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Technology, Safety and Costs of Decommissioning Reference Nuclear Research and Test Reactors

Main Report

Prepared by G. J. Konzek, J. D. Ludwick, W. E. Kennedy, Jr., R. I. Smith

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(a) Associated with McFarland Wrecking Corporation, Seattle, Washington.

FOREWORD
BY
NUCLEAR REGULATORY COMMISSION STAFF

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

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

The first report in this series covers a fuel reprocessing plant;[2] the second addresses a pressurized water reactor;[3] and the third deals with a small mixed oxide fuel fabrication plant.[4] The fourth report, an addendum to the pressurized water reactor report,[5] examines the relationship between reactor size and decommissioning cost, the cost of entombment, and the sensitivity of cost to radiation levels, contractual arrangements, and disposal site charges. The fifth report in this series deals with a low-level waste burial ground;[6] the sixth covers a large boiling water reactor power station;[7] and the seventh examines a uranium fuel fabrication plant.[8] The eighth report covers non-fuel-cycle nuclear facilities.[9] The ninth report, an addendum to the low-level waste burial ground report,[10] supplements the description of environmental radiological surveillance programs used in the parent document. The tenth report deals with a uranium hexafluoride conversion plant.[11] The eleventh report addresses the decommissioning of nuclear reactors at multiple-reactor power stations.[12] This report, twelfth in the series, examines the decommissioning of reference nuclear research and test reactors.

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

FY 1982 • LWR Post-Accidents

FY 1982 • Independent Spent Fuel Storage Installations

FY 1983 • Fuel Cycle Post-Accidents

The second series of studies covers supporting information on the decommissioning of nuclear facilities. Four reports have been issued in the second series. The first consists of an annotated bibliography on the decommissioning of nuclear facilities.[13] The second is a review and analysis of current decommissioning regulations.[14] The third covers the facilitation of the decommissioning of light water reactors,[15] identifying modifications or design changes to facilities, equipment, and procedures that will improve safety and/or reduce costs. The fourth report covers the establishment of an information base concerning monitoring for compliance with decommissioning survey criteria.[16] A fifth report on this same theme, entitled Technology and Cost of Termination Surveys Associated with Decommissioning of Nuclear Facilities, is intended for FY 1982.

The information provided in this report on nuclear research and test reactors, including any comments, will be included in the record for consideration by the Commission in establishing criteria and new standards for decommissioning. Comments on this report should be mailed to:

Chief
Chemical Engineering Branch
Division of Engineering Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

REFERENCES

1. Plan for Reevaluation of NRC Policy on Decommissioning of Nuclear Facilities. NUREG-0436, Rev. 1, Office of Standards Development, U.S. Nuