 448
Fuel Transfer Tube	<u>103.45</u>	<u>99 990</u>
Total	926.46	\$895 471

(a)The number of figures shown is for computational accuracy and does not imply precision to that many significant figures.

(b)The decommissioning cost equals \$966.55/tonne of concrete, including allowances for steel liner plates and other factors (see Section 3.6.1.6).

The scaling factor for the disposal of the Ginna spent fuel thus is $18/28 = 0.643$, and the estimated cost of disposing of the Ginna spent fuel is:

$$0.643 \times \$2,467,000 = \$1,586,280.$$

3.1.5 Turkey Point Power Plant Analysis

There are two Turkey Point PWR power plants, Turkey Point 3 and Turkey Point 4. Since the two plants are essentially identical, the dismantlement cost will be the same for either plant. The subject power plant will be referred to as the Turkey Point power plant.

The Turkey Point power plant has a rating of 2550 MW thermal and 728 MW electric. It contains three heat transfer loops, each of which includes a coolant pump and a steam generator. The design of the Turkey Point power plant, including the containment building and all major components, is similar to the design of the Trojan power plant.

The characteristics of the principal components of the Turkey Point Power plant are compared with corresponding components of the Trojan power plant.

Scaling factors are determined and applied to the Trojan costs to obtain estimates of the sectioning and disposal costs of the major components in the Turkey Point power plant. The comparative sectioning/disposal costs are listed in Table 3.1-15. The individual costs are then summed for the Turkey Point and Trojan power plants and the ratio of the sums provides a weighted, overall, power plant scaling factor. The total estimated dismantlement cost for the Turkey Point power plant is then calculated by multiplying the total dismantlement cost for the Trojan power plant as listed in Reference 1 by the overall scaling factor.

Detailed analyses are given in the following sections.

TABLE 3.1-15. Comparison of Estimated Dismantlement Costs for Turkey Point and Trojan PWR Power Plants

Major Component	Dismantlement Cost, 1978 Dollars ^(a)		Scaling Factor
	Trojan	Turkey Point	
Reactor Vessel	\$ 2 606 239	\$2 210 090	0.848
Vessel Internals	3 301 060	2 862 019	0.967
Primary Coolant Pumps and Piping	1 027 279	777 650	0.757
Steam Generators	767 798	487 552	0.635
Pressurizer	527 427	360 760	0.684
Containment Building	<u>2 361 481</u>	<u>1 585 703</u>	<u>0.671</u>
Total of Listed Dismantlement Costs	\$10 591 284	\$8 283 774	0.782

(a)The number of figures shown is for computational accuracy and does not imply precision to that many significant figures.

The total estimated cost of dismantling the Turkey Point power plant, including supplies, power, staff labor, etc., plus a 25% contingency factor, but not including the cost of spent fuel, is:

$$0.782 \times \$31,026,000 = \$24,262,332$$

The total estimated dismantlement cost of the Turkey Point power plant, including the cost of disposing of the spent fuel is:

$$\$24,262,332 + (1.25 \times \$2,025,410)^{(a)} = \$26,794,094$$

The corresponding cost for the Trojan power plant is \$34,112,000. These costs give a scaling factor of 0.786 for the dismantlement cost of the Turkey Point power plant, including the cost of disposing of the spent fuel.

3.1.5.1 Development of the Scaling Factor for the Sectioning and Disposal of the Turkey Point Reactor Vessel

The dimensions of the Turkey Point reactor vessel are listed in Table 3.1-16.

TABLE 3.1-16. Dimensions of Turkey Point Reactor Vessel

<u>Feature</u>	<u>Dimension</u>
Total Height Overall	12.98 m (4.258 ft)
I.D. of Shell	3.95 m (155.5 in.)
Shell Wall Thickness	233 mm (9.16 in.)
Lower Head Wall Thickness	125 mm (4.91 in.)
Closure Head Wall Thickness	161 mm (6.34 in.)
Length of Shell (cylinder)	9.03 m (29.62 ft)
Mean Diameter of Shell	4.18 m (164.66 in.)
Mean Diameter of Lower Head	4.07 m (160.41 in.)
Mean Diameter of Closure Head	4.11 m (161.84 in.)

From the listed data the overall height is 12.98 m and the O.D. of the shell equals 4.42 m (14.50 ft). The corresponding dimensions for the Trojan reactor vessel are:

$$\text{height} = 13.34 \text{ m and O.D. of shell below nozzle} = 4.84 \text{ m}$$

The mass ratio of the two vessels can be calculated by the method given in Section 3.6.3.1, as follows:

(a) From Section 3.1.5.7, includes a 25% contingency.

$$M_2/M_1 = \left(\frac{4.42}{4.84}\right)^2 \times \frac{(12.98 - 2.21)}{(13.34 - 2.42)} = 0.823$$

Based on the analysis of Yankee-Rowe (see Section 3.1.3.1), this value should be increased by about 3% to include structural variations from the simple model calculated, to obtain a scaling factor of 0.848.

This estimated scaling factor can be checked by calculating the masses of the three main portions of the reactor vessel--the closure head, the cylindrical body, and the lower head--and comparing the sum with the sum of the masses of the corresponding portions of the Trojan reactor vessel.

Cylindrical section:

Volume of steel = circumference at mean diameter x wall thickness x height

$$V = \pi \times D \times t \times h = \pi \times 4.18 \text{ m} \times 0.233 \text{ m} \times 9.03 \text{ m} = 27.63 \text{ m}^3 \text{ (975.7 ft}^3\text{)}$$

Add 1.29 m^3 for flange for attaching closure head to give a total volume of steel of 28.92 m^3 (1021.3 ft^3)

$$\text{Mass} = 28.92 \text{ m}^3 \times 7.861 \text{ tonne/m}^3 = 227.34 \text{ tonnes (250.60 tons)}$$

Closure head, hemisphere:

Volume of steel $\approx$ area of hemisphere of mean head diameter x wall thickness

$$V \approx 0.5 \times \pi D^2 \times t = 0.5 \times \pi \times 4.11^2 \text{ m}^2 \times 0.161 \text{ m} = 4.27 \text{ m}^3 \text{ (150.87 ft}^3\text{)}$$

Add 1.29 m^3 for flange to give Vol. of steel = 5.56 m^3 (196.35 ft^3)

$$\text{Mass} \approx 5.56 \text{ m}^3 \times 7.861 \text{ t/m}^3 = 43.71 \text{ tonnes (48.18 tons)}$$

Vessel bottom, or lower head, hemisphere:

Volume of steel $\approx$ area of hemisphere of mean diameter x wall thickness

$$V \approx 0.5 \times \pi \times D^2 \times t = 0.5 \times \pi \times 4.07^2 \text{ m}^2 \times 0.125 \text{ m} = 3.25 \text{ m}^3 \text{ (114.86 ft}^3\text{)}$$

$$\text{Mass} \approx 3.25 \text{ m}^3 \times 7.861 \text{ t/m}^3 = 25.55 \text{ tonnes (28.16 tons)}$$

The masses of the three components sum to 296.6 tonnes. If this total is increased by 15% of the mass of the cylindrical section to allow for the studs, nuts, washers, and nozzles, the mass of the Turkey Point reactor vessel is increased to 330.7 tonnes.

The sum of the masses of the corresponding portions of the Trojan reactor vessel equals 397.12 tonnes. This gives a ratio of the two masses of $330.7/397.12 = 0.83$, which is very close to the mass ratio calculated from the height and diameter dimensions.

The scaling factor for the Turkey Point reactor vessel is 0.848. The estimated cost of sectioning and disposing of the Turkey Point reactor vessel is:

$$0.848 \times \$2,606,239 = \$2,210,090$$

3.1.5.2 Development of the Scaling Factor for the Sectioning and Disposal of the Turkey Point Reactor Vessel Internals

The masses of the reactor vessel internals are compared by calculating the masses of the components in the Turkey Point reactor vessel for which the dimensions are given or can be estimated (thermal shield and core barrel), and estimating the mass of the other internals by comparing the core volumes.

The Turkey Point thermal shield is 3.759 m O.D. x 3.623 m I.D. x 5.03 m high (148.0 in. x 142.625 in. x 16.5 ft).

The volume of the metal is 3.97 m^3 (140.1 ft^3)

The mass of the thermal shield is 31.21 tonnes (34.4 tons)

The Turkey Point core barrel is 3.502 m O.D. x 3.400 m I.D. x 5.486 m high (137.875 in. x 133.875 in. x 18 ft).

The volume of metal is 3.03 m^3 (107.00 ft^3)

The mass is 23.82 tonnes (26.2 tons)

These compare with Trojan masses of 10.43 tonnes (11.50 tons) for the four thermal (neutron) shields and 45.36 tonnes (50.00 tons) for the upper and lower core barrels.

The two designs are quite different. The Turkey Point thermal shield is a solid circular ring of steel 3 in. thick. The neutron shields (thermal shields) in the Trojan reactor consist of four pads bolted to the outside of

the core barrel. The core barrel in the Turkey Point reactor is a single circular metal ring of steel 2-in. thick. The Trojan reactor contains an upper and a lower core barrel.

It is assumed, however, that the other portions of the internal structure (guide tubes, grid plates, shrouds, etc.) will be of comparable size and mass. These other portions, then, can be compared on the basis of the cross-sectional area of the core. Since the fuel assemblies are approximately the same length, this ratio is also the approximate volumetric ratio.

The total mass of the internals in the Trojan reactor equals 191.01 tonnes (210.5 tons). Excluding the core barrels and thermal shields reduces the mass to 135.22 tonnes (149.05 tons).

The transverse core area ratio is:

$(66.94/47)^2 = 0.818$, which is very close to the ratio of the number of fuel assemblies, $(157/193) = 0.814$.

Using a scaling factor of 0.818 for that portion of the vessel internals not covered in the Turkey Point FSAR gives a total mass for the Turkey Point reactor vessel internals of:

$$31.21 + 23.82 + 0.818 \times 135.22 = 165.64 \text{ tonnes (182.58 tons)}$$

The mass of the internals in the Trojan reactor vessel is 191.01 tonnes. The scaling factor for the Turkey Point reactor vessel internals is, then:

$$165.64/191.01 = 0.867$$

And the estimated cost of sectioning and disposing of the Turkey Point reactor vessel internals is:

$$0.867 \times \$3,301,060 = \$2,862,019$$

3.1.5.3 Development of the Scaling Factor for the Sectioning and Disposal of the Turkey Point Coolant Pumps and Piping

The pertinent features of the coolant pumps for the Turkey Point and the Trojan Power plants are listed in Table 3.1-17.

TABLE 3.1-17. Comparison of Turkey Point and Trojan Power Plant Coolant Pumps

<u>Feature</u>	<u>Trojan</u>	<u>Turkey Point</u>
Developed Head, "H", m (ft)	84.43 (277)	79.24 (260)
Flow Rate, "Q", m ³ /sec (gpm)	5.584 (88 500)	5.584 (88 500)
Discharge Nozzle I.D., m (in.)	0.699 (27.5)	0.698 (27.5)
Suction Nozzle I.D., m (in.)	0.787 (31.0)	0.787 (31.0)
Overall Unit Height, m (ft)	8.702 (28.55)	8.608 (28.24)
Mass, Dry, tonnes (wt, lb)	85.366 (188 200)	(a)
Motor Rated Power, kW (hp)	4 476 (6 000)	4 476 (6 000)

(a)Data not available.

Both pumps have nearly the same dimensions and both are powered by the same size of motor. The pump power outputs vary slightly,
 $Q \times H / Q \times H = 442.48 / 471.46 = 0.939$, ratio of Turkey Point output to Trojan output. If the masses of the pumps are compared by the one-third power ratio (see Section 3.6.3.2), the ratio of pump masses would equal $0.939^{1/3} = 0.979$, a relatively insignificant variation for estimating purposes. It can be assumed that the cost of sectioning and disposing of a Turkey Point coolant pump assembly would be the same as for a Trojan coolant pump assembly.

There are three loops, and thus three coolant pumps, in the Turkey Point power plant. There are four loops and four coolant pumps in the Trojan power plant. The scaling factor for dismantlement of the coolant pumps would thus equal $3/4$ or 0.75 .

The estimated mass of the Turkey Point power plant coolant pumps equals:

$$0.75 \times 341.10 = 255.83 \text{ tonnes}$$

The coolant flow is out of the reactor vessel, through the steam generator to the pump suction, and out of the pump back into the reactor vessel.

The reactor vessel inlet and outlet nozzles are at the same elevation. The inlet and outlet nozzles on the steam generators are at nearly the same elevation as are the suction and discharge nozzles on the coolant pumps. However, there is a U-section of pipe between a steam generator and a pump. There is also a short length of pipe between the main coolant lines and the pressurizer.

The coolant pipe data are tabulated in Table 3.1-18.

TABLE 3.1-18. Turkey Point Power Plant Coolant Piping Data

Component	Length, ^(a) m	Pipe Size, mm		Mass, ^(b) Tonne
		ID	Thickness	
Vessel to steam generator	5.49	737	63.5	20.65
Steam generator to pump	8.49	787	66.7	37.21
Pump to vessel	5.89	699	60.3	19.99
To pressurizer	3.0	267	28.6	<u>0.63</u>
Total				78.48

(a)Length per loop for coolant piping.

(b)Mass for three loops for coolant piping.

The estimated mass of the coolant pumps and piping in the Turkey Point power plant is $255.83 + 78.48 = 334.31$ tonnes (737,020 lb).

The mass of the coolant pumps and piping in the Trojan power plant is $341.10 + 100.70 = 441.80$ tonnes.

The scaling factor for the Turkey Point coolant pumps and piping equals $334.31/441.80 = 0.757$.

The estimated cost of sectioning and disposing of the Turkey Point coolant pumps and piping is $0.757 \times \$1,027,279 = \$777,650$.

3.1.5.4 Development of the Scaling Factor for the Sectioning and Disposal of the Turkey Point Steam Generators

The Turkey Point steam generators are similar to the Trojan steam generators in design and configuration. However, the Turkey Point power plant has three steam generators, whereas the Trojan plant has four.

A comparison of the pertinent features of the individual steam generators is given in Table 3.1-19.

TABLE 3.1-19. Comparison of Turkey Point and Trojan Steam Generators

Feature	Trojan	Turkey Point
Height, m (ft)	20.60 (67.6)	19.24 (63.13)
Diameter, Upper Portion, m (ft)	3.40 (11.15)	4.22 (13.83)
Lower Portion, m (ft)		3.24 (10.63)
Shell Thickness, Upper, mm (in.)		88.9 (3.5)
Lower, mm (in.)		66.8 (2.63)
Mass, tonnes (wt., lb)	311.6 (687 000)	264.9 (584 000)
Heat Transfer Surface Area, m ² (ft ²)	4 784.5 (51 500)	4 127.6 (44 430)
Rated Heat Capacity, MW	875	850
U-tube O.D., mm (in.)	22.2 (0.875)	22.2 (0.875)
U-tube Wall Thickness, mm (in.)	1.27 (0.50)	1.27 (0.050)
Tube Length, m (ft)	68 513 (224 793)	59 114 (193 943)

The length of heat transfer tubing is calculated from the heat transfer surface area and the U-tube outside diameter.

The volumetric ratio is approximately 0.85.

The heat transfer surface area ratio is 0.86.

The mass ratio can be estimated by the method given in Section 3.6.3.1:

$$M_2/M_1 = \left(\frac{3.24}{3.40} \right)^2 \times \frac{(19.24 - 1.62)}{(20.60 - 1.70)} = 0.847$$

This is the mass ratio for one Turkey Point steam generator compared with one Trojan steam generator. However, there are three steam generators in the Turkey Point power plant and four in the Trojan power plant. So the overall steam generator scaling factor for the Turkey Point power plant equals:

$$(3/4) \times 0.847 = 0.635$$

The estimated cost of sectioning and disposing of the Turkey Point steam generators equals:

$$0.635 \times \$767,798 = \$487,552$$

3.1.5.5 Development of the Scaling Factor for the Sectioning and Disposal of the Turkey Point Pressurizer

The Turkey Point pressurizer is a cylindrical vessel similar in design and configuration to the Trojan pressurizer. The scaling factor can thus be determined by the method described in Section 3.6.3.1.

The height and diameter of the Turkey Point and Trojan pressurizers are:

Turkey Point	height = 10.97 m	O.D. = 2.35 m
Trojan	height = 16.1 m (52.8 ft)	O.D. = 2.3 m (7.5 ft)

$$M_2/M_1 = \left(\frac{2.35}{2.3}\right)^2 \times \frac{(10.97 - 1.17)}{(16.1 - 1.15)} = 0.684$$

The estimated cost of sectioning and disposing of the Turkey Point pressurizer is:

$$0.684 \times \$527,427 = \$360,760$$

3.1.5.6 Development of the Scaling Factor for the Removal and Disposal of Contaminated Material from the Turkey Point Containment Building

The Turkey Point containment building is a post-tensioned reinforced concrete structure consisting of a cylinder and a shallow dome, connected to, and supported by, a massive reinforced concrete slab. The cylindrical section is 39.80 m (130.6 ft) high and 35.36 m (116 ft) inside diameter. The dome adds an additional 11.70 m (38.4 ft) to the internal height. The vertical wall is 0.965 m (38 in.) thick.

The reactor cavity at the bottom of the containment building is cylindrical in shape, and is 9.14 m (30 ft) deep by 5.79 m (19.0 ft) inside diameter. The wall is 2.29 m (7.5 ft) thick of concrete. An additional wall is added above the containment building floor to add 6.10 m (20 ft) to the height of the reactor cavity pit. This section has a wall thickness of 2.13 m (7.0 ft). The cavity plus extension constitute the primary shield and provide biological shielding.

The fuel transfer tube is 3.96 m (13 ft) long and 0.508 m (20 in.) I.D. x 0.610 m (24 in.) O.D. It is embedded in concrete.

The coolant pumps, steam generators, and pressurizer are all surrounded by secondary shielding walls of concrete. These walls also support the operating floor. These compartments are approximately 13.4 m (44 ft) high.

Refueling is performed under a protective pool of water. The refueling pool and spent fuel storage pool are reinforced concrete structures and are lined with 6.35 mm (0.250 in.) thick stainless steel plate.

Dismantlement of the Turkey Point containment building consists of removal and disposal of the activated and contaminated liners and concrete. The following components are considered:

1. Reactor cavity. The cavity consists of the cavity pit plus the biological shield above the containment building floor. The wall of the bio-shield will have been subjected to neutron irradiation and the concrete will be activated to a depth of roughly 1 m. This amount of concrete will have to be removed by blasting and chipping and transported to a nuclear waste storage facility.

Cavity I.D. = 5.79 m, remove a section 1.0 m thick

Mean diam. = 6.79 m, cavity depth = 9.14 m

Volume of activated concrete in cavity = $\pi \times 6.79 \text{ m} \times 1.0 \text{ m} \times 9.14 \text{ m} = 195.0 \text{ m}^3$

Volume in floor = $\pi/4 \times 7.79^2 \text{ m}^2 \times 0.10 \text{ m} = 4.77 \text{ m}^3$ (The floor would be contaminated, but not activated. Only a 100 mm thickness to be removed from the floor).

The extension of the reactor cavity above the containment building floor has a wall thickness of 2.13 m and a height of 6.10 m. It would be best to remove this in its entirety.

Volume = $\pi/4 \times (10.05^2 - 5.79^2) \text{ m}^2 \times 6.10 \text{ m} = 323.3 \text{ m}^3$

Total volume of concrete to be removed from the reactor cavity equals:

$$195.0 \text{ m}^3 + 4.77 \text{ m}^3 + 323.3 \text{ m}^3 = 523.07 \text{ m}^3$$

The mass of the concrete equals $523.07 \text{ m}^3 \times 2.403 \text{ tonnes/m}^3 = 1256.94 \text{ tonnes}$.

2. Shielding walls for coolant pumps and steam generators. The concrete in the 63.5 mm thick exposed surface layer of walls, floors, and ceilings must be removed and disposed of. There are three double compartments, each holding a coolant pump and a steam generator. There is also a compartment for the pressurizer. The wall height was taken as 13.4 m (44 ft). The total estimated wall areas equal 1422 m^2 ($15,311 \text{ ft}^2$) the floor and ceiling total 414 m^2 . This gives a total surface area of 1836 m^2 .

Volume of concrete to be removed = $1836 \text{ m}^2 \times 0.0635 \text{ m} = 116.6 \text{ m}^3$.

Mass of concrete = $116.6 \times 2.403 = 280.19 \text{ tonnes}$ (308.85 tons)

3. Fuel transfer tube. The tube and surrounding concrete would both have to be removed and transported to a nuclear waste disposal site for burial. The fuel transfer tube is 3.96 m (13 ft) long and appears to consist of two steel tubes 508 mm (20 in.) and 610 mm (24 in.) in diameter. It is surrounded by concrete 914 to 1372 mm (3 ft to 4.5 ft) thick. The concrete would have to be broken up and disposed of in a nuclear waste storage burial ground. The steel liners would also have to be segmented and disposed of.

The concrete to be removed can be considered as having a rectangular cross section, 914 mm x 914 mm (3 ft x 3 ft) inside dimensions with a 914 mm thickness at the bottom and 1.372 m (4.5 ft) thick side and top. The cross-sectional area of concrete then equals $(1.372 + 0.914 + 0.914) \text{ m} \times (1.372 + 0.914 + 1.372) \text{ m} - (0.914 \times 0.914) \text{ m}^2 = 10.87 \text{ m}^2$. The volume of concrete would equal $10.87 \text{ m}^2 \times 3.96 \text{ m} = 43.05 \text{ m}^3$. Some of this concrete would be in the wall of the containment building and some would be in the wall of the spent fuel storage pool.

The mass of the concrete to be removed and disposed of is estimated to equal $43.05 \text{ m}^3 \times 2.403 \text{ tonnes/m}^3 = 103.45 \text{ tonnes}$.

The estimated costs of removing and disposing of the activated/contaminated material from the Turkey Point containment building are tabulated in Table 3.1-20.

TABLE 3.1-20. Costs of Removing and Disposing of Activated/Contaminated Material

Feature	Mass of Concrete to be Removed (tonnes)	Cost of Removal and Disposal (1978 dollars)(a)
Reactor Cavity	1 256.94 ^(b)	\$1 214 895
Pump/Steam Generator Shielding Walls	280.19	270 818
Fuel Transfer Tube	<u>103.45</u>	<u>99 990</u>
	1 640.58	\$1 585 703

(a)The number of figures shown is for computational accuracy and does not imply precision to that many significant figures.

(b)The cost of removal and disposal equals \$966.55/tonne of concrete, including allowance for steel liner plates and other factors (see Section 3.6.1.6).

The total estimated cost of removing and disposing of the activated/contaminated material from the Turkey Point containment building compares with a cost of \$2,361,481 for removal and disposal of activated/contaminated material from the Trojan containment building. Comparison of the two costs gives a scaling factor of $1,585,703/2,361,481 = 0.671$ for the Turkey Point containment building.

3.1.5.7 Development of the Scaling Factor for Disposing of the Turkey Point Spent Fuel

As noted previously (Section 3.1.2.7), the cost of disposing of the spent fuel is primarily the cost of cask rental and of transporting the fuel to an approved fuel storage facility. The transportation cost, in turn, depends on the number of fuel assemblies that must be disposed of.

The Turkey Point reactor contains 157 fuel assemblies that measure 214 mm x 214 mm. These are very nearly the same size as the Trojan fuel assemblies.

The spent fuel assemblies are transported in fuel casks. Each cask holds seven fuel assemblies. There are 193 fuel assemblies in the Trojan power plant reactor. Transportation of the core would require 28 fuel cask loads. The 157 fuel assemblies in the Turkey Point power plant reactor would require 23 fuel cask loads. The relative cost of disposing of the fuel would thus equal $23/28 = 0.821$, which is the scaling factor for the disposal of the Turkey Point spent fuel.

The estimated cost of disposing of the Turkey Point spent fuel is $0.821 \times \$2,467,000 = \$2,025,410$.

3.1.6 Discussion of Results

The estimated total dismantlement costs for the four PWR power stations examined in this addendum are listed in Table 3.1-21, together with the scaling factors derived from the ratios of the estimated cost for a given reactor divided by the estimated cost for the reference reactor (Trojan). The costs and scaling factors are derived for dismantlement, including and excluding the cost of spent fuel disposal.

The derived scaling factors listed in Table 3.1-21 are plotted as a function of the thermal power rating of the individual power stations in Figures 3.1-1 and 3.1-2 for the cases of excluding spent fuel disposal and including spent fuel disposal, respectively. The scaling factors are fitted with linear functions of the plant thermal power ratings to obtain expressions for the overall scaling factor (OSF) for immediate dismantlement:

$$\text{OSF (excluding fuel disposal)} = 0.2352 + 2.173 \times 10^{-4} \text{ (MWt)}$$

$$\text{OSF (including fuel disposal)} = 0.2527 + 2.122 \times 10^{-4} \text{ (MWt)}$$

TABLE 3.1-21. Comparison of Estimated Dismantlement Costs of Four PWR Power Plants

Power Plant	Power Rating (MW thermal)	Including Spent Fuel Disposal		Excluding Spent Fuel Disposal	
		Scaling Factor(a)	Total Dismantlement Cost(b) (1978 dollars)(c)	Scaling Factor(a)	Total Dismantlement Cost(b) (1978 dollars)(c)
Yankee-Rowe	600	0.297	\$10 147 402	0.288	\$ 8 935 488
Ginna	1 300	0.532	18 147 396	0.521	16 164 546
Turkey Point	2 550	0.786	26 794 094	0.782	24 262 332
Trojan	3 500	1.00	34 110 000	1.000	31 026 000

(a) The scaling factor is the ratio of the dismantlement cost of the reactor as developed in this report compared with the dismantlement cost of the Trojan reactor.

(b) The total cost includes all costs--staff labor, insurance, power, supplies, etc. It also includes an added 25% contingency.

(c) The number of figures shown is for computational accuracy and does not imply precision to that many significant figures.

FIGURE 3.1-1 Normalized Decommissioning Costs for PWR Power Plants as a Function of Plant Power Rating, Excluding Costs of Disposing of Spent Fuel

FIGURE 3.1-2 Normalized Decommissioning Costs for PWR Power Plants as a Function of Plant Power Rating, Including Costs of Disposing of Spent Fuel

Because the Yankee-Rowe plant is quite different from the three larger, similar plants, only the data for the three larger, similar plants are used in the fitting analysis employed to obtain the scaling factor equations. These equations and the lines resulting from their evaluation are also shown in Figures 3.1-1 and 3.1-2. As these figures show, the equations predict the scaling factors of dismantlement of the three largest, similar reactors quite well, but overestimate the scaling factor for dismantlement of Yankee-Rowe.

The estimated immediate dismantlement cost for a reactor station with a given power rating can be obtained from:

$$\text{Immediate Dismantlement (\$)} = \$31.026 \text{ million} \times \text{OSF (MWt)}$$

excluding spent fuel disposal, and

$$\text{Immediate Dismantlement (\$)} = \$34.112 \text{ million} \times \text{OSF (MWt)}$$

including spent fuel disposal. Unless specifically stated otherwise, the term OSF (MWt) as used elsewhere in this report refers to the case excluding spent fuel disposal.

The scaling factors derived for the individual components examined in this study are summarized in Table 3.1-22.

TABLE 3.1-22. Individual Component Scaling Factors for Immediate Dismantlement

<u>Component</u>	<u>Yankee-Rowe</u>	<u>R. E. Ginna</u>	<u>Turkey Point</u>	<u>Trojan</u>
Reactor Vessel	0.343	0.548	0.848	1.0
Vessel Internals	0.180	0.665	0.867	1.0
Pumps and Piping	0.547	0.493	0.757	1.0
Steam Generators	0.289	0.424	0.635	1.0
Pressurizer	0.172	0.316	0.684	1.0
Containment Bldg.	0.290	0.379	0.671	1.0

These individual component scaling factors can also be fitted with equations to facilitate interpolation. Since each of the individual sets of data tends to exhibit a definite curvature, the sets are fitted to equations of the form $SF_i = A_i + B_i (\text{MWt}) + C_i (\text{MWt})^2 + D_i (\text{MWt})^3$ where the subscript i refers

to the i^{th} major component. In two cases (vessel internals, and pumps and piping) the Yankee-Rowe scaling factors are not used in the fitting analysis because they depart very significantly from the general pattern for the other three plants. The individual component scaling factors, together with the fitted equations and the curves defined by the equations, are shown in Figures 3.1-3, -4, -5, -6, -7, and -8 for the reactor vessel, vessel internals, pumps and piping, steam generators, pressurizer, and containment building dismantlements, respectively.

3.2 RELATIONSHIP OF DEMOLITION COST TO REACTOR POWER PLANT SIZE

Following decommissioning it may be desirable, in some instances, to demolish the decontaminated and released power plant structures and restore the site to pre-facility conditions. Such a demolition procedure would include removal of all above-grade structures, removal of below-grade structures to a depth of 1 m below grade level, and fracturing of base floors and substructures sufficiently to permit normal drainage of surface waters through those floors and substructures.

The estimated demolition costs for the Trojan power plant are listed in Table 10.1-3 of NUREG/CR-0130. These estimates were determined by an experienced demolition contractor and were based on information available to him at that time. Since then, however, more accurate demolition cost information regarding the two major items in the table has become available. Published information regarding the actual costs of demolishing cooling towers in Europe indicates that the estimated cooling tower demolition cost listed in Table G.4-10 of NUREG/CR-0130 is probably about \$1,000,000 higher than it should be. On the other hand, further study of the type of construction employed in the Trojan containment building indicates that the cost of demolishing that building (listed in Table G.4-10) would probably be about \$1,000,000 higher than originally estimated.

The costs given in Table 10.1-3, modified in accordance with the later information discussed above and including a 25% contingency, are listed in Table 3.2-1.

FIGURE 3.1-3. Scaling Factor for Dismantlement of Reactor Vessel versus Plant Power Rating

FIGURE 3.1-4. Scaling Factor for Dismantlement of Reactor Vessel Internals versus Plant Power Rating

FIGURE 3.1-5. Scaling Factor for Dismantlement of Primary Pumps and Piping versus Plant Power Rating

FIGURE 3.1-6. Scaling Factor for Dismantlement of Steam Generators versus Plant Power Rating

FIGURE 3.1-7. Scaling Factor for Dismantlement of Pressurizer versus Plant Power Rating

FIGURE 3.1-8. Scaling Factor for Dismantlement of Containment Building versus Plant Power Rating

The data in Table 3.2-1 show that the principal demolition cost items are the containment building, the cooling tower(s), the turbine building, and the auxiliary building.

TABLE 3.2-1. Estimated Demolition Costs for the Trojan PWR Power Plant

<u>Component</u>	<u>Estimated Demolition Cost 1978 dollars(a,b)</u>	<u>Percent of Total Cost</u>
Cooling Tower	\$1 835 000	22.9
Containment Building	2 908 750	36.3
Auxiliary Building	832 250	10.4
Fuel Building	472 750	5.9
Control Building	534 250	6.6
Turbine Building	1 087 375	13.6
Turbine Auxiliary Building	134 250	1.7
Condensate Demineralizer Building	35 500	0.4
Administration Building	23 375	0.3
Shop and Warehouse	2 750	0.0
Chlorine Building	8 000	0.1
Allowance for Other, Undefined Structures/Components	69 500	0.9
Area Land Filling, Excluding Roadways	<u>69 500</u>	<u>0.9</u>
Total	\$8 013 250	100.0

(a)The number of figures shown is for computational accuracy and does not imply precision to that many significant figures.

(b)Includes a 25% contingency.

3.2.1 Containment Building Demolition

All PWR power plants have containment buildings. The estimated demolition costs for these buildings can be compared on the basis of the volume of concrete contained in the building for containment buildings of similar design. The dimensions of, and the volume of concrete contained in, the containment buildings of the three larger power plants considered in this study are listed in

Table 3.2-2. The Yankee-Rowe containment buildings is of such a markedly different design and construction that it cannot be compared on the same basis as the other three containment buildings, so data regarding the Yankee-Rowe containment building are not included in the table.

TABLE 3.2-2. Dimensions and Volumes of Concrete in Containment Buildings

Component	Ginna	Turkey Point	Trojan
Cylindrical Section			
I.D., m (ft)	32.09 (105.3)	35.36 (116)	42.67 (140)
Wall Thickness, mm (ft)	1 067 (3.5)	1 143 (3.75)	1 219 (4.0)
Height, m (ft)	30.17 (99)	46.02 (151)	41.60 (136.5)
Volume of Concrete, m ³ (ft ³)	3 344 (118 100)	6 031 (213 000)	6 994 (247 000)
Dome			
Form	Hemisphere	Paraboloid	Hemisphere
I.D., m (ft)	32.09 (105.3)	35.36 (116)	42.67 (140)
Height, m (ft)	16.00 (52.5)	5.49 (18)	21.33 (70)
Wall Thickness, mm (ft)	762 (2.5)	991 (3.25)	914 (3.0)
Volume of Concrete, m ³ (ft ³)	1 285 (45 390)	1 169 (41 300)	2 730 (96 400)
Base Slab			
Diameter, m (ft)	34.23 (112.3)	37.64 (123.5)	45.11 (148)
Thickness, m (ft)	1.00 (3.28)	1 00 (3.28)	1.0 (3.28)
Volume of Concrete, m ³ (ft ³)	920 (32 500)	1 114 (39 300)	1 598 (56 400)
Total Volume of Concrete, m ³ (ft ³)	5 550 (196 000)	8 314 (29 600)	11 321 (399 800)
Volume Concrete Volume Trojan Concrete	0.490	0.734	1.00

The internal volume of a cylindrical PWR containment building increases as the power rating of the reactor increases. Thus, $V \propto P$ (MWt). That same internal volume is also proportional to the square of the diameter times the height, D^2H , or D^3 , since the height-to-diameter ratio is usually near unity. Therefore, P (MWt) $\propto D^3$ and $D \propto P^{1/3}$. The volume of material contained in the cylindrical wall of the containment building is proportional to DH or D^2 . By substitution, $D^2 \propto P^{2/3}$, and the scaling factor for containment building demolition can be expressed as the ratio of the given plant power rating to the Trojan power rating, raised to the two-thirds power.

The ratio of the volume of concrete in each containment building divided by the volume of concrete in the Trojan containment building is plotted against the power rating of the power plant in Figure 3.2-1. Also plotted in the figure is a curve of the ratio of plant power rating divided by the power rating of the Trojan power plant with the ratio raised to the 2/3 power, or $(MWt/3500)^{2/3}$. The curves and the data points are very close to one another, so a reasonable estimation of the cost of demolishing a containment building,

FIGURE 3.2-1. Containment Building Shell Concrete Volume as a Function of Plant Power Rating

over a range of thermal ratings from 600 MWt to 3500 MWt, may be obtained from the following relationship:

$$CBEDC(\$) = (MWt/3500)^{2/3} \times \$2,908,750$$

3.2.2 Cooling Tower Demolition

The Trojan power plant is the only one of the four power plants considered in this study that employs a cooling tower for condenser water cooling. The Yankee-Rowe power plant utilizes pond water for cooling and contains provisions for the possible future installation of a cooling tower. The Ginna power plant is located on the shore of Lake Ontario and utilizes lake water for condenser cooling. The Turkey Point power plant draws water from Biscayne Bay for condenser cooling. Demolition of these three condenser water cooling systems would be much less expensive than demolishing a cooling tower with the same cooling water capacity as the pond or lake water presently used. However, the present trend is definitely toward increased use of cooling towers for supplying condenser cooling water rather than using stream or lake water for ecological reasons.

Because of the trend toward greater use of cooling towers and because many of the existing PWR power plants include cooling towers, the estimated cost of demolition determined in this study includes the cost of cooling tower demolition.

It is assumed that the cooling capacity of a cooling tower is roughly proportional to its internal volume (cross-sectional area times distance of air flow). It is also assumed that the height-diameter ratio is about the same for different sizes of cooling towers and that the wall thickness does not vary widely for different sizes in the range being considered. If the shape is simplified to that of a right circular cylinder, then the volume of concrete in the cooling tower body will vary approximately as the 2/3 power of the ratio of the thermal power rating of the i^{th} power plant to the Trojan plant. The estimated demolition cost of a cooling tower is roughly proportional to the volume of concrete in the shell so a reasonable approximation

for the cooling tower estimated demolition cost (CTEDC) can be represented by the following relationship:

$$\text{CTEDC}(\$) = (\text{MWt}/3500)^{2/3} \times 1,835,000, \text{ including a 25\% contingency factor.}$$

This approximation does not take into consideration the fact that the wall of a larger cooling tower would probably be somewhat thicker than the wall of a small one, though not in proportion to diameter nor to thermal rating. Since the comparison is made on the basis of the large Trojan power plant cooling tower, the simplification is conservative. Neither is any account taken of the fact that many of the larger power plants use two smaller cooling towers rather than one larger one. The cost of demolishing two smaller cooling towers would probably be greater than the cost of demolishing a single cooling tower which has a thermal rating equal to the sum of the thermal ratings of the two smaller ones. These two variables tend to balance one another. Moreover, the effect of these variables is not large enough to significantly affect the estimated demolition cost for a cooling tower of this type of design.

3.2.3 Auxiliary Building Demolition

All PWR power plants have auxiliary and control buildings. The costs of demolishing these buildings would be proportional to their size and the mass of concrete contained in them. The sizes of the buildings will be roughly proportional to the plant size, or the thermal rating of the power plant. It is assumed that the buildings will all be of roughly the same design and construction, and that the thicknesses of the walls, ceilings, foundations, etc., will all be very nearly the same. The areas of the walls, floors, etc., and thus the volumes (and masses) of the materials to be dismantled and disposed of, will be proportional to the volumes, or sizes, of the buildings to the $2/3$ power. Thus, a reasonable approximation of the estimated cost of demolition of the auxiliary building for a given power plant can be arrived at by multiplying the estimated demolition cost of the Trojan buildings by the ratio of the power rating of the plant being considered to the power rating of the

Trojan power plant, raised to the 2/3 power, or, for the auxiliary building:

$$ABEDC(\$) = (MWt/3500)^{2/3} \times \$832,250, \text{ including a 25\% contingency.}$$

The same reasoning applies to the other, smaller miscellaneous buildings, including those listed in Table 3.2-1, with the possible exception of the turbine building.

3.2.4 Turbine Building Demolition

The Turkey Point power plant has no covering over the turbines, so it might be said not to have a turbine building. However, the most important and most massive portion of a turbine building is the foundation constructed to hold the turbine and prevent vibration. The shell portion that protects the turbine from the weather would be relatively easy to demolish compared with the turbine and the foundation. So the matter of whether or not there is a weather protection shell over the turbine would not have any marked effect on the demolition cost.

The foundation for a large turbine would be larger than that for a smaller one, but not in linear proportion. The 2/3 power ratio used previously for the other structures will also give a reasonable basis for estimating the demolition cost of a turbine building. For example, $2^{2/3} = 1.59$, which implies that if the turbine power rating is doubled, 59% more structure would be required to support it. This seems reasonable, so the approximation also appears reasonable for the purpose of estimating the demolition costs of the turbine building.

3.2.5 Miscellaneous and Undefined Demolition Costs

These costs, plus the cost of landfilling, sum to only 1.8% of the total demolition cost. Considering these costs to be in the same proportion as the other major costs will introduce negligible error.

3.2.6 Power Plant Demolition Cost Estimate

The major demolition cost items discussed above all conform to the 2/3 power relationship with acceptable accuracy for the purpose of cost estimation within the range of power plants considered. For example, the use of this relationship implies that the cost of demolishing the structures of a 600-MWt rated power plant would equal about $(600/3500)^{2/3} = 0.309$, or 31% of the estimated cost of demolishing the structures of the Trojan Power plant. This appears to be a reasonable estimate for the whole, and the 2/3 power relationship has been shown to provide a reasonable estimating relationship for the major power plant structures considered above. Thus, a reasonable value for the estimated demolition cost (EDC) in 1978 dollars for a PWR power plant in sizes equal to or larger than 600 MWt can be obtained from the following relationship:

$$\begin{aligned} \text{EDC} &= (\text{MWt}/3500)^{2/3} \times \$8,013,250, \text{ or} \\ \text{EDC} &= (\text{MWt})^{2/3} \times \$34,761 \end{aligned}$$

3.3 SAFE STORAGE WITH DEFERRED DISMANTLEMENT

As an alternative to immediate dismantlement, a nuclear power plant may be placed in safe storage, with dismantlement to be accomplished at some future time. Continuing surveillance and maintenance of the power plant facilities are required throughout the interim period between the time the plant is placed in safe storage and the time that it is dismantled. A more complete discussion of the definition and conditions of safe storage is contained in NUREG/CR-0130.

The estimated cost of placing the Trojan power plant in safe storage may be determined from the data in Table 10.2-1 of NUREG/CR-0130. The pertinent data are listed in Table 3.3-1.

The cost of preparing a power plant for safe storage includes many of the same factors as were included in the study of the costs of immediate dismantlement. The cost of preparing a particular PWR power plant for safe storage, as compared with preparing the Trojan power plant for safe storage, would then

TABLE 3.3-1. Estimated Costs of Preparing the Trojan
PWR Power Plant for Safe Storage

<u>Cost Item</u>	<u>Cost in Thousands of Dollars (1978 dollars)(a)</u>
Staff Labor (includes indirect cost)	3 641.3
Other Costs ^(b)	<u>3 984.3</u>
Subtotal	7 625.6
25% Contingency	<u>1 906.4</u>
Total	\$9 532.0

(a)Number of significant figures shown is for computational accuracy and does not imply precision to that many significant figures.

(b)Does not include disposal of spent fuel.

be in roughly the same proportion as the costs of dismantlement. Thus, the cost of preparing a PWR power plant for safe storage can be estimated by multiplying the cost of preparing the Trojan power plant for safe storage by the overall scaling factor (OSF), as derived in Section 3.1.6.7.

The cost of dismantlement will decrease with time because of the decay of the contaminating radionuclides. The estimated reduced costs for different lapses of time are listed in Table H.5-2 of NUREG/CR-0130. The applicable data are repeated in Table 3.3-2.

The items in the table are much the same as those considered in Section 3.1 to determine the estimated cost of immediate dismantlement. Therefore, the overall scaling factor will also apply here. The estimated cost of dismantling a PWR power plant after a period of safe storage will thus equal the overall scaling factor times the estimated cost of dismantling the Trojan power plant after a similar lapse of time in safe storage.

Another expense item that must be considered in estimating the cost of safe storage with delayed dismantlement is the cost of continuing surveillance and maintenance during the period of safe storage. The estimated yearly cost for surveillance and maintenance for the Trojan power plant is determined in Table H.4-1 of NUREG/CR-0130 and equals \$79,824/yr, including a 25% contingency.

TABLE 3.3-2. Estimated Costs of Dismantlement for the Trojan PWR Power Plant After Different Lengths of Time in Safe Storage

Cost Item	Dismantlement Cost in megadollars (1978 dollars) ^(a,b)			
	Immediate Dismantlement	Dismantlement Deferred for		
		10 or 30 Years	50 Years	100 Years
Equipment	1.028	0.953	0.953	0.953
Supplies	1.949	1.057	1.057	1.057
Power	4.375	4.117	4.117	4.117
Activated Materials	3.418	3.418	3.418	3.418
Contaminated Materials	6.479	6.479	0.040	0.040
Radioactive Waste	0.866	0.413	0.319	0.261
Staff Labor	11.233	11.233	11.233	11.233
Contractor Services	0.680	0.680	0.680	0.680
Nuclear Insurance	<u>1.000</u>	<u>0.500</u>	<u>0.500</u>	<u>0.500</u>
Total	\$31 028	\$28 850	\$22.317	\$22.259

(a)The number of significant figures shown is for computational accuracy and does not imply precision to that many significant figures.

(b)Values include a 25% contingency.

The cost breakdown in the NUREG/CR-0130 table includes allowances for security, health physics, instrumentation, repairs, radiochemistry, utilities, supplies, secretarial services, and other miscellaneous charges. All of these are for limited usage and part-time servicing. They are merely caretaking functions and, as such, cannot be expected to vary a great deal with the size of the power plant, with the possible exception of the cost of utilities. The cost of the utilities is only a small portion of the yearly cost and a variation in that cost would not markedly affect the total; thus no allowance is made for power plant size in the estimated yearly cost of surveillance and maintenance (S&M) during the period of safe storage. The estimated cost of \$79,824/yr is assumed to apply equally to all sizes of PWR power plants.

To estimate present costs of future dismantlements on a uniform basis the different costs--present, future, and yearly--should all be compared on

either a present cost basis or a future cost basis, with a sinking fund for the yearly S&M costs. However, interest rates are not stable and vary not only with time, but also with company policy. The picture is further clouded by the changing rate of inflation. As a result, no meaningful net interest rate can be established. So no attempt is made here to establish total costs on either a present value or future value basis. Instead, the three different costs are given on the basis of 1978 dollars. This permits each user to apply his own accounting procedures to the basic data.

The present cost equals the safe storage cost. The costs of preparing the Trojan power plant for safe storage are itemized in Table 10.2-1 of NUREG/CR-0130. The costs listed in the table include the cost of disposal of the spent fuel and the cost of the security program. The cost of disposing of the spent fuel is not included in this estimate of present cost.

The costs of installing and setting up of the security hardware are detailed in Table H.4-3 of NUREG/CR-0130. These costs will be nearly the same for all power plants, regardless of size. For the purpose of this method of estimation, the security program installation, maintenance, and operational costs are considered to be the same for all sizes of power plants.

The subtotal of Table 10.2-1, modified in accordance with the above, thus becomes \$10,092,600 - \$2,467,000 (spent fuel) - \$85,800 (security) = \$7,539,800. Adding a 25% contingency factor gives an estimated cost of \$9,424,700 for preparing the Trojan power plant for safe storage, omitting the costs of disposal of the spent fuel and installation of the security program. The estimated cost of installing the security program, including the first year of operation equals (Table H.4-3, NUREG/CR-0130) \$85,800 plus a 25% contingency, or \$107,250.

3.3.1 Initial Costs of Safe Storage

The estimated total cost of preparing a PWR power plant for safe storage (ETCSS) thus equals the overall scaling factor times the preparation cost for Trojan of \$9,424,700 plus the cost of installing the security program of \$107,250.

$$\text{ETCSS}(\$) = [\$9,424,700 \times \text{OSF}(\text{MWt})] + \$107,250.$$

3.3.2 Yearly Costs of Surveillance and Maintenance

The yearly cost of surveillance and maintenance is estimated to be \$79,824, the same for all sizes of PWR power plants, as given in Table H.4-1 of NUREG/CR-0130.

3.3.3 Costs of Safe Storage and Deferred Dismantlement

The total cost of safe storage with dismantlement at the end of 10 years, based on 1978 dollars and ignoring the effects of interest and inflation, can be estimated as follows (ref. Sections 3.3.1 and 3.3.2 and Table 3.3-2):

$$[10 \text{ yr} \times \$79,824/\text{yr}] + \{\text{OSF (MWt)} \times [\$24,850,000 + \$9,424,700]\} + \$107,250,$$

since 10 years of surveillance and maintenance equals \$798,240, dismantlement after 10 years equals $\text{OSF(MWt)} \times \$28,850,000$, the preparations for safe storage equals $\text{OSF(MWt)} \times \$9,424,700$, and installation of the security system equals \$107,250.

The total costs for the other periods of time treated in Table 3.3-2 can be calculated in a similar fashion. The costs are listed in Table 3.3-3.

TABLE 3.3-3. Total Estimated Cost of Safe Storage and Deferred Dismantlement for PWR Power Plants

	<u>Decommissioning Cost in 1978 Dollars^(a,b)</u>
Immediate Dismantlement	$31\,026\,000 \times \text{OSF (MWt)}^{(c)}$
Safe Storage + Deferred Dismantlement (10 yrs)	$905\,490 + [\text{OSF (MWt)} \times 38\,274\,700]$
Safe Storage + Deferred Dismantlement (30 yrs)	$2\,501\,970 + [\text{OSF (MWt)} \times 38\,274\,700]$
Safe Storage + Deferred Dismantlement (50 yrs)	$4\,098\,450 + [\text{OSF (MWt)} \times 31\,742\,000]$
Safe Storage + Deferred Dismantlement (100 yrs)	$8\,089\,650 + [\text{OSF (MWt)} \times 31\,684\,000]$

(a) The number of significant figures shown is for computational accuracy and does not imply precision to that many significant figures.

(b) The figures given are based on constant dollars and ignore the effects of interest and inflation.

(c) OSF(MWt) = overall scaling factor as a function of plant thermal power rating.

The estimated costs of dismantlement as calculated by the relationships in Table 3.3-3 for the four power plants considered in this study are tabulated in Table 3.3-4 for the purpose of comparison.

TABLE 3.3-4. Estimated Costs of Safe Storage and Deferred Dismantlement (calculated with the relationships given in Table 3.3-3)

Dismantlement Deferral Time (years)	Dismantlement Costs, megadollars (a,b)			
	Power Plant Rating, MWt			
	600	1300	2550	3500
0	12.050	16.538	24.639	31.026
10	15.770	21.306	31.299	39.180
30	17.367	22.903	32.896	40.777
50	16.426	21.016	29.304	35.840
100	20.395	24.978	33.250	39.774

(a) Number of figures shown is for computational accuracy and does not imply precision to that many significant figures.

(b) In constant value 1978 dollars. No allowance for interest or inflation.

3.4 ENTOMBMENT

Another alternative to immediate dismantlement is entombment--the encasement of all radioactive materials remaining at the site of the power plant, in concrete or other structural material that is sufficiently strong and structurally long-lived to assure retention of the radioactivity until it has decayed to levels that permit unconditional release of the site. Entombment of the Trojan power plant is discussed in detail in Section 4 of this addendum.

The operations required for entombment include, basically, chemical decontamination where necessary, and storage, in the containment building below the operating floor level, of as much as possible of the contaminated equipment and material located elsewhere in the power plant. A continuous slab of concrete is then poured above the operating floor level in the containment building, and all wall penetrations below the floor level are sealed.

Included in the entombment process is dismantlement of all power plant facilities except those located below the containment building operating floor (which are buried). The entombment operations are similar in nature to the dismantlement operations, and many of the same components are included. It therefore seems reasonable that the ratio of entombment costs would be very nearly the same as the ratio of dismantlement costs. Estimated entombment preparation costs are thus taken as equal to the estimated entombment preparation cost for the Trojan power plant, derived in Section 4 of this addendum, times the OSF derived in Section 3.1.6.7.

The estimated entombment preparation costs for the Trojan power plant equal \$20,344,000 for entombment with reactor internals and \$25,114,000 for entombment with reactor internals removed to an appropriate nuclear waste storage facility (data from Table 4.5-1 of this report).

In addition to the entombment preparation cost there would be continuing costs of surveillance and maintenance. These are estimated at \$30,000 to \$40,000 per year, somewhat less than the surveillance and maintenance costs for safe storage (see Section 3.3). The surveillance and maintenance costs are assumed to be the same for all sizes of power plants, as discussed in Section 3.3.

The total estimated cost of entombment (TEEC), in constant 1978 dollars, for the case of reactor internals removed is given by:

$$\text{TEEC}(\$) = [\text{OSF (MWt)} \times \$25,114,00] + [n \times \$40,000],$$

where n = number of years of safe storage.

The total estimated entombment costs, assuming a 100 year surveillance and maintenance requirement, for the four power plants considered in this study are listed in Table 3.4-1. These estimates do not include any costs associated with termination of the entombed storage condition.

TABLE 3.4-1. Total Estimated Entombment Costs, Reactor Internals Removed, after 100 Years of Storage

Reactor Power Rating, MWt	Total Estimated Entombment Costs ^(a,b) 1978 Dollars
600	13 754 000
1 300	17 386 000
2 550	23 943 000
3 500	29 114 000

(a)The number of significant figures shown is for computational accuracy and does not imply precision to that many significant figures.

(b)The estimated costs assume constant 1978 dollars with no allowance for interest or inflation.

The total estimated entombment cost (TEEC) for a PWR power plant in which the reactor vessel internals are retained in the containment building equals:

$$\text{TEEC}(\$) = [\text{OSF (MWt)} \times \$20,344,000] + [n \times \$40,000],$$

where n has no limit.

3.5 PUBLIC AND OCCUPATIONAL SAFETY

The public and occupational safety impacts resulting from the different methods of decommissioning considered in this report (immediate dismantlement, safe storage and deferred dismantlement, and entombment) are discussed in detail for the Trojan power plant in NUREG/CR-0130 and in Section 5 of this report. The individual equations for radiation dose developed in this section are evaluated and presented in Table 3.5-1 for the four reactors considered in this report.

The amount of radiation produced by the activated/contaminated materials during the decommissioning operation will be in direct proportion to the amount of the activated/contaminated material of similar types in the different power plants. Thus, the amount of radiation dose, both occupational and public,

TABLE 3.5-1. Public and Occupational Radiation Dose Estimates for Decommissioning (in man-rem)(a)

	<u>Yankee-Rowe</u>	<u>R. E. Ginna</u>	<u>Turkey Point</u>	<u>Trojan</u>
Overall Scaling Factor	0.388	0.533	0.794	1.000
Immediate Dismantlement				
Decommissioning Worker	544	746	1 112	1 404
Transport Worker	40	55	82	103
Public	8	12	17	22
Entombment (with/without internals)				
Decommissioning Worker	349/388	480/533	715/794	900/1 000
Transport Worker	6/8	9/11	13/17	16/21
Public	2/2	2/2	3/3	4/4
Preparations for Safe Storage				
Decommissioning Worker	165	227	338	426
Transport Worker	5	8	11	14
Public	1	2	2	3
Safe Storage				
for 30 Years	14	14	14	14
for 50 Years	14	14	14	14
for 100 Years	14	14	14	14
Deferred Dismantlement				
After 30 Years	12	16	24	30
After 50 Years	1	1	2	2
After 100 Years	1	1	1	1

(a)All dose estimates are rounded to the nearest whole man-rem.

will be proportional to the mass of material handled. Since most of the components that make up the overall scaling factor are derived on a mass basis, the occupational radiation dose should also be expressed in terms of the overall scaling factor, i.e., Reference Radiation dose x OSF (MWt).

3.5.1 Estimated Accumulated Radiation Dosage to Public

Public exposure to radiation dosage would occur principally during the transportation of activated/contaminated materials from the power plant to an approved nuclear waste disposal site. Table 11.4-2 of NUREG/CR-0130 lists a public radiation dose of 0.015 man-rem per shipment of contaminated material and a total of 1363 shipments of activated and contaminated material from the reference PWR. These data give an estimated total public radiation dose of 21 man-rem spread out over the entire dismantlement process. In addition, transport of spent fuel from the reactor site to a storage facility will also cause some public exposure, estimated to be less than 1 man-rem.

The estimated public radiation dose (EPRD) for a given PWR power plant equals the overall scaling factor times the dose for Trojan, or,

$$\text{EPRD} = 22 \text{ man-rem} \times \text{OSF (MWt)}.$$

From Table H.5-1 of NUREG/CR-0130, the total estimated public radiation dose would be the same for safe storage with dismantlement deferred for periods of 10 and 30 years. The estimated public dose would decrease to 10.2% of the listed amounts for dismantlement deferred for 50 years and to 9.9% of the listed amounts for dismantlement deferred for 100 years.

3.5.2 Estimated Accumulated Occupational Radiation Dose

The occupational dosage occurs to two groups: 1) transport workers, including truck drivers and garagemen who drive and service trucks transporting contaminated material, and trainmen who transport spent fuel, and 2) power plant employees, including contractor personnel engaged in decommissioning functions.

The external radiation dose to transport workers during immediate dismantlement of the Trojan power plant is estimated to be 99 man-rem to truck drivers and garagemen (Tables 11.4-2 of NUREG/CR-0130). In addition, transport of the spent reactor fuel contributes about 3.5 man-rem to the railroad workers (Table 11.4-1, NUREG/CR-0130). Summing these radiation doses with the 1404 man-rem estimated dose to decommissioning workers (Table 5.0-1 of

this report) gives a total of 1507 man-rem for the occupational radiation dose during the process of immediate dismantlement of the Trojan power plant.

The total estimated occupational radiation dose (TEORD) during the process of immediate dismantlement for other PWR power plants equals the overall scaling factor times 1507 man-rem, or:

$$\text{TEORD (man-rem)} = 1507 \times \text{OSF (MWt)}$$

The estimated external occupational radiation dose resulting from preparations for safe storage is listed as 426 man-rem in Table 5.0-2 of this report. The total estimated occupational radiation dose resulting from safe storage preparation thus equals the overall scaling factor times 426, or:

$$\text{TEORD (man-rem)} = 426 \times \text{OSF (MWt)}$$

The estimated external occupational radiation doses during deferred dismantlement operations are given in Table H.6-1 of NUREG/CR-0130. The relative doses determined from that table are listed in Table 3.5-2.

TABLE 3.5-2. Percent of Dismantlement Occupational Exposure as a Function of Time of Dismantlement

<u>Time Dismantlement is Deferred (Years)</u>	<u>Portion of Original Dose Remaining (Percent)</u>
0	100
10	26.9
30	1.96
50	0.16
100	0.08

The total estimated occupational radiation dose at the time of deferred dismantlement can be determined by multiplying the value of the TEORD (Dismantlement) as determined for immediate dismantlement by the percentage factors

listed in Table 3.5-2. As an example, to determine the total radiation dose to decommissioning workers resulting from placing the facility in safe storage for 30 years and then dismantling,

$$\text{TEORD (man-rem)} = [426 + (0.0196)(1507)] \text{ OSF (MWt)}$$

The estimated external occupational radiation exposures for the entombment of the Trojan power plant are given in Table 5.0-3 of this report. The estimated exposures are 920 man-rem for entombment with the reactor vessel internals retained and 1025 man-rem for entombment with the reactor vessel internals removed. The estimated external occupational radiation exposures resulting from the entombment of other PWR power plants can be obtained by multiplying the appropriate value by the overall scaling factor,

$$\text{TEORD (man-rem)} = \left\{ \begin{matrix} 920 \\ 1025 \end{matrix} \right\} \text{ OSF (MWt)}$$

3.6 DETAILED DETERMINATION OF DISMANTLEMENT COSTS FOR THE MAJOR POWER PLANT COMPONENTS

The estimated costs for dismantling the major power plant components in the Trojan PWR power plant are used as a basis for estimating the dismantlement costs of similar components in the other three power plants treated in this study. These base dismantlement costs are determined primarily from the data in NUREG/CR-0130, and are derived in subsequent sections of this section. The bases for developing the methods of determining the scaling factors for the different components are also discussed.

3.6.1 Component Costs from the Reference PWR Study

The major power plant components that are definable and that are responsible for the majority of the dismantlement costs are as follows: 1) reactor vessel, 2) reactor vessel internals, 3) primary coolant pumps and piping, 4) steam generators, 5) pressurizer, and 6) containment building. The cost of disposing of the spent fuel is also discussed and derived.

The basic dismantlement costs of these components used for comparison purposes are listed in Table 3.6-1.

TABLE 3.6-1. Dismantlement Costs Estimated for the Reference PWR(a)

<u>Component</u>	<u>Base Dismantlement Cost 1978 Dollars(b)</u>
Reactor Vessel	\$2 606 239
Reactor Vessel Internals	3 301 060
Primary Coolant Pumps and Piping	1 027 279
Steam Generators	767 798
Pressurizer	527 427
Containment Building	2 361 481
Spent Fuel	\$2 467 000

(a)From NUREG/CR-0130.

(b)The number of figures shown is for computational accuracy and does not imply precision to that many significant figures.

3.6.1.1 Reactor Vessel

The estimated direct labor costs for segmenting the Trojan reactor vessel, from Figure G.2-2 (page G-10) of NUREG/CR-0130, equal \$476,400. Adding the indirect costs of $2.327 \times \$476,000 = \$1,107,650$ gives a total estimated segmentation cost of \$1,584,050. The estimated vessel disposal cost, from Table G.4-3 (page G-27) of NUREG/CR-0130, is \$1,022,189. The estimated cost of segmenting and disposing of the Trojan reactor vessel thus equals \$2,606,239. This is the base cost figure used for comparison purposes in this study.

The scaling factor, as discussed in Section 3.6.4, is taken as the ratio of the masses of the reactor vessels. The mass ratio is determined, when the actual mass is not known, by comparing the different features of the reactor vessels which are available as discussed in Section 3.6.3.1.

The reactor vessel as considered in this report includes the closure head, the cylindrical body, and the bottom or lower head. Included also are vessel attachments and nozzles, but none of the internals.

3.6.1.2 Reactor Vessel Internals

The first step in the segmentation of the vessel internals is to remove them from the reactor vessel and place them in the refueling cavity. The internals are segmented remotely under a protective shield of water. The segments are packaged and transported to an approved nuclear waste storage facility.

The estimated direct costs of moving the Trojan power plant reactor vessel internals to the refueling cavity, segmenting them, and loading the resulting pieces into containers are given in Figure G.2-2 (page G-10) of NUREG/CR-0130 and equal: moving the internals, \$45,000; segmenting the internals and loading the pieces, \$505,000. The total estimated direct labor costs equal \$550,000. To this figure must be added the indirect costs of $2.327 \times \$550,000 = \$1,279,850$ and the disposal cost of \$1,471,210 (from Table G.4-3 of NUREG/CR-0130). This gives a total estimated cost of \$3,301,060 for dismantling and disposing of the Trojan reactor vessel internals. This is the base cost figure used for comparison purposes in this study.

The scaling factor is taken as the ratio of the masses of the internals. Where the mass of the internals is not given, it is estimated by calculating the masses of those internal components whose dimensions are known and estimating the mass of the remainder by comparing them with those of the Trojan reactor.

3.6.1.3 Primary Coolant Pumps and Piping

These two components are grouped together and treated as a single entity. The direct costs of removing the reactor coolant pumps and primary piping is given in Figure G.2-2 (page G-10) of NUREG/CR-0130 as \$262,000. To this must be added the indirect costs of $2.327 \times \$262,000 = \$609,674$. The disposal costs for the coolant pumps and coolant piping are listed in Table G.4-4 (page G-31) of NUREG/CR-0130 and equal, respectively, \$89,970 and \$65,635.

The total base cost estimate for segmentation and disposal of the Trojan power plant primary coolant pumps and piping thus equals \$1,027,279. This is the base cost figure used for comparison purposes in this study.

The scaling factor, as discussed in Section 3.6.4, is taken as the ratio of the masses of the pumps, motors, and coolant piping. The relationships for determining the relative masses of pumps and the pump motors are determined in Sections 3.6.3.2 and 3.6.3.3.

The primary coolant pumps and piping include the coolant pumps, the attached coolant pump motors, and the connected coolant piping.

3.6.1.4 Steam Generator

There is one steam generator in each loop. The estimated direct labor cost of segmenting the four steam generators in the Trojan power plant, and preparing the resulting pieces for shipment, is given in Figure G.2-2 (page G-10) of Reference 1 as \$187,000. To this would have to be added the estimated indirect costs of $2,327 \times \$187,000 = \$435,149$. The estimated disposal cost, from Table G.4-4 (page G-31) of NUREG/CR-0130, equals \$145,649. The total estimated cost for dismantling and disposing of the four Trojan power plant steam generators thus equals \$767,798. This is the base cost used for comparison purposes in this study.

The steam generators are pressure vessels with internal heat transfer tubes. The scaling factor is taken as the ratio of the masses as discussed in Sections 3.6.3.1 and 3.6.4.

3.6.1.5 Pressurizer

There is one pressurizer per power plant. The estimated direct labor cost of removing the Trojan pressurizer, with the associated relief tank and safety injection system, is given in Figure G.2-2 (page G-10) of NUREG/CR-0130 as \$131,000. To this would have to be added indirect costs of $2.327 \times \$131,000 = \$304,837$. The estimated cost of disposal of the pressurizer is given in Table G.4-4 (page G-31) of NUREG/CR-0130 as \$73,970. The estimated cost of disposal of the pressurizer relief tank is given in the same table as

\$17,620. The total base cost of segmenting and disposing of the Trojan pressurizer assembly thus equals \$527,427. This is the base cost used for comparison purposes in this study.

The pressurizer is a vessel and the scaling factor is taken as the ratio of the masses as discussed in Sections 3.6.3.1 and 3.6.4.

3.6.1.6 Containment Building

The estimated costs of dismantling the Trojan containment building from NUREG/CR-0130 are listed in Table 3.6-2.

TABLE 3.6-2. Estimated Costs for Dismantling and Disposing of the Trojan Containment Building

<u>Operation</u>	<u>Estimated Cost (1978 dollars)(a)</u>
Remove Contaminated Internal Structures	
Direct Cost (Figure G.2-2)	\$ 508 772
Indirect Cost (direct cost x 2.327)	1 183 912
Dispose of Bioshield Concrete (Table G.4-3)	235 284
Dispose of Refueling Cavity Liner (Table G.4-4)	77 069
Dispose of Pressurizer Enclosure Concrete (Table G.4-4)	65 957
Dispose of Steam Generator Enclosure Concrete (Table G.4-4)	126 715
Dispose of Missile Shield (Table G.4-4)	4 817
Dispose of Base Slab Liner and Concrete (Table G.4-4)	154 138
Dispose of Reactor Cavity Liner (Table G.4-3)	<u>4 817</u>
Total	\$2 361 481

(a)The number of figures shown is for computational accuracy and does not imply precision to that many significant figures.

Dismantlement of the containment building consists primarily of 1) removing the activated and contaminated concrete and disposing of it at a nuclear waste disposal facility, and 2) removing and disposing of the contaminated liners. This would be accomplished after the radioactive and contaminated equipment had been removed from the containment building.

A tabulation of the activated and contaminated material which must be removed from the containment building and then disposed of is contained in Table 3.6-3.

TABLE 3.6-3. Activated and Contaminated Concrete and Steel Liner Plate in the Trojan Containment Building

<u>Component</u>	<u>Mass, tonnes</u>	<u>Weight, pounds</u>
Activated Concrete (Table G.4-3)	884.5	1 950 000
Contaminated Concrete		
Refueling Cavity (Table G.4-4)	275.8	608 000
Pressurizer Enclosure (Table G.4-4)	244.9	540 000
Steam Generator Enclosure (Table G.4-4)	480.8	1 060 000
Missile Shield (Table G.4-4)	17.2	38 000
Base Slab (Table G.4-4)	521.6	1 150 000
Internal Surface (Table G.4-4)	<u>18.4</u>	<u>40 500</u>
Total Concrete	2 443.2	5 386 500
Refueling Cavity Liner (Table G.4-4)	17.2	38 000
Base Slab Liner (Table G.4-4)	<u>54.4</u>	<u>120 000</u>
Total Steel Liner	71.6	158 000

From data in the table it can be seen that the mass of liner plate to be removed and disposed of is less than 3% of the mass of the concrete. The estimated direct labor cost for removing steel liner plate is \$11.90/tonne, while the estimated direct labor cost for removing and loading contaminated surface concrete is \$170/tonne (Section 3.6.2.5). The comparable figures, including overhead, are \$39.59/tonne and \$565.59/tonne. Disposal cost for

liner plate is \$330/tonne and for concrete is \$265/tonne. This gives costs of \$369.59/tonne and \$830.59/tonne for removal and disposal of steel liner plate and contaminated concrete surface.

The cost of removing and disposing of steel liner plate is less than half the cost of removing and disposing of contaminated surface concrete on a mass basis, and the mass of the steel liners is less than 3% of the mass of the concrete to be removed from the containment building. These two factors combine to indicate that, for the purpose of estimating the cost of dismantling the containment building, the cost of removing and disposing of the liner plate can be ignored with negligible effect on the resulting total dismantlement cost. Dismantlement cost estimates for the different containment buildings can thus be determined by comparing the mass of activated and contaminated concrete that must be removed and disposed of. Moreover, the ratio of liner plate to contaminated/activated concrete will be roughly similar for the different power plants, and this will further reduce the effect of ignoring the amount of liner plate in determining the estimated dismantlement costs of the different containment buildings.

It is also assumed that the proportion of concrete that must be removed by the different methods (blasting, spalling, chipping, etc.) will be about the same in the different containment buildings, regardless of size.

These factors all combine to indicate that a reasonable estimate for the cost of dismantling a containment building may be obtained by determining the amount of activated/contaminated concrete that must be removed and then multiplying that amount by the unit cost of removal and disposal as determined in NUREG/CR-0130. The unit cost can be determined from the data in Tables 3.6-2 and 3.6-3.

The total estimated dismantlement cost for the Trojan power plant containment building is \$2,361,481. The mass of concrete postulated to be removed and disposed of is 2,443.2 tonnes. The average unit cost of removal and disposal of all of the concrete, including allowance for steel liners, etc., equals:

$$\$2,361,481 / 2,443.2 \text{ tonne} = \$966.55/\text{tonne}$$

The containment building scaling factor will equal the ratio of the mass of concrete to be removed and disposed of divided by the corresponding mass of concrete from the Trojan containment building, 2,443.2 tonnes.

3.6.1.7 Spent Fuel Disposal

Costs associated with spent fuel consist of the costs of loading and transporting to a repository. The estimated cost of disposing of the spent fuel from the Trojan reactor is \$2,467,000.

The scaling factors for spent fuel disposal for the different power plants are based on the ratios of the number of fuel assemblies compared to Trojan.

3.6.2 Cost of Dismantlement Operations

These are a number of operations involved in the dismantlement of a PWR power plant, and it is necessary to estimate the costs of those operations to determine their influence on the estimated costs of dismantling the different major components. These operations include sectioning of steel plate and steel components, removal of the surface of concrete shielding walls, blasting to demolish large sections of concrete, and loading of concrete. The costs of disposal of the different materials and components are of major importance and are also discussed and defined in the following sections.

3.6.2.1 Cost of Cutting Steel Liner Plate

The reactor cavities and refueling pools are lined with 6.35-mm (0.250-in.) steel plate. This plate must be cut into pieces for transportation to a nuclear waste disposal site.

It is estimated by an experienced welding foreman that 6.35-mm (0.25-in.) thick steel plate can be torch-cut at the rate of 915 mm/min (3 ft/min) by one man with good equipment and an adequate supply of oxygen. This cutting rate was concurred with by a welding engineer.

Spread out over a day, allowing for breaks, repositioning, etc., this would probably average out to 610 mm/min (2 ft/min).

Plasma arc cutting of stainless steel plate in air is a much more rapid process. Cutting speeds in excess of 3 m/min (10 ft/min) of 6.35 mm (0.25-in.) plate can be achieved with the plasma arc process.

For the purpose of estimating costs, a cutting speed of 915 mm/min (3 ft/min) is assumed with a cost of \$200/man-day of cutting. This gives an estimated cutting cost of \$0.455 per meter for 6.35 mm plate (\$0.139/ft).

The \$200/day cost is based on one craftsman to do the cutting plus one laborer per craftsman to move the equipment, set up scaffolding, and perform other required supportive functions.

Costs of cutting thicker plate, or of cutting pipe walls, are estimated to be in proportion to the thickness (i.e., a plate or pipe wall that is twice as thick would have twice the cutting cost, or \$0.91 per meter for 12.7-mm thick plate).

3.6.2.2 Cost of Removing Surface Layer Concrete

Much of the surface of the concrete walls and floors in the containment building will be contaminated. The walls and floor of the spent fuel storage pool will also be contaminated. Dismantlement requires that the exposed surface to a depth of 63.5 mm (2.5 in.) be removed and sent to a radioactive waste storage facility.

It is estimated by the manager of a demolition company in Seattle, Washington, that one man could remove 2.5 m^2 (27 ft^2) of concrete surface 63.5 mm thick per shift using a rivet buster." This equals:

$$\begin{aligned} 0.064 \text{ m} \times 2.5 \text{ m}^2 &= 0.160 \text{ m}^3 (5.65 \text{ ft}^3) \text{ per man day} \\ &0.384 \text{ tonne (848 lb) per man-day} \end{aligned}$$

There is also available a mounted impulse breaker, a hydraulically activated concrete breaker usually mounted on a backhoe. It is reported by the Ingersoll-Rand Company that mounted impulse breakers have been used very successfully by different demolition contractors in demolishing concrete structures. The mounted impulse breakers have proven many times more effective than wrecking balls. Experience has shown that they are at least 10 times as fast as manual demolition.

Such a backhoe-mounted impulse breaker could be used to remove the surface layer of concrete walls and floors wherever space permitted. It is estimated that, where it could be used, the surface concrete could be removed at a rate in excess of 1.5 m^3 (53 ft^3) per day or 3.6 tonnes (7940 lb) per day.

Another alternative method that can be employed is to use a specifically designed concrete spalling tool to remove the surface of concrete--a gang drill and a hydraulic expander-puller to spall off the surface. It is estimated that one man could remove at least 18.6 m^2 (200 ft^2) of concrete surface per day with the aid of such a device:

$$18.6 \text{ m}^2 \times 0.064 \text{ m} = 1.19 \text{ m}^3/\text{shift} \text{ (} 42 \text{ ft}^3/\text{shift)}$$
$$\text{or } 2.86 \text{ tonnes (6300 lb) per shift}$$

Removal of some portions of the concrete surface would be complicated by the presence of reinforcing steel near the surface, and by restricted access. The surface layer in these areas would have to be removed manually.

For estimating purposes, a conservative average ratio of surface removal of 8.85 m^2 (95.3 ft^2) per shift can be assumed. This equals 0.56 m^3 (19.85 ft^3), or 1.35 tonnes (1.49 tons) of concrete per shift. Assuming one craftsman plus one laborer helper per shift for a labor cost of \$223, the estimated cost of surface removal of the concrete becomes \$165/tonne (\$150/ton), or $\$25.20/\text{m}^2$ ($\$2.34/\text{ft}^2$) of surface area, or, on a volumetric basis, $\$396/\text{m}^3$ ($\$303/\text{yd}^3$).

In addition, the broken concrete would have to be loaded and hauled at an additional cost of $\$13/\text{m}^3$ ($\$10/\text{yd}^3$), or $\$5.41/\text{tonne}$ ($\$4.94/\text{ton}$).

The total estimated average cost of removing and loading the contaminated surfaces from concrete walls, floors, and ceilings is $\$165 + \$5 = \$170/\text{tonne}$ ($\$155/\text{ton}$), $\$409/\text{m}^3$ ($\$313/\text{yd}^3$), or $\$26/\text{m}^2$ ($\$2.42/\text{ft}^2$) of surface area removed.

3.6.2.3 Costs of Breaking and Removing Thick Layers of Concrete

The fuel transfer tube must be removed completely, the wall of the reactor cavity must be removed to a depth of 1 m, and the extension of the reactor cavity above the containment building floor would have to be removed completely

The reactor cavity wall and the fuel transfer tube are in relatively confined locations. They would not be accessible to a mounted impulse breaker (see Section 3.6.2.2) nor to balling. Blasting would probably be the preferred method of removing the activated and contaminated concrete from the locations. Because of the restricted space and the requirement for removing only a portion of the wall of the reactor cavity proper (lower portion), the cost of blasting would be on the high side, estimated at $\$60/\text{m}^3$ ($\$46/\text{yd}^3$). The cost of loading and hauling would also be higher than for the spalled concrete for the same reasons. Loading and hauling costs are estimated at $\$20/\text{m}^3$ ($\$15/\text{yd}^3$), or $\$8.30/\text{tonne}$ ($\$7.50/\text{ton}$).

The total cost of blasting, loading, and hauling for the thicker sections of concrete is $\$80/\text{m}^3$ ($\$61/\text{yd}^3$), or $\$33/\text{tonne}$ ($\$30/\text{ton}$).

3.6.2.4 Disposal Costs for Steel and Concrete

The costs of packing contaminated material into containers, transporting the contained material to an approved nuclear waste storage facility, and then disposing of it are taken from NUREG/CR-0130. The average disposal cost for concrete equals $\$265/\text{tonne}$ ($\$240/\text{ton}$).

The disposal cost for steel is more difficult to estimate, since it is measurably affected by the packing efficiency of the steel components. The estimated disposal cost for steel liner plate is $\$330/\text{tonne}$ ($\$300/\text{ton}$), but the disposal cost for coolant piping, which has a much lower packing efficiency, is $\$650/\text{tonne}$ ($\$590/\text{ton}$). The unit disposal costs in dollars/tonne for the other components are not needed, since the components are compared on an overall basis.

3.6.2.5 Segmenting and Disposal Costs of Contaminated Concrete Surfaces and Steel Liner Plates

Each power plant has a considerable amount of concrete surface area to be removed and disposed of. Each power plant also has a considerable amount of steel liner plate 6.35 mm (0.025 in.) thick to be removed and disposed of. The removal and disposal costs can be combined into a single dismantlement cost for these items, which are common to all of the power plants.

The cost of removal of a surface layer of concrete is, from Section 3.6.2.2, \$170/tonne (\$155/ton). The cost of disposal, from Section 3.6.2.4, is \$265/tonne (\$240/ton). The basic cost of removal and disposal equals \$435/tonne (\$395/ton), or $\$66.38/\text{m}^2$ ($\$6.17/\text{ft}^2$) of surface area. This does not include any overhead or miscellaneous costs.

The steel liner plate must be cut into pieces 1.2 m x 2.1 m (3.94 ft x 6.89 ft) for packing and transportation. A length of cut of 3.3 m (10.83 ft) would thus be required for each piece. The volume of each piece would equal 0.016 m^3 (0.563 ft^3) and would have a mass of 0.126 tonne (276 lb). The cutting (segmenting cost) would equal $3.3 \text{ m} \times \$0.455/\text{m} = \1.50 per piece (from Section 3.6.2.1). The estimated direct labor cost of segmenting of steel liner plate would thus equal $\$1.50/0.126 \text{ tonne} = \$11.90/\text{tonne}$. The estimated disposal cost for the steel liner plate is \$330/tonne.

3.6.3 Methods of Comparing Similar Components

The different power plants all contain many similar items of equipment, (e.g., reactor vessels, coolant pumps, etc.). These items are compared on a one-to-one basis in the body of this report, and individual scaling factors, or decommissioning cost ratios, are determined.

Methods of comparing vessels, pumps, and motors are derived in the following sections.

3.6.3.1 Comparison of Masses of Cylindrical Vessels as a Function of Their Diameter and Length for Similar Temperature, Pressure and Stress Conditions

The different vessels treated in this report are all of the same general type (i.e., they all have cylindrical bodies and approximately hemispherical ends). The different vessels considered include the reactor vessels, the steam generators, and the pressurizers.

The stress in a hemispherical end because of internal pressure is one-half the stress in the cylindrical body, so the thickness of the steel in the hemispherical ends will be about half the thickness of the steel in the cylindrical

portion. The thickness, t , of the wall of the body of the vessel equals:
 $t = (P/2 \times S) \times D$ where P = pressure, S = stress, and D = diameter. The pressure, temperatures, and stresses are very nearly the same for the different power plants, so the wall thicknesses of the different vessels will be proportional to their diameters.

The volume of the metal in a cylindrical vessel with hemispherical ends is : $V_M = \pi D \times t \times L + \pi D^2 \times (t/2)$ Where L = length of cylindrical section. But for the conditions being considered, t is proportional to D , or $t = CD$, where C is a constant. So:

$$V_M = C \times \pi \times D^2 \times L + C \times \pi \times D^2 \times (D/2) = C \times \pi \times D^2 (L + D/2)$$

The relative masses of the vessels being considered in this study can then be determined by the following relationship:

$$M_2 = M_1 \times (D_2/D_1)^2 (L_2 + D_2/2)/(L_1 + D_1/2)$$

If the L/D ratio is the same for the two vessels, the masses will be in the same ratio as the cubes of the diameters, or:

$$M_2 = M_1 \times (D_2/D_1)^3$$

If the overall vessel height is given, the relationship can be written as:

$$M_2 = M_1 \times (D_2/D_1)^2 (H_2 - D_2/2)/(H_1 - D_1/2)$$

More conservative, and probably more accurate, estimates of vessel mass will be obtained if the diameter used in the above equations is the outside diameter in accordance with the Barlow formula for hoop stress.

3.6.3.2 Comparison of Mass versus Power Output for Centrifugal Pumps

Data for a number of different sizes of centrifugal pumps of a similar type were selected from a pump manufacturer's catalogue. The pertinent data are listed in Table 3.6-4.

TABLE 3.6-4. Comparative Data for Single-Stage Centrifugal Pumps Over a Range of Sizes

Size	Q		H		Q X H m ⁴ /min	Pump		(QH) ^{1/3} • mass
	m ³ /min	gpm	m	ft		Mass kg	Weight lb	
6x8-15	5.30	1 400	61.0	200	323.3	277	610	0.025
6x8-13	7.57	2 000	33.5	110	253.6	254	560	0.025
3.4-13	1.89	500	36.6	120	69.2	150	330	0.027
4x6-10	3.41	900	21.3	70	72.6	138	305	0.030
1.5x3-8	0.57	150	15.2	50	8.7	49	108	0.041

The power output of a pump in watts equals:

$$\frac{\text{kg} \times \text{m/min}}{6.12} = \text{watts}$$

or:

$$\frac{(\text{m}^3/\text{min}) \times \text{density} \times \text{head}}{6.12} = \text{watts} = \frac{W \times H \times \rho}{6.12}$$

so the power output of a pump is proportional to Q x H for the same liquid.

The data in the above table show a reasonable correlation between the mass of a pump and the cube root of its output as measured in watts (or horsepower) for pumps in the same size and performance range.

3.6.3.3 Comparison of Mass versus Power for Large Electric Motors

Data concerning the mass of three-phase, 1750 rpm, induction type electric motors were obtained from different motor manufacturers and compared. The data are listed in Table 3.6-5.

TABLE 3.6-5. Comparison of Mass versus Power for Three-Phase 1750-rpm, Induction-Type Electric Motors

Size Motor		Manufacturer A		Manufacturer B		Manufacturer C	
kW	hp	Mass, kg	Weight, lb	Mass, kg	Weight, lb	Mass, kg	Weight, lb
224	300	1 720	3 200				
522	700	2 790	5 200				
746	1 000	4 130	7 700	2 970	5 550	4 290	8 000
1 120	1 500					6 970	13 000
1 490	2 000			6 970	13 000	8 040	15 000
2 240	3 000			7 830	14 600	11 790	22 000
2 980	4 000			13 610	25 400	13 940	26 000
3 730	5 000			15 920	29 700	16 620	31 000
4 480	6 000			17 960	33 500		

The data are plotted in Figure 3.6-1. A curve drawn through the points for motors of 2000 kW (2680 hp) and larger conforms to the relationship:

$$M = 3800 + 3.3 \times P$$

where

M = mass, kg

P = power, kW

This indicates that the mass of an induction motor in the larger sizes increases linearly with power, over the range considered, to a good approximation for motors of the same type.

3.6.4 Comparison of Segmentation and Disposal Costs and Determination of Vessel Scaling Factor Relationship

The basic segmentation costs for four of the major components in the Trojan power plant can be compared with their disposal costs from the data provided in NUREG/CR-0130. The segmentation costs given include only the labor costs for the torch cutting operation to segment the component and do not include costs of supervision, overhead, supplies, or other miscellaneous

FIGURE 3.6-1. Plot of Mass versus Power Rating for 3-Phase, 1750 rpm Induction Motors

costs. They are thus not accurate representations of the true segmentation costs, but are useful for indicating the magnitude of segmentation costs for metal components in comparison with the disposal costs.

For the item listed, cutting costs were calculated on the basis of one person using a torch plus one laborer to help the torch operator. The sum of the labor rates for the two is \$25.13/hr.

The costs and cost ratios are listed in Table 3.6-6.

These data indicate that the segmentation costs are only a small fraction of the disposal costs. Moreover, the time required for segmentation will be a function of thickness (see Section 3.6.2.1) as well as length of cut, or surface area of vessel. Thus, cutting time is proportional to surface area times wall thickness, or $\text{Time} = A \times t \times (\text{constant})$.

TABLE 3.6-6. Comparison of Cutting Costs and Disposal Costs for Trojan Power Plant Components (1978 dollars)

Component	Cutting Time hours	Segmentation Cost(a)	Disposal Cost(a)	Ratio
Reactor Vessel	692	\$17 390	\$1 022 189	0.017
Vessel Intervals	960	24 125	1 471 210	0.016
Steam Generators	545	13 696	145 649	0.094
Coolant Pumps and Piping	277	6 961	155 605	0.045

(a)The number of figures shown is for computational accuracy and does not imply precision to that many significant figures.

From Section 3.6.3.1 for vessels of similar shape and configuration (same L/D ratio) the wall thickness is proportional to the vessel diameter. The volume of the vessel is proportional to the diameter cubed and the surface area is proportional to the diameter squared. Also, the mass of the vessel is proportional to the cube of the diameter.

Combining these relationships gives the following:

$$A_2/A_1 = (D_2/D_1)^2$$

$$t_2/t_1 = D_2/D_1$$

$$\text{Segmentation time, } T \propto t \text{ or } T_2/T_1 = (D_2/D_1)^3$$

The ratio of the masses $M_2/M_1 = (D_2/D_1)^3$, so the time required to segment, or dismantle, a vessel is roughly proportional to its mass (the different vessels in the four power plants are not exactly similar in all regards).

The disposal costs are also a function of size, mass, and configuration. For similar components, the sizes will be proportional to the masses, and the configuration costs (packaging efficiency, segmentation difficulties, etc.) will be proportional to the sizes.

Based on the above, both segmentation and disposal costs will be very nearly proportional to the masses. Since the mass ratio is determinable with reasonable accuracy, and dismantlement costs are roughly proportional to the masses of similar components, the mass ratio is used as the scaling factor for the different vessels, for the reactor vessel intervals, and for the coolant piping.

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4.0 DECOMMISSIONING THE REFERENCE PWR BY ENTOMBMENT

Two conceptual approaches to decommissioning a typical large (1,175 MWe) pressurized water reactor (PWR) were described in NUREG/CR-0130, together with related considerations of costs, occupational radiation doses, potential radiation doses to the public, and other safety impacts. The approaches considered were immediate dismantlement and safe storage with deferred dismantlement, with the ultimate effective release of the site and any remaining structures to unrestricted public access. The present analysis is limited to consideration of entombment for the reference PWR, its equipment components and/or structures, and to related hazards and costs. Detailed consideration of the problems of preventing unauthorized access to entombed radioactive materials and maintenance of structural integrity during decay of long-lived radioisotopes is not within the scope of this study.

Entombment of a reactor facility requires the encasement of radioactive materials in concrete or other structural material sufficiently strong and structurally long-lived to ensure retention of the radioactivity until it has decayed to levels that permit unconditional release of the site.

The above definition of entombment permits basically two technical approaches: entombment without internals and entombment with internals. In the first case, the reactor vessel internals with their long-lived activation products (^{59}Ni , ^{94}Nb) are removed and transported to a federally owned nuclear waste repository for disposal. The remaining radioactive material is consolidated within the containment building and entombed. Because of the relatively short half-lives of the entombed radioactivity, it is anticipated that the entombed structure can be released for unrestricted use after a surveillance and maintenance period of about 100 years and the nuclear facility license can be terminated, assuming that it can be adequately demonstrated that the level of residual radioactivity is less than the level acceptable for unrestricted use.

In the second case, the long-lived radionuclides in the reactor vessel internals are entombed together with the rest of the radioactive material. In this case, the entombed structure must be kept under surveillance and be

maintained as a nuclear waste repository. Under existing regulations, the licensee has the responsibility for surveillance and maintenance in perpetuity.

Several other situations are conceivable. Legislation similar to the recent uranium mill tailings bill⁽¹⁾ could be enacted that would require the transfer of the property and the responsibility to the federal government, thus creating a federal nuclear waste repository at each entombed site. Another possible (but unlikely) situation would be for the NRC to establish as policy that an entombed facility can be relased for unrestricted use after an extended (~100 years) period of surveillance and maintenance, even though the long-lived activation products are present.

The analysis in this addendum is limited to consideration of the costs and safety impacts of the first two technical approaches. The socio-political implications of other possible choices for ultimate disposition of the entombed sites makes consideration of these other choices beyond the scope of this study.

Entombment of the reference PWR is limited essentially to the containment building and its contents, along with as many of the contaminated components as can be removed from other buildings and stored within the containment building. It is necessary that containment barrier penetrations for personnel, equipment, services, and process materials be sealed and backfilled with concrete.

The available void volume within the containment building below the operating floor level is used to contain selected contaminated items, with an entombment barrier poured at the operating floor level. This approach results in reduction of packaging, transportation, and land burial costs and hazards, and is the approach assumed for this analysis.

Structures external to the containment building are not considered adaptable to decommissioning by entombment because of their size, type of construction, and the number of access points that would have to be secured. These structures are dismantled in the manner outlined in NUREG/CR-0130.

4.1 POSTULATED ENTOMBMENT SCENARIOS

For this analysis, it is assumed that entombment takes place within the confines of the reactor containment building, and that the portion of the containment building above the entombment barrier is decontaminated to permit unrestricted use of that space.

The entombment barrier is postulated to be poured at the operating floor level in the containment building. The shielded enclosures for the steam generators and the pressurizer, which rise about 5 m (~15 ft) above the operating floor, are capped at their tops. To accomplish this, the steam separator portions of the steam generators are removed and stored below the operating floor, and the pressurizer is disconnected and lowered to the bottom of the containment building. All of the steam lines and other potentially contaminated equipment present above the operating floor level are removed and stored below. The location of the postulated entombment barrier is illustrated in Figure 4.1-1.

All penetrations through the containment building wall below the operating floor level are capped and filled with concrete. The equipment hatch and the normal personnel access hatch, which are at or above the operating floor level, remain operable after entombment of the lower portion of the building.

Two cases are examined. In the first, the reactor vessel internals are removed and transported to a federally owned nuclear waste repository. In the second, the reactor vessel internals are entombed with the rest of the radioactive material. In both cases, the entombed structure remains under license, with surveillance and maintenance required until the property can be released for unrestricted use.

Dismantlement of the remaining structures is carried out in the same way as in the case of immediate dismantlement in NUREG/CR-0130, with the difference that most of the contaminated equipment and material is placed within the containment building and entombed rather than being packaged and shipped to a disposal site.

FIGURE 4.1-1. Location of Entombment Barrier

4.2 ESTIMATED VOLUME AVAILABLE WITHIN THE BOUNDARIES OF THE ENTOMBMENT STRUCTURE

Within the containment building, the available space selected for enclosure of radioactive materials is between the operating floor, at about 28 m (~93 ft) and the foundation slab, at about 13.7 m (~45 ft). The volume within this 42.672-m (140-ft) diameter cylindrical containment, exclusive of the below-grade central reactor vessel cavity and instrument tunnel, is about 20,500 m³ (~724,000 ft³). A portion of this volume will be occupied by the entombment barrier. Estimated volumetric displacements from the containment

building volume include: about 2,500 m³ (~88,300 ft³) of concrete shielding; about 2,500 m³ (~88,300 ft³) of vessels and pumps; about 500 m³ (17,600 ft³) of piping; and a qualitatively estimated 500 m³ (17,600 ft³) of miscellaneous structural components such as supporting columns or beams, gratings, stairways, and ladders. A net void volume of about 14,500 m³ (513,300 ft³) is potentially available for use, including incremental spaces of a variety of shapes, dimensions, and accessibility, for insertion of selected dismantled equipment.

4.3 SEQUENCE OF ENTOMBMENT ACTIVITIES

The sequence of the various efforts leading to entombment is given below, along with a brief discussion of each activity.

1. Two years prior to scheduled final reactor shutdown, initiate detailed planning and processing of administrative and regulatory arrangements.
2. Shut down, discharge, and disable reactor and dispose of all fuel.
3. Complete plant radiation surveys and chemical decontamination of reactor-related liquid systems.
4. Remove all liquids from within the reactor containment building.
5. Remove all contaminated equipment from above the operating-floor level and store below the operating-floor level.
6. Decommission onsite structures (other than the reactor containment building), with transfer of contaminated material and selected non-combustible wastes to void spaces below the containment building operating-floor level.
7. Pour a continuous concrete slab within the containment building at the operating-floor level and seal all containment building wall penetrations below the operating-floor level.
8. Install security and surveillance monitoring equipment.
9. Remove all residual non-contaminated structures not deemed essential or desirable for unrestricted public use (optional).

10. Complete landscaping, grading, and site restoration outside of the containment building (optional).
11. Release remainder of site to unrestricted public access.

Sequencing considerations, as described in NUREG/CR-0130, are modified in several respects. Modifications due to selection of entombment include detailed planning for use of the containment building as a receiving location for contaminated materials and deletion of planning for disposal of the containment building and its contents. Corollary changes in packaging, transportation, and burial of contaminated and activated waste components are also necessary. Considerations in common with those of NUREG/CR-0130 include requirements for conformance with regulatory guides and regulations, maintenance of necessary services for as long as needed, and routine shipments of removed contaminated materials designated for offsite disposal.

The schedule of events for entombment is very similar to the schedule for immediate dismantlement, which is given in Figure 9.1-2 of NUREG/CR-0130. Efforts within the containment building are limited to relocating contaminated equipment to below the operating floor level and preparing to receive the contaminated material and equipment from the dismantlement of the fuel, auxiliary, control, and turbine buildings. Shipment of the spent fuel from the site becomes a key item on the critical path since much of the fuel and auxiliary buildings cannot be dismantled until the fuel is gone.

Final sealing of the entombment volume would take place about 3 years after reactor shutdown. If the optional building demolition and site restoration are performed, these efforts would be concluded within about 3.5 years after reactor shutdown.

Descriptions of how entombment is effected in the containment building and related impacts on costs and occupational radiation dose are given in the next three sections.

4.4 CONTAINMENT VESSEL ADAPTATION TO ENTOMBMENT

The containment building is a cylindrical structure with a hemispherical dome. It is mounted on a concrete pad with a central cavity, as illustrated in Figure 4.1-1. The region within this building selected for entombment of radioactive materials is the available void volume below the operating-floor level (as illustrated in Figure 4.1-1). The estimated net void space, as derived in Section 4.8, consists of a variety of shapes and dimensions and has a volume of approximately 14,500 m³.

Following chemical decontamination of the reactor and related systems and transfer of liquids to waste disposal, the containment building is considered ready for receipt of contaminated residues from the decommissioning of other buildings. Beyond removal of any economically recoverable nonradioactive items for salvage, and relocation of the steam separators and piping and the pressurizer to below the operating-floor level, no additional dismantling or sectioning of installed equipment is undertaken. Access openings provided for equipment installation or maintenance are used to place contaminated materials into the entombment volume. A variety of choices exists for selection of contaminated equipment, equipment segments, and structural remnants to be entombed.

A review of the volumes of packaged wastes postulated to be transported to and buried at an offsite location, as given in NUREG/CR-0130, indicates contaminated concrete to be the largest single category requiring such handling. Since concrete from decontamination of structure surfaces will be in fragmented form, it can be utilized to fill irregularly shaped volumes more readily than can other contaminated equipment or material. Concrete volume, including shipping containers, comprises about 71% of all contaminated, packaged material shipped to burial during immediate dismantlement. It is conservatively estimated that this entire volume can be contained in the void spaces within the containment building below the 27-m (88.6-ft) level. In addition to contaminated concrete, approximately 50% of discarded equipment pieces and/or segments can be included without overfilling the void spaces below the 27-m (86.6-ft) level. Candidate non-combustibles of this category are small-sized

items such as pumps, valves, and piping sections. Bases for the preceding volumetric estimates are described in highlight entries below:

- The 11,962.982 kg of contaminated concrete rubble (from Table G.4-5, NUREG/CR-0130) is estimated to have a density of about $1,090 \text{ kg/m}^3$, resulting in a volume of about $11,000 \text{ m}^3$ ($388,460 \text{ ft}^3$) to be placed in the entombment volume.
- Total volume of packaged contaminated materials, other than concrete, is calculated to be $3,948 \text{ m}^3$ ($139,447 \text{ ft}^3$). At least 50% of this material, without credit for container volume deduction, could be included with the concrete rubble. It is suggested that inclusion of stainless steel systems and piping sections and small equipment items be made the first choice for such inclusion ($\sim 2,210 \text{ m}^3$ [$78,000 \text{ ft}^3$]).

The effect on decommissioning costs of using the reactor containment building void volume as a radioactive waste repository is described in the following section.

4.5 ESTIMATED COSTS FOR ENTOMBMENT

The initial cost for entombment is estimated to be somewhat smaller than the cost for immediate dismantlement. These cost reductions result from not dismantling the containment building, from not transporting and burying the radioactive material from the containment building, and from not transporting and burying much of the radioactive material from the other buildings when they are dismantled. Some new costs related just to entombment are incurred. These include installation of electronic surveillance and security systems, installation of the entombment barrier, cutting and sealing of penetrations through the containment building wall, staff labor associated with emplacement of the radioactive materials from the other buildings, and final decontamination of the areas outside of the entombment barrier. Estimates of the cost of entombing the lower half of the containment building, with and without the reactor vessel internal components, are presented in Table 4.5-1, together with the estimate for immediate dismantlement from NUREG/CR-0130.

TABLE 4.5-1. Comparison of Costs for Dismantlement and Entombment of the Reference PWR (millions of 1978 dollars)

Category	Dismantlement ^(a)	Entombment (w/internals)	Entombment (internals removed)
Activated Material Disposal	2.734	---	2.498
Contaminated Containment Material Disposal	0.961	---	---
Other Buildings Contaminated Material Disposal	4.222	0.472	0.472
Radioactive Waste Disposal	0.693	0.693	0.693
Dismantlement Staff Labor	8.986	6.910	7.416
Entombment Staff Labor	---	1.196	1.196
Electrical Power	3.500	3.500	3.500
Special Equipment	0.822	0.822	0.822
Miscellaneous Supplies	1.559	1.559	1.559
Nuclear Insurance	0.800	0.800	0.800
Specialty Contractors	0.390	0.280	0.280
Environmental Surveillance	0.154	0.154	0.154
Security and Surveillance System	---	0.086	0.086
Entombment Barrier Installation	---	0.310	0.310
Subtotal	24.821	16.782	19.786
Contingency (25%)	6.205	4.196	4.947
Decommissioning Totals	3.1026	20.978	24.733
Optional Activities			
Demolition and Restoration	8.013	6.354	6.354
Spent Fuel Disposal	3.084	3.084	3.084
Deep Geologic Disposal	2.250	---	2.250

(a) Data from Table 10.1-1, p. 10-2, NUREG/CR-0130.

The cost of surveillance and maintenance for the entombed structure is expected to be no greater than the costs estimated for passive safe storage (Table 10.3-1, p. 10-22, NUREG/CR-0130), and should probably be less, more in

the range of \$30,000 to \$40,000 per year, assuming no other utilization of the property to help defray expenses. Thus, over a holding period of 100 years, additional expenses of \$3 to \$4 million would be incurred. In the case where the reactor vessel internals are removed and placed in a federally owned nuclear waste repository, it is possible that the remaining radioactivity contained within the entombment structure will have decayed to unrestricted release levels after about 100 years. However, in the case where the reactor vessel internals are also entombed on the site, there is no likelihood that the contained radioactivity will decay to unrestricted release levels within times conceivable to man (~100,000 years), and the surveillance and maintenance program will have to be continued in perpetuity.

4.6 RADIATION DOSES FOR ENTOMBMENT

The estimated occupational radiation doses for immediate dismantlement are given in Table 11.3-1 of NUREG/CR-0130. These data are compared with estimates for the two entombment options in Table 4.6-1. Based on the scenarios postulated for entombment, the radiation doses associated with the containment building are the only ones significantly affected by performing an entombment rather than a dismantlement. The steam separators are removed from the steam generators and stored below the operating floor level, and the pressurizer is disconnected and lowered to the bottom of the building to permit capping the shielding enclosures at about 5 m (15 ft) above the operating floor. Decontamination of surfaces within the containment building is limited to areas above the entombment barrier level. As a result, the occupational radiation dose associated with the containment building is reduced from 587 man-rem for immediate dismantlement to about 30 and 130 man-rem, respectively, for entombment with and without the reactor vessel internals. Additional effort involved in transferring contaminated equipment from the fuel and auxiliary buildings into the lower levels of the containment building, the additional forming and pouring of concrete for the entombment barrier, and the effort involved in cutting and sealing penetrations into the containment building are estimated to add about 53 man-rem to the occupational dose. The total occupational radiation doses estimated for the entombment scenarios

TABLE 4.6-1. Comparison of Estimated Occupational Radiation Dose for Dismantlement and Entombment of the Reference PWR^(a)

Description	Immediate ^(b,c) Dismantlement (man-rem)	Entombment ^(c)	
		w/Internals (man-rem)	w/o Internals (man-rem)
Reactor Building			
Move Internals to Refueling Cavity	8.0	---	8.0
Comprehensive Predismantling Radiation Survey	9.0	9.0	9.0
Segment Vessel Internals and Load Containers	78	---	92
Segment Steam Generators (4) and Prepare for Shipment	140	15	15
Remove RCS Pumps (4) and RCS Piping	67	---	---
Remove Pressurizer, Relief Tank, and Safety Injection System	65	3.0	3.0
Remove HXs and Assorted Pumps	29	---	---
Remove Contaminated Internal Structures	81	---	---
Remove Spray Piping and Ventilation Systems	12	1.0	1.0
Decontaminate Remaining Internal Surfaces	<u>6.0</u>	<u>2.0</u>	<u>2.0</u>
Reactor Building Total	587	30	130
Auxiliary Building Total	292	292	292
Fuel Building Total	147	147	147
Ancillaries Total	<u>378</u>	<u>378</u>	<u>328</u>
Subtotals	1 404	847	947
Transfer of Materials into Containment	---	15	20
Cutting and Sealing Containment Penetrations	---	20	28
Forming and Pouring Entombment Barrier	<u>---</u>	<u>5.0</u>	<u>5.0</u>
Subtotal	1 404	900	1 000
Transportation-Related Exposure	<u>125</u>	<u>20</u>	<u>25</u>
Totals	1 529	920	1 025

(a) These estimates assume the RCS, CVCS, and related systems have been chemically decontaminated.

(b) From Tables 11.3-1 and 11.4-2, NUREG/CR-0130.

(c) Estimates are not adjusted for radioactive decay during decommissioning.

postulated are about 900 and 1,000 man-rem, respectively. These estimated doses are based on the radiation dose rates present at the time of final reactor shutdown and are not adjusted for radioactive decay during the decommissioning effort, since an individual task will probably be accomplished at a different time after shutdown during entombment than during dismantlement. The resultant estimates are therefore conservative.

The radiation dose to the public, including truck drivers and garage workers, is reduced from 125 man-rem for immediate dismantlement to about 20 and 25 man-rem, respectively, for entombment with and without the reactor vessel internals by the reduction in the number of radioactive shipments to the low-level waste burial ground. Therefore, the total radiation dose resulting from entombment is estimated to be in the 900 to 1,000 man-rem range, as compared with about 1,500 man-rem for immediate dismantlement.

4.7 SUMMARY

Two technical approaches to entombment are examined. In the first, the highly-activated reactor vessel internal components are retained within the reactor vessel and are entombed together with as much of the contaminated material from the balance of the plant as can be accommodated within the lower section of the containment building. In the second approach, those activated components that contain long-lived radionuclides (^{59}Ni , ^{94}Nb) are removed and transported to a shallow-land burial facility, and the remainder of the facility is treated in the same manner as in the first approach. Both approaches result in a facility that has the lower portion of the containment building entombed and the upper portion of the containment building and the supporting buildings in the complex dismantled and released for unrestricted use.

The costs and occupational radiation doses associated with decommissioning the reference PWR power station by entombment are developed by examining how the entombment efforts are different from immediate dismantlement. The estimated initial cost for dismantlement, passive safe storage, and the two entombment options are listed in Table 4.7-1. Also presented in the table are the estimated initial radiation doses to occupational workers resulting from these

decommissioning options, and some indication of the status of the nuclear license. Not included are radiation doses from long-term surveillance and maintenance operations for safe storage and entombment.

Examination of the information in Table 4.7-1 leads to several conclusions. To minimize initial expenditures and radiation dose for decommissioning, placing the facility in a passive safe storage is the best choice. The two entombment options are a distant second and third choice compared with the safe storage choice. In all three, the nuclear license has to be maintained for an extended period of time: in safe storage, until dismantled and released; in entombment, until the radioactivity contained within the entombed structure has decayed to unrestricted-use levels. For the entombment containing the reactor vessel internals, under the present definitions and regulations the property could essentially never be released without further decommissioning action. For the

TABLE 4.7-1. Initial Cost, Radiation Dose, Annual Cost, and License Status for Different Decommissioning Approaches

Category	Immediate Dismantlement ^(a)	Placement into Passive Safe Storage ^(a)	Entombment	
			w/Internals	w/o Internals
Initial Cost (\$ millions)	31.0	9.5	21.0	24.7
Initial Radiation Dose (man-rem)	1 404	426	900	1 000
Annual Care Cost (\$ thousands)	---	80	40	40
License Status Following Initial Decommissioning Action	terminated	maintained	maintained	maintained
Accumulated Cost at License Termination or at 100 years (\$ millions)	31.0	39.7 ^(b)	25.0 ^(c)	28.7 ^(d)

(a)From NUREG/CR-0130, excluding costs of spent fuel shipment and demolition of structures.

(b)Includes deferred dismantlement.

(c)License and cost accumulations not terminated, any final disposition costs not included.

(d)License might be terminated, based on calculation of radioactive decay.

entombment without the reactor vessel internals, if an accurate inventory of the entombed radioactivity were made initially, it might be possible to declare the property releasable after about 100 years when calculations would show that the contained inventory of radioactivity had decayed to unrestricted-use levels.

When comparing the eventual accumulated cost for each decommissioning approach, entombment looks more favorable, provided the cost of any final decommissioning action for entombment is neglected. However, it is not certain that either of the entombment options could result in termination of the license and release of the property without additional decommissioning action. Dismantlement of an entombed structure, while not evaluated in this analysis, is expected to be a rather costly undertaking and could result in accumulated costs significantly exceeding either immediate dismantlement or safe storage with deferred dismantlement.

4.8 DETAILED CALCULATIONS SUPPORTING THE ENTOMBMENT COST ESTIMATES

Details of the various calculations related to the development of the cost estimates for entombment are given in the following subsections.

4.8.1 Estimate of Reactor Containment Building (RCB) Net Volume

The selected section is from the base pad, elevation 13.7 m, to 28 m, $\Delta h = 14.3$ m. The operating floor level is 28.3 m, or 0.3 m (~ 1 ft) above the 28 m level. Inside RCB radius = 21.336 m (70 ft).
Gross cylindrical volume = $\pi r^2 \Delta h = 20,450 \text{ m}^3$, say, $\sim 20,500 \text{ m}^3$ (724,000 ft^3).
(No credit for any additional volumes [e.g., instrument tunnel and reactor cavity] is taken.)

Volume displacements in the selected RCB section are tabulated in Table 4.8-1 (calculated on basis of best estimates, in some cases).

After deduction of major items from the available void volume, an additional 500 m^3 of displacement is assumed as related to miscellaneous items (e.g., supports, ladders, etc.). The estimated useful volume is thus:

$$\sim 20,500 \text{ m}^3 - (\sim 5,500 \text{ m}^3 + 500 \text{ m}^3) \approx 14,500 \text{ m}^3 (\sim 513,300 \text{ ft}^3)$$

TABLE 4.8-1. Reactor Containment Building
Volume Displacements

<u>Major Item</u>	<u>Volume (m³)</u>	<u>NUREG/CR-0130 Identification</u>
Concrete		
Biological Shield	754	Table A.2-1 & Figure A.2-1 through A.2-10
Missile Shield	41	
Refueling Cavity	460	
Pressurizer Enclosure	410	
Steam Generator Enclosures (4)	<u>807</u>	
Subtotal	2 452	
Equipment		
Reactor Vessel	350	Figure A.3-1, A.3-2
Steam Generators (4)	1 560	Table A.3-2 & Figure F.2-4
Coolant Pumps (4)	207	Figure A.3-9, A.3-10 & Table A.3-3
Safety Injection Accumulators (4)	270	Table A.3-7
Pressurizer	67	Figure A.3-11
Pressure Relief Tank	68	Table A.3-7
Excess Letdown HX	0.2	
RC Drain Tank	3.7	
Regenerative HX	0.6	
Major Piping Systems	500	Table A.3-5
Cavity Drain Pump (1)	3.6	Table A.3-7
Sump Pump (2)	<u>2.9</u>	
Subtotal	<u>3 033.0</u>	
Total	5 485.0	
	(193 701 ft ³)	

4.8.2 Onsite Handling to Entombment

Container, transportation, and burial costs for stainless steel items and for concrete are summed from data from Table G.4-5 of NUREG/CR-0130 as follows:

<u>Constituent</u>	<u>Container Cost</u>	<u>Transportation Cost</u>	<u>Burial Cost</u>	<u>Total Cost</u>
Concrete	\$1,055,200	\$1,227,600	\$894,810	\$3,177,610
SS Systems	240,400	125,500	206,694	<u>572,594</u>
Total Cost				\$3,750,204

It is estimated that about 20% of cost for offsite disposal would be experienced for onsite handling into the RCB available void volume. Thus:

$$(0.2) (\$3,750,204) = \$750,041, \text{ Rounded to } \$750,000$$

Similarly, the staff labor required within the containment building to accomplish entombment is estimated to be about 20% of the staff labor that was developed in Figure G.2-2 of NUREG/CR-0130 for immediate dismantlement. Thus,

$$(0.2) (\$2,230,000) = \$446,000$$

4.8.3 Slab Pouring and Penetration Sealing

An overall estimate of $\sim 550 \text{ ft}^2$ of access openings through the RCB outer wall (of sizes ranging from small conduits to the equipment hatch of $\sim 320 \text{ ft}^2$) is based on qualitative scaling from the referenced figures. Bases for development of the estimated \$310,000 cost for these operations are described as follows:

Sealing of RCB Wall Penetrations

Penetrations to be sealed include:

- liquid discharges and inputs to pipe chase
- fuel transfer tube
- electrical and instrument conduits
- HVAC System
- steam lines to turbine building.

After removal of piping, etc., from the penetrations, 1/4-in. plate is cut to match openings and covers are welded to RCB liner.

~300 lineal ft of cutting, estimated as	~\$ 300
~550 ft ² of 1/4 in. plate will require ~300 lineal ft of weld	
Estimate welding cost of ~\$12/ft	~\$ 3,600
Material at ~\$500/ton x ~2.75 ton	~\$ 1,400
Install reinforcing bar grids in openings through wall	~\$ 2,200
Install concrete pouring forms, (550 ft ² @ ~\$4/ft ²)	~\$ 2,200
Concrete pours at \$100/yd ³ [(550 ft ²) x (6 ft)/27 ft ³ /yd]	~\$12,200
Clean up after concrete pours (remove forms, etc.)	~\$ 1,000
Finish and coat outside of new concrete	~\$ 1,000
Inspect and test welds	<u>~\$ 1,000</u>
Wall Sealing Total	~\$24,700

Concrete Pour at Operating-Floor Level

Slab radius = 21.336 m, thickness = 1.524 m	Volume = 2,179.5 m ³
(70 ft) (5 ft)	= 76,969 ft ³
	= 2,851 yd ³

At ~\$100/yd ³ (including costs of preparation of surface below pour and costs of procurement and installation of rebar), an estimated cost for the entombment barrier is:	<u>~\$285,100.00</u>
Total	~\$309,800.00

REFERENCES

1. U.S. Congress, 95th Congress, Public Law 95-604, "The Uranium Mill Tailings Radiation Control Act of 1978."

5.0 IMPACT OF INCREASED RADIATION DOSE RATES ON ESTIMATES OF DECOMMISSIONING COSTS AND RADIATION DOSE

The radiation dose rate data utilized in the analyses presented in NUREG/CR-0130 were based on a composite of measured data from six PWRs that had been operating for 3 to 6 years. The deposition of radioactive corrosion products within the systems in those plants has probably not reached an equilibrium level, and the measured radiation dose rates may be significantly less than would be encountered after 30 or 40 years of operation. Data on the trends in radiation dose rates from PWR coolant system piping⁽¹⁾ suggest that equilibrium values may be a factor of two or three greater than the values used in the PWR study (see Figure 5.0-1).

For purposes of this analysis, an increase in the radiation dose rates from deposited activated corrosion products of a factor of three has been postulated. It is recognized that radiation dose rates of that magnitude are unlikely to be permitted to exist in operating plants since the dose to operations and maintenance personnel would become prohibitive, and chemical decontamination of these systems would likely be performed at intervals to keep

FIGURE 5.0-1. Shutdown Radiation Levels on PWR Coolant System

the radiation dose rates at or below present levels. Thus, the postulated factor of three increase probably represents an upper-limit situation.

The estimated radiation doses to decommissioning workers resulting from immediate dismantlement of the reference PWR, given in Table 11.3-1 of NUREG/CR-0130, are presented here in Table 5.0-1, and estimated doses resulting from preparations for safe storage, given in Table 11.3-2, are presented in Table 5.0-2. The estimated doses resulting from entombment, given in the previous chapter of this addendum, are presented in Table 5.0-3. Those decommissioning events likely to be affected by the increased radiation levels are designated with an asterisk in the description column and in the X3 dose column of each table. Some of the remaining events are handled using remote or semi-remote handling and shielding and are not influenced significantly by the increased dose rates from deposited corrosion products. The other remaining events are performed after removal of the more radioactive components and are also not affected.

If the decommissioning work is done as postulated in NUREG/CR-0130, the total dose to decommissioning workers would be as shown in the right-hand columns of Tables 5.0-1 through 5.0-3. For immediate dismantlement, 2,900 man-rem is estimated, compared with about 1,400 man-rem for the base PWR study. For preparations for safe storage, the estimated dose increases from 426 man-rem to 578 man-rem, reflecting the smaller amount of contact work necessary to complete the preparations. For entombment, the estimated dose increases about a factor of two. It is obvious that twice as many people would be required to accomplish the work to keep the individual radiation exposures near the levels postulated in the PWR study.

One alternative could be to install temporary shielding in many areas to reduce the radiation dose rates to the workers during dismantlement. A second alternative could be to increase the effectiveness of the chemical decontamination effort to reduce the radiation levels to those estimated for the PWR study. A third alternative could be to do as little as possible for 15 to 20 years, then proceed with dismantlement.

TABLE 5.0-1. Summary of the Estimated External Occupational Radiation Dose for the Immediate Dismantlement of the Reference PWR^(a)

Description	Event Total Dose (man-rem) ^(b,c)	X3 Dose (man-rem) ^(c)
Reactor Building		
Move Internals to Refueling Cavity	8.0	8.0
Comprehensive Pre-dismantling Radiation Survey ^(d)	9.0	27*
Segment Vessel Internals and Load Containers	92	92
Segment Reactor Pressure Vessel and Load Containers	78	78
Segment Steam Generators (4) and Prepare for Shipment*	140	420*
Remove RCS Pumps (4) and RCS Piping*	67	201*
Remove Pressurizer, Relief Tank, and Safety Injection System*	65	195*
Remove HXs and Assorted Pumps*	29	87*
Remove Contaminated Internal Structures	81	81
Remove Spray Piping and Ventilation Systems	12	12
Decontaminate Remaining Internal Surfaces	<u>6.0</u>	<u>6.0</u>
Total	587	1 207
Auxiliary Building		
Remove Electrical Equipment	1.5	1.5
Decontamination (contact work and internal flushes)*	13	39*
Remove Selected Building Internal (plugs, walls, platforms) Package	1.5	1.5
IX Resin and Filters Removal	23	23
Remove IX and Filters System Piping*	96	288*
Remove Tanks, Pumps, and HXs*	150	450*
Remove HVAC and Fire Sprinkler Systems and Monorails	<u>7.0</u>	<u>7.0</u>
Total	292	810
Fuel Building		
Remove CVC System*	85	255*
Remove Condensate Holding Tank System*	7.0	21
Remove New Fuel Storage Racks and Install Electropolishing System	1.0	1.0
Remove Boric Acid System, Tanks, and Piping*	34	102*
Remove CCW System	4.0	4.0
Remove Spent Fuel Racks, Fuel Transfer System, and Peripheral Equipment	8.0	8.0
Remove SFP Recirculation System, Liners, and Contamination Concrete	<u>8.0</u>	<u>8.0</u>
Total	147	399
Ancillaries		
Comprehensive Plant Radiation Survey	2.0	2.0
Special Radiation Surveys*	6.3	19*
RCS and CVCS Chemical Decontamination*	26	78*
Decontamination (electropolishing) and disposal (packaging and shipping of contaminated equipment and debris)*	4.6	14*
Packaging (combustible wastes)	29	29
Fuel Handling (defuel reactor and ship fuel offsite)	140	140
Miscellaneous Work	<u>170</u>	<u>170</u>
Total	<u>378</u>	<u>452</u>
Total for Immediate Dismantlement	1 404	2 868

(a) These estimates are based on the assumption that the RCS, CVCS, and other related systems are chemically decontaminated internally.

(b) For a detailed discussion of these estimates, consult Appendix G, Table G.3-1, NUREG/CR-0130.

(c) Individual estimates of man-rem of radiation dose are rounded to two significant figures.

(d) Events likely to be affected by increased radiation levels are designated by an asterisk.

TABLE 5.0-2. Summary of the Estimated External Occupational Radiation Dose for Preparations for Safe Storage^(a)

Description	Event Total Dose (man-rem) ^(b,c)	X3 Dose (man-rem) ^(c)
Reactor Building		
Comprehensive Precommissioning Survey ^(d)	6.6	20*
Decontaminate Reactor and Refueling Cavities (contractor)	4.0	4.0
Chemical Decontamination (RCS, CVS, and related systems)*	26	78*
Purge RCS and CVC Systems*	1.1	3.3*
Decontaminate Remaining Internal Surfaces and Place Reactor Building in Safe Storage*	17	51*
Intrusion, Radiation, and Fire Alarm Installation (contractor)	4.5	4.5
Final Reactor Building Radiation Survey*	<u>1.1</u>	<u>3.3*</u>
Total	61	164
Auxiliary Building		
Comprehensive Precommissioning Survey*	3.6	11*
IX Resin and Filters Removal	23	23
Decontamination (contact work and internal flushes)*	6.3	19*
Place Auxiliary Building in Safe Storage*	0.16	0.5*
Intrusion, Radiation, and Fire Alarm Installation (contractor)	0.67	0.7
Final Auxiliary Building Radiation Survey*	<u>0.79</u>	<u>2.4*</u>
Total	34	57
Fuel Building		
Comprehensive Precommissioning Survey*	1.2	3.6*
Decontamination (contact work and internal flushes)*	9.6	29*
Miscellaneous Work	0.13	0.1
Place the Spent Fuel Pool in Safe Storage (contractor)	5.0	5.0
Intrusion, Radiation, and Fire Alarm Installation (contractor)	0.67	0.7
Final Fuel Building Radiation Survey*	<u>0.36</u>	<u>1.1*</u>
Total	17	40
Ancillaries		
Radiation Surveys (weekly)*	1.32	4.0*
Packaging (combustible wastes)	6.0	6.0
Fuel Handling (defuel reactor and ship fuel offsite)	137	137
Miscellaneous Work	<u>170</u>	<u>170</u>
Total	<u>314</u>	<u>317</u>
Total for Preparations for Safe Storage	426	578

(a) These estimates assume that the RCS, CVCS, and related systems are chemically decontaminated internally.

(b) For a detailed discussion of these estimates, consult Appendix H, Table H.2-1 of NUREG/CR-0130.

(c) Individual estimates of man-rem of radiation doses are rounded to two significant figures.

(d) Events likely to be affected by increased radiation levels are designated by an asterisk.

TABLE 5.0-3. Summary of the Estimated External Occupational Radiation Dose for Entombment^(a)

Description	Entombment Dose ^(b,c)		Entombment Dose (X3) ^(c)	
	w/Internals (man-rem)	w/o Internals (man-rem)	w/Internals (man-rem)	w/o Internals (man-rem)
Reactor Building				
Move Internals to Refueling Cavity	---	8.0	---	8.0
Comprehensive Predismantling Radiation Survey*	9.0	9.0	27*(d)	27*
Segment Vessel Internals and Load Containers	---	92	---	92
Remove Steam Separators (4) and Prepare for Storage*	15	15	45*	45*
Lower Pressurizer*	3.0	3.0	9.0*	9.0*
Remove Spray Piping and Ventilation Systems	1.0	1.0	1.0	1.0
Decontaminate Remaining Internal Surfaces	<u>2.0</u>	<u>2.0</u>	<u>2.0</u>	<u>2.0</u>
Reactor Building Total	30	130	84	184
Auxiliary Building Total	300	300	310	810
Fuel Building Total	150	150	399	399
Ancillaries Total	<u>380</u>	<u>380</u>	<u>452</u>	<u>452</u>
Subtotal	860	960	1 745	1 845
Transfer of Materials into Containment*	15	15	45*	45*
Cutting and Sealing Containment Penetrations*	20	20	60*	60*
Forming and Pouring Entombment Barrier*	<u>5.0</u>	<u>5.0</u>	<u>15*</u>	<u>15*</u>
Subtotal	900	1 000	1 865	1 965
Transportation-Related Exposure	<u>20</u>	<u>25</u>	<u>20</u>	<u>25</u>
Total for Entombment	920	1 025	1 885	1 980

(a) These estimates assume that the RCS, CVCS, and related systems are chemically decontaminated internally.

(b) From Table 4.6-1, NUREG/CR-0130 Addendum.

(c) Individual estimates of man-rem of radiation dose are rounded to two significant figures.

(d) Events likely to be affected by increased radiation levels are designated by an asterisk.

The impact of the higher radiation dose rates on decommissioning costs is felt in several areas: staff labor charges, supplies, utilities, packaging costs, and disposal charges. These impacts, the costs and benefits of more extensive chemical decontamination efforts, and other considerations leading to the selection of the second alternative are discussed in the subsequent sections.

5.1 STAFF LABOR CHARGES

The impact of increased radiation levels on staff labor costs will vary, depending on the decommissioning mode selected. For immediate dismantlement and for entombment, because of the large amount of direct contact work on the piping systems and associated equipment, the impact can be significant. For

preparations for safe storage, the fraction of direct contact work is much less, resulting in a much smaller impact. These impacts are examined in the following subsections.

5.1.1 Immediate Dismantlement

One approach used in the industry when faced with jobs involving high radiation dose rates is to employ temporary laborers, utilize them until they have received their allowable radiation dose, and then replace them with new temporary laborers, and so on until the job is finished. Because of the time required to train these workers and because of their lack of familiarity with the plant, it is estimated that these workers are only about 60% as efficient as the workers who come from the plant's operating staff. Thus, the staff labor costs for the craftsmen and decommissioning technicians would be increased by 60 to 70%, which results in a 28% increase in total staff labor costs, or about \$2.5 million in the case of immediate dismantlement, not including any contingency. This conclusion is based on the manpower costs given in Table 10.1-2 of NUREG/CR-0130, and includes the following staff categories: Health Physics technicians, QA technicians, Craftsmen, Utility Operators, and Laborers.

Another approach would utilize temporary laborers to install large amounts of temporary shielding, thereby reducing the radiation dose rates to the dismantlement staff to the levels postulated in the PWR study. This approach would be only partially successful, since the piping and equipment has to be handled during removal, and shielding during that phase of the operations would be difficult (if not impossible) in many cases. There is no clear-cut way to evaluate the cost of this approach, but it seems likely that the cost differential for staff labor would be in the same range as the \$2.5 million estimated for the first approach. The cost of the additional shielding is estimated to be on the order of \$100,000. It is also likely that the radiation dose absorbed during the placement of the shielding would be large, such that the total occupational radiation dose may be as large as for the unshielded case.

5.1.2 Preparations for Safe Storage

The nature of the activities performed during preparations for safe storage is such that the occupational radiation dose to workers is increased by about 36% because of an increase of a factor of three in radiation levels throughout the facility. This increased dose could be absorbed by the postulated work force without exceeding existing guidelines. Therefore, the impact of increased radiation levels on staff labor costs would be minimal.

5.1.3 Entombment

Since the entombment mode requires immediate dismantlement of all buildings except the containment building, the impact of increased radiation levels on staff labor costs would be similar to that of immediate dismantlement. Making the same assumptions about the use of temporary laborers as were made in Section 5.1.1, the staff labor costs would be increased by about \$1.8 million, not including any contingency.

A more extensive effort on chemical decontamination of the systems would have a small impact on staff labor costs and on the cost of supplies, utilities, waste packaging and waste disposal, as discussed in Section 5.2.

5.2 EXPANDED CHEMICAL DECONTAMINATION EFFORT

The chemical decontamination method postulated for the reference PWR utilized a complexing agent, EDTA, together with citric and oxalic acid in a one-step process. An average decontamination factor (DF) of 10 was postulated. Laboratory experiments and in-reactor loop decontamination studies⁽²⁾ have shown that the dissolution of the deposited film containing the various radionuclides proceeds in a decreasing exponential manner relative to the length of time of circulation. These data suggest that to reduce the radiation dose from the internally deposited radionuclides in the piping systems from the postulated X3 level to the levels assumed in NUREG/CR-0130, would simply require circulation of the solution for a longer period. Other factors, such as the thermolytic and radiolytic decomposition of the EDTA during circulation, require monitoring and continuous addition of the decontamination chemicals

throughout the recirculation process to maintain the optimum conditions for removal and suspension of the radionuclides in the circulating fluid. Since the reduction in radiation dose rates tends to follow an exponential decay curve, the circulation time required to obtain a factor of three, in addition to the factor ten postulated in NUREG/CR-0130, would be about an additional 50%.

The principal cost impact from the extended chemical decontamination effort would be the cost of electricity to operate the recirculation pumps. In the reference study, NUREG/CR-0130, this cost was estimated to be \$105,000 to obtain a DF of ten. Thus, to obtain a DF of thirty, the electricity cost would be about \$160,000. The cost of chemicals in the reference study was based on a 5% solution. This is probably an upper-limit estimate, even including the cost of the chemicals added during the recirculation period; thus, no incremental expense is postulated for the chemicals. Similarly, the volume of fluid to be evaporated, solidified, transported, and buried remains the same as given in the reference study. The staff labor involved is roughly proportional to the recirculation time, and the additional staff labor cost would be about \$30,000. Therefore, the incremental cost of achieving a DF of thirty, as compared with a DF of ten, is postulated to be about \$85,000.

From a practical point of view, it is unlikely that dose rates in operating plants will be allowed to reach anything approaching three times present levels, because of the considerable difficulty such increases would cause for normal operation and maintenance. Studies are presently in progress within the nuclear industry to develop decontamination solutions that can be injected into the reactor coolant stream immediately following reactor shutdown and circulated through the primary coolant system with the fuel in place in the core. The decontamination chemicals and the suspended and dissolved radionuclides are removed from the coolant water by side-stream cleanup, resulting in reactor quality water by the end of the outage. It is anticipated that these decontaminations will produce a DF of about two, which should be sufficient to keep the radiation dose rates at a manageable level for the life of the plant.

5.3 DISPOSAL COSTS

If the chemical decontamination cycle is not extended, the residual radioactivity in the piping and other system components would be about a factor of three greater than was estimated in the PWR study. The effect of these higher residual radioactivity levels would be seen principally in the area of container shielding.

Of the 4,154 shipping containers designated for disposal of contaminated material in NUREG/CR-0130, it is estimated that only about 900 would require some degree of shielding. An allowance of \$100,000 is suggested as a reasonable figure for the cost of this additional shielding. The higher residual contamination level would have no significant effect on the handling and disposal of the neutron-activated components, since the radiation dose from the activated materials completely overwhelms the radiation dose from the deposited corrosion products.

5.4 SUMMARY

For the situation where the radiation dose rates from radionuclides deposited in the fluid systems are postulated to be three times present-day levels:

- If no corrective actions are taken to reduce the radiation dose rates, the accumulated radiation dose to decommissioning workers would be increased about 1,500 man-rem, the decommissioning costs could be increased by about \$2.5 million for additional staff labor and about \$100,000 for additional container shielding, for a total of about \$2.6 million for the case of immediate dismantlement. For entombment, the radiation dose would be increased about 105 man-rem and the cost could be increased about \$1.8 million, and for preparations for safe storage, the radiation dose would be increased about 150 man-rem and there would be no significant change in the cost.
- If corrective action is taken, such as an extended chemical decontamination cycle, the total additional cost could be about \$85,000.

On the basis of these estimates, it appears that additional chemical decontamination would be the most cost-effective approach to handling the

higher initial radiation levels postulated. This approach would also be more consistent with the principles of ALARA, since the occupational radiation dose associated with a chemical decontamination cycle is relatively small, compared with the radiation dose associated with installing temporary shielding, or with attempting to perform the dismantlement without additional shielding. In addition, it appears likely that annual decontaminations of the reactor coolant system and related fluid-handling systems will become standard procedure when the present technology development for decontamination solutions has been completed, thus preventing the large buildups of radionuclides on the piping systems prevalent today.

REFERENCES

1. S. G. Sawochka, N. P. Jacob and W. L. Pearl, Primary System Shutdown Radiation Levels at Nuclear Power Generating Stations, EPRI 404-2, Figure 11, p. 57, December 1975.
2. K. Oertel, E. Glaser, J. Bosholm and H. J. Hoffman, Decontamination of Primary Loop Equipment with Ethylenediaminetetracetic Acid, Kernenergy, Vol. 19, No. 1, pp. 128-132, 1976.

6.0 SENSITIVITY OF DECOMMISSIONING COSTS TO CONTRACTUAL ARRANGEMENTS

In NUREG/CR-0130, the basic premise concerning the decommissioning work force was that the bulk of the staff consisted of personnel who were members of the facility's operating organization prior to shutdown of the facility. It was also postulated that the utility functioned as the general contractor for the decommissioning effort and that general maintenance mechanics handled all craft-type jobs carried on throughout the decommissioning. These assumptions tended to minimize staff labor costs by reducing or eliminating jurisdictional problems in work assignments.

A fair question to ask in this addendum is how are the staff labor costs affected if the utility places the entire decommissioning job on a contract basis? Numerous organizations presently exist to provide specialized services to reactor sites during outages. It seems likely that when a significant number of reactor plants are approaching retirement, organizations will be formed specifically to decommission such facilities. This section examines the possible impacts of this contract-type approach to decommissioning on the overall decommissioning costs.

6.1 POSTULATED ORGANIZATIONAL STRUCTURE FOR DECOMMISSIONING

The plant owner, as the licensee, has the responsibility for assuring that the decommissioning work is performed in accordance with applicable regulations. Therefore, the plant owner is the prime contractor and provides the quality assurance, industrial safety, and contracts and accounting functions in addition to the overall supervision of the job. Specialized contractors provide the working level supervision and the decommissioning workers. It is anticipated that separate contractors would be employed to provide the functions of security, health physics, transport and physical dismantlement of the plant. The functional organization presented in Figure 9.1-3 of NUREG/CR-0130 would be modified to the organization shown in Figure 6.1-1. The specialty contractors identified in NUREG/CR-0130 (explosives, radwaste treatment) would be subcontractors to the dismantlement contractor.

NOTE: HEALTH PHYSICS TECHNICIANS AND CRAFTSMEN WILL BE ATTACHED TO CREWS AS WORK SITUATION DEMANDS

FIGURE 6.1-1. Postulated Organization for Decommissioning by Immediate Dismantlement

6.2 IMPACT ON DECOMMISSIONING COSTS OF UTILIZING CONTRACTORS

The principal costs impacts associated with utilizing contractors to accomplish decommissioning of the reference PWR are: different contractual arrangements, including the type of contract, fees, and incentives; higher overhead rates on staff labor for contractors than for the utility; and mobilization and demobilization of the contractor forces and equipment. A discussion of these factors and of the likely circumstances of contracting this type of work are presented in the following subsections.

6.2.1 Contractual Considerations

Clearly, the degree of subcontract activity varies with the proportion of services that can be performed in-house by the owner. The type of contract is primarily conditioned by financial risk or uncertainty of performance. Where specific work packages are prepared and are suitable for definitive pricing, a firm fixed-price contract best serves the interests of each contracting party. A definitive work scope generally is compatible with advertised bids and enhances the prospect for competition and obvious savings. In situations where the owner must maintain day-to-day surveillance and supervision of decommissioning tasks, a less definitive work statement is called for. In this situation, a cost reimbursement contract or one that specifies a fixed price per hour for labor is most suitable.

In the safe storage mode, ongoing services probably can be fixed-priced. These services (such as radiation monitoring, building maintenance, and security) are relatively quantifiable. It is easily understood that the least definitive aspect of decommissioning involves dismantlement. Employment of labor in health physics programs and in high-risk skills (such as explosive demolition) add to built-in inefficiencies resulting from radioactive decontamination efforts to impose cost burdens on the owner. Very conservative estimating is to be anticipated from proposers for work under these circumstances. Further, it would be prudent for utilities to include an "inefficiency" factor in budgeting for these types of decommissioning tasks. Budgeting is also impacted by the long-term planning desired in the decommissioning process.

Estimates in excess of 1 year degrade rapidly in accuracy, if they are available at all. General economic conditions, inflation rates, regulatory impacts, energy costs, and labor costs are all interdependent elements requiring careful evaluation from either a budgeting or cost proposal viewpoint.

A number of factors need to be considered in the process of establishing subcontracts. Following is a list of selected contract terms and conditions that should be considered in a contract for PWR decommissioning:

- indemnity and insurance
- third-party liability (public liability)
- delay of work
- default
- changes
- licenses, permits, approvals
- safety equipment
- inspection (quality assurance)
- disputes
- overtime premium
- hazardous material handling
- accident reporting
- salvage rights.

Not all of these provisions are necessarily called for in a given contract situation, but all certainly deserve consideration. Costs, of course, are traded off in instances where public indemnity by state or federal government is substituted for such items as insurance coverage. Each contract situation must be evaluated in terms of work statement, period of performance, cost risk, and terms and conditions before a meaningful estimate or proposal is possible. There are simply no model contracts or auditable trails to study for specific experience in subcontracting for nuclear power plant decommissioning. This situation is not unique, however, and yet it requires acknowledgement and proper emphasis by management in designating a professional procurement staff.

Incentives may be considered for accelerated completion, reduced contract cost, or some other specific performance objective. Such incentives must be

carefully determined and, as a general rule, selected on the basis of easy measurement. A less-objective incentive may be negotiated in the form of an Award Fee, which is determined on the basis of subjectively measured criteria after performance. An Award Fee is thus a bonus that may apply in whole or in part and becomes added to a base fee.

The major decommissioning expenses are those incurred from labor and material costs. Special tools, leased equipment, and transportation expenses constitute major additional costs. Indirect expenses could vary significantly from one contractor to another within the same industry. Overheads for labor, plant equipment, and materials could be anticipated in a range from 50% to 150% of total costs. Profit or Fee could reasonably be anticipated in the range of 10% to 15%, depending on such things as type of contract and risk of performance. Some consideration to geographical spread for decommissioning cost is appropriate, as regional labor bases vary.

To estimate the impacts of these contractual considerations on decommissioning costs, it is necessary to make several assumptions about how selected costs are paid. For example, it is assumed that the utility pays the radioactive material transportation and disposal costs directly, rather than channeling those costs through the dismantlement contractor. The utility also is assumed to provide the electric power needed on the job. On the other hand, the costs for special equipment and supplies, as well as those for specialty subcontractors, are assumed to flow through the dismantlement contractor and would be subject to the fee percentage increment. Thus, of the items listed in Table 10.1-1 of NUREG/CR-0130, only staff labor, special equipment, miscellaneous supplies, and specialty contractors are subject to the fee incremental cost. Another significant cost item, not separately identified in Table 10.1-1 but included in the disposal costs for radioactive materials, is the cost of shipping containers. It is assumed that these costs would also be subject to the contractor's fee increment.

6.2.2 Increased Overhead Rates

Overhead rates applied to direct staff labor are expected to be significantly higher for subcontracting organizations than for operating utilities,

because of the larger ratio of supervisory and support personnel to direct labor that usually exists in subcontracting organizations. Having personnel in the field rather than in the home office also increases the overhead costs, because of travel and living expenses for many of the personnel. In view of these factors, an overhead rate on direct staff labor of 110% is assumed to be applicable to all subcontractor personnel. The projected manpower utilization and staff costs presented in Table 9.1-1 of NUREG/CR-0130 are regrouped to reflect the organizational structure shown in Figure 6.1-1. The staff labor costs for the subcontractors are adjusted for the higher overhead rates assumed for the subcontractors. The staff labor costs for the utility-only operation and for the combined utility-contractor operation are shown in Table 6.2-1. The combined operation results in a cost increase of about \$2.6 million from staff labor alone, not including any contingency.

6.2.3 Mobilization and Demobilization Costs

There are significant costs associated with a contractor establishing its presence at the work site. These costs include temporary office facilities, obtaining the required special equipment, and assembling the work force. Similarly, there are costs associated with closing down a work site. These costs, called mobilization and demobilization costs, will vary with the size and complexity of the job. For the dismantlement of a large PWR, these costs are estimated by an engineer experienced in estimating costs for utility construction projects to be about \$1.25 million.⁽¹⁾

TABLE 6.2-1. Projected Manpower Utilization and Staff Costs during Immediate Dismantlement

Title or Function	Time in Years Relative to Reactor Shutdown						Total Man Years	Total Cost (\$ millions)	
	-2	-1	1	2	3	4		Utility Operation	Subcontractor Operation
Utility Staff	0.3	1	1	1	1	1	5.3	0.3948	1.8458
Decommissioning Superintendent	0.3	1	1	1	1	1	5.3	0.3948	
Secretary	1	1	1	1	1	1	6	0.1218	
Industrial Safety Specialist	0.3	1	1	1	1		4.3	0.1883	
Quality Assurance Supervisor	0.3	1	1	1	1	1	5.3	0.2321	
Quality Assurance Engineer	0.5	2	1	1	0.6		5.1	0.2009	
Quality Assurance Technicians		0.5	4	4	3	1	12.5	0.2900	
Contract and Accounting Specialist	0.3	1	1	1	1	1	5.3	0.2035	
Accounting Clerk		0.3	1	1	1		3.3	0.0670	
Safety Review Committee Consultants	0.5	0.5	0.5	0.5	0.2		2.2	0.1474	
Subcontractors									
Security Supervisor			1	1	1	1	4	0.1316	0.1626
Security Patrolman			15	10	8	8	41	0.8733	1.2226
Health Physics Supervisor	0.3	1	1	1	1		4.3	0.2167	0.2677
Health Physicist		0.5	1	1	1		3.5	0.1379	0.1703
Senior Health Physics Technician		1	2	2	1		6	0.1740	0.2436
Health Physics Technician		3	7	7	5		22	0.5522	0.7731
Protective Equipment Attendant			2	2	1.5		5.5	0.1276	0.1786
Dismantlement Supervisor	1	1	1	1	1		5	0.3175	0.3922
Assistant Dismantlement Engineer	1	1	1	1	0.5		4.5	0.1971	0.2435
Radioactive Shipment Specialist		1	1	1	1		4	0.1316	0.1626
Procurement Specialist	0.3	1	1	1			3.3	0.1013	0.1251
Craft Supervisor			2	2	2		6	0.2364	0.2920
Craftsman			16	16	7		39	1.0569	1.4797
Tool Crib Attendant			2	2	1.5		5.5	0.1276	0.1786
Shift Engineer			2	2	2		6	0.2364	0.2920
Crew Leader			7	7	5		19	0.6251	0.8751
Utility Operator			10	7	3.4		20.4	0.5528	0.7739
Laborer			18	18	11.2		47.2	1.2225	1.7115
Secretary		1	2	2	1		6	0.1218	0.1705
Man Years/Year	5.8	18.8	103.5	95.5	63.9	14			
Cost (\$ millions)	0.2653	0.7164	2.9456	2.7578	1.8975	0.4035		8.9861	11.561
Total Man Years	---	---	---	---	---	---	301.5		

6.3 SUMMARY

The various cost items are separated into utility costs and contractor costs in Table 6.3-1, for comparison with the utility-only approach assumed in NUREG/CR-0130. A 15% fee is applied to all contractor costs.

TABLE 6.3-1. Comparison of Costs Estimated for Dismantlement Using the Utility-Only or the Utility + Contractor Approach

Category	Cost (\$ millions)		
	Utility-Only ^(a)	Utility + Contractor	
Radioactive Material Disposal	4.875	4.875	---
Shipping Containers	3.735	---	3.735
Dismantlement Staff Labor	8.986	1.856	9.705 ^(b)
Electrical Power	3.500	3.500	---
Special Equipment	0.822	---	0.822
Miscellaneous Supplies	1.559	---	1.559
Nuclear Insurance	0.800	0.800	---
Specialty Contractors	0.390	---	0.390
Environmental Surveillance	0.154	0.154	---
Mobilization and Demobilization	---	---	1.250
		11.185	17.461
Contractor's Fee (15%)	---	---	2.619
			20.080
Subtotal	24.821	31.265	
Contingency (25%)	6.205	7.816	
Decommissioning Total	31.026	39.081	
Optional Activities			
Demolition and Restoration	8.013		
Spent Fuel Disposal	3.084		
Deep Geologic Disposal	2.250		

(a) Data from Table 10.1-1, p. 10-2, NUREG/CR-0130.

(b) Data from Table 6.2-1, this section.

The net result of using the utility plus contractor approach is an increase in decommissioning costs of about 26%, for a total of \$39 million. This total does not include any incentive or bonus payments that might also be negotiated for an undertaking of this magnitude.

REFERENCES

1. Direct testimony of R. F. Brzezinski, Consumers Power Company before the Michigan Public Service Commission, Case U-6041, March 7, 1979.

7.0 SENSITIVITY OF DECOMMISSIONING COSTS TO WASTE DISPOSAL CHARGES

The costs for disposal of the radioactive materials removed from the reference PWR during dismantlement, as developed in NUREG/CR-0130 were based on the assumption that all of these wastes were placed in a shallow land burial facility. These costs were developed using the fee schedule for a commercially licensed radioactive waste burial ground, published in September 1977. The cost of placing selected portions of the reactor internals in a deep geologic disposal facility was also estimated. The impact of increased disposal costs on the total cost of immediate dismantlement are examined in Sections 7.1 and 7.2 of this report for shallow land burial and for deep geologic disposal, respectively.

7.1 IMPACT OF INCREASES IN SHALLOW LAND BURIAL COSTS

The component parts that make up the total disposal cost for immediate dismantlement of the reference PWR are shown in Table 7.1-1 (condensed from Table 10.1-4 of NUREG/CR-0130). The cost for removal of the final core of spent fuel is deleted from the table, since it might be considered as a final operating expense rather than a decommissioning one. The costs shown in this section do not include a 25% contingency unless explicitly stated.

The cost of all items that make up the total dismantlement cost are shown in Table 7.1-2 (modified from Table 10.1-1 of NUREG/CR-0130).

Table 7.1-2 shows that disposal of radioactive materials constitutes 34.7% of the total dismantlement cost. Table 7.1-1 shows that the actual charges at the disposal facility constitute only 25.4% of the total disposal costs. Thus, only about 8.8% of the dismantlement costs are sensitive to the fee schedule at the disposal facility. As an example, if the burial ground charges are doubled, from \$2.184 million to \$4.368 million, the total dismantlement cost increases from \$24.821 million to \$27.005 million, or about 8.8%.

The burial ground fee schedule used in NUREG/CR-0130 was increased on June 1, 1978 by the facility operator. The fees for burial (in dollars per cubic foot) were increased 79% for containers with low radiation levels,

TABLE 7.1-1. Estimated Costs for Disposal of Radioactive Material^(a)

Category	Millions of Dollars			Total
	Container ^(b)	Transportation ^(c)	Burial ^(d)	
Activated Material	1.740	0.485	0.509	2.734 ^(e)
Containment Internals	0.370	0.311	0.280	0.961
Other Building Internals	1.488	1.470	1.264	4.222
Waste	<u>0.137</u>	<u>0.425</u>	<u>0.131</u>	<u>0.693</u>
Totals	3.735	2.691	2.184	8.610
% of Total	43.4	31.2	25.4	100

(a) All footnotes refer to NUREG/CR-0130.

(b) Container costs as given in Table I.2-1, Appendix I.

(c) Includes cask rental for 5 days/shipment, plus trucking costs, as given in Tables I.3-1 and I.4-4, Appendix I.

(d) Handling, burial, and surcharges as given in Table I.5-1, Appendix I.

(e) Cost differential for deep geologic disposal of highly activated material is +\$1.8 million.

increased 30% for containers having high radiation levels, and increased on a sliding scale in between. The basic curie surcharge per load was increased by 25%. The surcharge for personnel radiation exposure was increased by 117%. The net impact of the increased fee schedule on the costs presented in NUREG/CR-0130 is to increase the burial costs from \$2.184 million to \$3.585 million, for a 5.6% increase in total dismantlement costs.

TABLE 7.1-2. Summary of Estimated Dismantlement Costs for the Reference PWR Facility(a)

Category	Cost in Millions of 1978 Dollars(b)	Percent of Total
Activated Materials Disposal	2.734 ^(c)	34.7
Containment Internals Disposal	0.961	
Other Building Internals Disposal	4.222	
Waste Disposal	0.693	
Staff Labor	8.986	36.2
Electrical Power	3.500	14.1
Special Equipment	0.822 ^(d)	3.3
Miscellaneous Supplies	1.559	6.3
Specialty Contractors	0.390	1.6
Nuclear Insurance	0.800	3.2
Environmental Surveillance	0.154	0.6
Subtotal	24.821	100
25% Contingency	6.205	
Total Dismantling Cost	31.026	
Other Possible Costs		
Facility Demolition (non-radioactive)	6.410	
Spent Fuel Disposal	2.467	
Subtotal	8.817	
25% Contingency	2.219	
Total	11.094	

(a) All footnotes refer to NUREG/CR-0130.

(b) Number of figures shown is for computational accuracy and does not imply precision to the nearest thousand dollars.

(c) Cost differential for deep geologic disposal of highly activated reactor vessel components = \$1.8 million. (See Appendix G.4.2.1.)

(d) See Table F.3-1 or Table I.6-1.

7.2 IMPACT OF INCREASES IN DEEP GEOLOGIC DISPOSAL COSTS

The analysis presented in NUREG/CR-0130 as an alternative to using the low-level waste burial ground was based on placing only selected portions of the reactor vessel internals in a deep geologic disposal facility. The unit cost of emplacement was assumed to be \$7,100/m³.⁽¹⁾ Other estimates⁽²⁾ have been made of the cost of deep geologic emplacement that range from about \$9,000/m³ to about \$19,000/m³, depending on whether the geologic medium is salt or various types of crystalline rock. The total cost of deep geologic disposal estimated in NUREG/CR-0130 is shown in Column 1 of Table 7.2-1. Also shown are the upper-limit values based on the other set of estimates of emplacement costs. From the table, it can be seen that essentially doubling the emplacement cost per unit volume of waste increases the total disposal cost by less than 6%. Tripling the emplacement cost per unit volume increases the total disposal cost by less than 12%.

TABLE 7.2-1. Estimated Costs of Deep Geologic Disposal in Millions of 1978 Dollars

		Emplacement Costs at:			
		<u>\$7 100/m³</u>	<u>\$8 000/m³</u>	<u>\$14 000/m³</u>	<u>\$21 000/m³</u>
Containers	\$0.315	\$2.165	0.621	0.700	1.225
Cask Rental	\$1.323				
Transportation	\$0.527				
Total Disposal Cost		2.796	2.865	3.390	4.003
Funds <u>NOT</u> Expended in Shallow Land Burial		<u>(0.982)</u>	<u>(0.982)</u>	<u>(0.982)</u>	<u>(0.932)</u>
Incremental Cost for Deep Geologic Disposal		1.804	1.883	2.408	3.021
Disposal Costs from Table 7.1-2		<u>8.610</u>	<u>8.610</u>	<u>8.610</u>	<u>8.610</u>
Total Disposal Costs		10.414	10.493	11.018	11.631
Percent Increase		0	0.8	5.8	11.7

If all the activated metal components and activated concrete from the biological shield are emplaced in a deep geologic disposal facility, about 1,181 m³ of waste would be involved, at about \$8.5 million for emplacement

and about \$4.3 million for the required 857 canisters, for a total cost of about \$12.8 million. The cost for disposal via shallow land burial of the contaminated (not activated) material is about \$5.9 million. Thus, the total cost for waste disposal is \$18.7 million, or an increase of \$10 million over the cost for disposal of all wastes in a shallow land burial facility.

In the unlikely event that all radioactive wastes from immediate dismantlement are placed in a deep geologic disposal facility, the cost increase becomes quite significant. If it is assumed that the wastes are packaged with the same packing density as assumed in NUREG/CR-0130, so that the disposal volume is constant, 17,998 m³ of waste would have to be emplaced, at a minimum cost (\$7,100/m³) of nearly \$127 million for disposal alone. A total of 12,979 canisters would be required at a cost of over \$64 million. Thus, the cost of waste disposal becomes more than \$191 million, or more than 22 times the cost for shallow land burial.

From the discussion above, it can be seen that if only the highly activated material is placed in a deep geologic disposal facility, the overall disposal costs are not very sensitive to the emplacement cost, increasing about 6% for a doubling of emplacement cost. On the other hand, if all activated materials are placed in a deep geologic disposal facility, the disposal costs increase about 66% for a doubling of the emplacement cost. Obviously, there are strong incentives to minimize the volume of material placed in such a facility.

7.3 SUMMARY

The cost for shallow land burial of the radioactive materials resulting from dismantlement of the reference PWR constitutes only 8.8% of the total decommissioning cost. Doubling the burial costs increases the total decommissioning cost by 8.8%, or about \$2.8 million. An analysis of the impact of recent actual disposal-charge increases on the costs given in NUREG/CR-0130 results in a 5.6% increase, or about \$1.4 million.

The costs for deep geologic disposal of radioactive materials are tied to the emplacement fees at the disposal site. Since the volume of material postulated in NUREG/CR-0130 to be placed in such a facility is small, about

87.5 m³, the incremental cost of such an emplacement is also small; \$1.8 million, or about a 7% increase in decommissioning costs, assuming an emplacement fee of \$7,100/m³. Tripling the emplacement fee from \$7,100/m³ to \$21,000/m³ increases the total decommissioning cost by about 5%, or \$1.2 million, not including any contingency.

Placing all of the activated material (1,191 m³) from the reference PWR in a deep geologic disposal facility (at an emplacement fee of \$7,100/m³) results in disposal costs of nearly \$19 million; and placing all of the radioactive material from the PWR in such a facility results in disposal costs of more than \$191 million. Thus, disposal of radioactive material becomes the dominant cost factor in decommissioning if either of these latter two situations is realized.

REFERENCES

1. C. E. Jenkins and K. J. Schneider, Technology, Safety and Costs of Decommissioning a Reference Fuel Reprocessing Plant, NUREG-0278, Prepared by Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, pp. 7-129, September 1977.
2. Technology for Commercial Radioactive Waste, DOE/ET-0028, Vol. 1, p. 1.5.5, Battelle Pacific Northwest Laboratory Report for the U.S. Department of Energy, May 1979.

8.0 GLOSSARY

Abbreviations, terms, and definitions directly related to decommissioning work and associated technology are defined and explained in this section. It is divided into two parts, with the first part containing abbreviations and the second part containing terms and definitions (including those used in a special sense for this work). Common terms covered adequately in standard dictionaries are not included.

8.1 GLOSSARY ABBREVIATIONS

ALARA	As Low As Reasonably Achievable ^(a)
CFR	Code of Federal Regulations ^(a)
Ci	Curie ^(a)
DF	Decontamination Factor ^(a)
DOT	Department of Transportation
EDTA	Ethylenediamine tetraacetic acid
FASR	Final Safety Analysis Report
HP	Health Physicist ^(a)
HVAC	Heating, Ventilation and Air Conditioning
LWR	Light Water Reactor
MDP	Master Decommissioning Plan
mrad	Millirad ^(a)
mr	Milliroentgen ^(a)
mrem	Millirem, see rem also
MWe	Megawatts, electric
MWt	Megawatts, thermal

(a) See Section 8.2 for additional information or explanation.

NRC	Nuclear Regulatory Commission
OSF	Overall Scaling Factor
PWR	Pressurized Water Reactor
Q.A.	Quality Assurance ^(a)
R	Roentgen ^(a)
RCB	Reactor Containment Building
rad	Radiation Absorbed Dose ^(a)
rem	Roentgen Equivalent Man ^(a)
SFP	Spent Fuel Pool
SNM	Special Nuclear Material ^(a)
SS	Stainless Steel

8.2 GLOSSARY DEFINITIONS

Activity:	Sometimes used for the term "radioactivity."
Airborne Radio- active Material:	Radioactive particulates, mists, fumes, and/or gases in air.
ALARA:	A philosophy to maintain exposure to radiation <u>As Low As is Reasonably Achievable</u> .
Burial Grounds:	Areas designated for storage of containers of packaged radioactive wastes in near-surface soils.
Cask:	A heavily shielded shipping container for radioactive materials. Some casks weigh as much as 100 tons.

(a)See Section 8.2 for additional information or explanation.

**Code of Federal
Regulations (CFR):**

The Code of Federal Regulations is a codification of the general rules by the Executive departments and agencies of the federal government. The Code is divided into 50 Titles that represent broad areas subject to federal regulation. Each Title is divided into Chapters that usually bear the name of the issuing agency. Each Chapter is further subdivided into Parts covering specific regulatory areas.

Contact Maintenance:

"Hands-on," or maintenance performed by direct contact of personnel with the equipment. Most non-radioactive maintenance is contact maintenance.

Containment Building:

A strongly reinforced structure that encloses the nuclear steam supply system. Also called Reactor Building.

Contamination:

Radioactive material or materials that have been deposited on the surfaces of structures or equipment or that have been mixed with another material.

Continuing Care Period:

The surveillance and maintenance phase of Safe Storage, with the facility secured against intrusion.

Curie:

The special unit of activity. One curie equals 3.7×10^{10} nuclear transformations per second. (Abbreviated Ci.) Several fractions of the curie are in common usage:

- Millicurie. One-thousandth of a curie. Abbreviated mCi.
- Microcurie. One-millionth of a curie. Abbreviated μ Ci.
- Nanocurie. One-billionth of a curie. Abbreviated nCi.
- Picocurie. One-millionth of a microcurie. Abbreviated pCi; replaces the term $\mu\mu$ c.

Decay, Radioactive:

- A spontaneous nuclear transformation in which a particle, gamma radiation or x radiation is emitted following orbital electron capture or spontaneous fission of the nucleus.

Decommissioning:	Preparation of nuclear facilities for retirement from active service accompanied by the execution of a program to reduce or stabilize radioactive contamination to reduce the potential health and safety impacts on the public.
Decontamination:	Those activities employed to reduce the levels of contamination in or on structures and equipment.
Decontamination Agents:	Those chemical materials used to effect decontamination.
Decontamination Factor (DF):	The ratio of the initial concentration of an undesired material to the final concentration resulting from a treatment process. The term may also be used as a ratio of quantities.
Deep Geologic Disposal:	Placement of radioactive materials in stable geologic formations far beneath the earth's surface.
Dismantlement:	Those actions required to remove sufficient radioactive or contaminated material from the facility to permit unrestricted release of the property.
Dispersion:	A process of mixing one material within a larger quantity of another. For example, the mixing of material released to the atmosphere with air causes a reduction in concentration with distance from the source.
Disposal:	The disposition of materials with the intent that they will not enter man's environment in sufficient amounts to cause a health hazard.
Dose, Absorbed:	The mean energy imparted to matter by ionizing radiation per unit mass of irradiated material at the place of interest. The unit of absorbed dose is the rad. One rad equals 0.01 Joules/kilogram in any medium (100 ergs per gram.)
Dose, Equivalent:	Expresses the amount of effective radiation in man, in rems, when modifying factors have been considered. The product of absorbed dose multiplied by a quality factor multiplied by a distribution factor.
Dose, Occupational:	The exposure of an individual to radiation above background as imposed by his employment.

Dose, Radiation:	As commonly used, it is the quantity of radiation absorbed in a unit mass of a medium, frequently a human organ.
Dose Rate:	The radiation dose delivered per unit time and measured, for instance, in rems per hour.
Entombment:	The encasement of radioactive materials in concrete or other structural material sufficiently strong and structurally long-lived to assure retention of the radioactivity until it has decayed to levels which permit unconditional release of the site.
Exposure:	A measure of the ionization produced in air by x or gamma radiation. It is the sum of the electrical charges on all ions of one sign produced in air when all electrons liberated by photons in a volume element of air are completely stopped in air, divided by the mass of the air in the volume element. The special unit of exposure is the roentgen.
Facility:	The physical complex of buildings and equipment within a site.
Fuel Assembly:	A grouping of fuel elements that supply the nuclear heat in a nuclear reactor. A fuel element is the smallest structurally discrete part of a reactor or fuel assembly that has nuclear fuel as its principal constituent.
Fuel Element:	A rod, tube, plate or other form into which nuclear fuel is fabricated for use in a reactor.
Fuel Pool Cooling System:	The system that cools and purifies the water in the fuel storage pool.
Fuel Storage Pool:	A large pool full of water that provides storage and servicing facilities for nuclear fuel elements.
Half-Life, Radioactive:	The time in which half the atoms of a particular radioactive substance disintegrate to another nuclear form. Each radionuclide has a unique half-life. Measured half-lives vary from millionths of a second to billions of years.

Health Physicist:	A person trained to perform radiation surveys, oversee radiation monitoring, estimate the degree of radiation hazard, and advise on radiation hazards.
Health Physics:	The science concerned with recognition, evaluation, and control of health hazards from ionizing radiation.
Hot Spots:	Areas of radioactive contamination of higher than average concentration.
Immobilization:	Treatment and/or emplacement of materials (e.g., radioactive contamination) so as to impede its movement.
Intrusion Alarm:	A secure, electrical, electro-mechanical, electro-optical, electronic, mechanical or similar device capable of detecting intrusion by individuals into a protected area by means of visible or audible alarmed signal.
Ion Exchange:	A chemical process involving the absorption or desorption of various chemical ions in a solution onto a solid material, usually a plastic or resin. The process is used to separate and purify chemicals, such as fission products or hardness in water (i.e., water softening).
Licensed Material:	Source material, special nuclear material, or byproduct material received, possessed, used, or transferred under a license issued by the NRC.
Liquid Radioactive Waste:	Solutions, suspensions, and mobile sludges contaminated with radioactive materials.
Long-Lived Nuclides:	For this study, radioactive isotopes with long half-lives typically taken to be greater than about 10 years. Most nuclides of interest to waste management have half-lives on the order of one year to millions of years.
Low-Level Waste:	Wastes containing types and concentrations of radioactivity such that no shielding or relatively little shielding is required to minimize personnel exposure.
Management (Waste):	The planning, execution, and surveillance of essential functions related to radioactive waste, including treatment, solidification, interim or long-term storage, transportation and disposal.

Man-rem:	Used as a measure of population dose and calculated by summing the dose equivalent in rem received by each person in the population. Also, it is used as the absorbed dose of one rem by one person with no rate of exposure inferred.
Maximum-Exposed Individual:	A hypothetical individual in the general population who is located at the point of highest ground-level concentration of radioactive materials and is subject to the greatest concentration of the radioactive materials that are discharged from the plant.
Millirad:	A unit of absorbed dose (one-thousandth of a rad).
Milliroentgen:	A submultiple of the roentgen, equal to one-thousandth of a roentgen. (See Roentgen.)
Monitoring:	Taking measurements or observations for recognizing adequacy, significant changes in, conditions or performance of a facility or area.
Nuclear Steam Supply System:	A contractual term which designates those components of the nuclear system and its related safeguards and instrumentation furnished by the nuclear steam supply system supplier.
Nuclear System:	<p>Generally includes those systems most closely associated with the reactor vessel, designed to contain or be in communication with the water coming from or going to the reactor core. The nuclear system includes the following:</p> <ul style="list-style-type: none"> • reactor • reactor assembly and internals • reactor core • neutron monitoring system • reactor recirculation system • control rod drive system • residual heat removal system • chemical volume control system • emergency core cooling systems.

Offsite:	Beyond the boundary line marking the limits of plant property.
Onsite:	Within the boundary line marking the limits of plant property.
Package:	The packaging plus the contents of radioactive materials.
Packaging:	The assembly of radioactive material in a container and other components necessary to assure compliance with prescribed regulations.
Possession-only License:	A license issued to a nuclear facility owner by the NRC entitling the licensee to own a nuclear facility but not operate it.
Power Reactor:	A generator of heat through controlled nuclear fission. Such heat energy, in turn, is used to generate power.
Protective Clothing:	Special clothing worn in a radioactively contaminated area to prevent personal contamination.
Pressurizer:	A pressure vessel containing heaters, used to control the pressure within the primary coolant system.
Primary Coolant System:	The system that confines the coolant that transports heat from the reactor fuel to the steam generators. It includes the reactor vessel, pressurizer, pumps and piping, and the steam generators.
Process Equipment:	The functional equipment items or systems associated directly with the operation of a chemical or mechanical operation.
Quality Assurance:	The systematic actions necessary to provide adequate confidence that a material, component, system, process, or facility performs satisfactorily or as planned.
Rad:	The unit of absorbed dose. The energy imparted to matter by ionizing radiation per unit mass of irradiated material at the place of interest. One rad equals 0.01 Joules/kilogram of absorbing material.

Radiation:	1) The emission and propagation of radiant energy; for instance, the emission and propagation of electromagnetic waves, or of sound and elastic waves. 2) The energy propagated through space or through a material medium; for example, energy in the form of alpha, beta, and gamma emissions from radioactive nuclei.
Radiation Area:	Any area, accessible to personnel, in which there exists radiation at such levels that a major portion of the body could receive in any one hour a dose in excess of 2 millirem, or in any 7 consecutive days a dose in excess of 100 millirem.
Radiation Survey:	An evaluation of the radiation and its hazards incidental to the production, use or existence of radioactive materials. It normally includes a physical survey of the arrangement and use of equipment and measurements of the radiation dose rates under expected conditions of use.
Radioactive Material:	Any material or combination of materials which spontaneously emits ionizing radiation and which has a specific activity in excess of 0.002 microcuries per gram of material. (49 CFR 173.389(e)).
Radioactivity:	The property of certain nuclides of spontaneously emitting particles or gamma radiation or of emitting x radiation. Often shortened to "activity."
Radioactivity, Induced:	Radioactivity produced in a substance after bombardment with neutrons or other particles. The resulting radioactivity is "natural radioactivity" if formed by nuclear reactions occurring in nature, and "artificial radioactivity" if the reactions are caused by man.
Radiological Protection:	Protection against the effects of internal and external human exposure to radiation and to radioactive materials.

**Regulatory
Guides:**

Regulatory Guides are issued to describe and make available to the public methods acceptable to the NRC staff for implementing specific parts of the NRC's regulations, to delineate techniques used by the staff in evaluating specific problems or postulated accidents, or to provide other guidance to applicants for nuclear operations. Guides are not substitutes for regulations and compliance with them is not explicitly required. Methods and solutions different from those set out in the guides are acceptable if they provide a basis for the findings requisite to the issuance or continuance of a permit or license by the NRC.

Rem:

A unit of dose equivalent. The dose equivalent in rems is numerically equal to the absorbed dose in rads multiplied by the quality factor, the distribution factor, and any other necessary modifying factors.

Remote Maintenance:

Maintenance by remote means, i.e., the human is separated by a shielding wall from the item being maintained.

**Repository
(Federal):**

A site owned and operated by the federal government for long-term storage or disposal of radioactive materials.

Restricted Area:

Any area to which access is controlled to protect individuals from exposure to radiation and radioactive materials.

Roentgen:

A unit of exposure to ionizing radiation. It is that amount of gamma or X rays required to produce ions carrying one electrostatic unit of electrical charge (either positive or negative) in one cubic centimeter of dry air under standard conditions. One roentgen equals 2.58×10^{-4} coulomb per kilogram of air. (See also Exposure.)

Safe Storage:

Those actions required to place and maintain a nuclear facility in such a condition that future risk from the facility to public safety is within acceptable bounds and that the facility can be safely stored for as long as desired.

- Custodial Safe Storage: active equipment required.
- Passive Safe Storage: no active equipment required.
- Hardened Safe Storage: a form of temporary entombment.

Security Officer: A guard or watchman whose primary duty is the protection of material and property.

Shield: A body of material used to reduce the passage of particles or radiation. A shield may be designated according to what it is intended to absorb (as a gamma-ray shield or neutron shield), or according to the kind of protection it is intended to give (as a background, biological, or thermal shield).

It may be required for the safety of personnel or to reduce radiation enough to allow use of counting instruments for research or for locating contamination or airborne radioactivity.

Short-Lived Radionuclides: For this study, those radioactive isotopes with half-lives less than about 10 years.

Shutdown: The time during which a site is not in production operation.

Site: The geographic area upon which the facility is located and which is subject to controlled public access by the facility licensee (includes the restricted area as designated in the NRC license).

Solid Radioactive Waste: Material that is essentially solid and dry but may contain sorbed radioactive fluids in sufficiently small amounts as to be immobile.

Solidification: Conversion of radioactive wastes (gases or liquids) to dry, stable solids.

Special Nuclear Material: Plutonium, uranium enriched in the isotope 233 or 235, and any other material as defined in 10 CFR 51 by the NRC.

Spent Fuel: Nuclear fuel that has been removed from the reactor for disposal.

Surface Contamination: The deposition and attachment of radioactive materials to a surface.

Surveillance: Those activities necessary to assure that the site remains in a safe condition (including periodic inspection and monitoring of the site, maintenance of barriers limiting access to radioactive materials left on the site, and prevention of activities on the site which might impair these barriers).

**Technical
Specifications:**

Requirements and limits which encompass nuclear safety but are simplified to facilitate use by plant operation and maintenance personnel. They are prepared in accordance with the requirements of 10 CFR 50.36, and are incorporated by reference into the operating and/or possession-only license issued by the NRC.

Tonne:

A metric ton, or 1000 kg, or 2204.6 lb.

Waste, Radioactive:

Equipment and materials (from nuclear operations) that are radioactive and for which there is no further use. Also called radwaste.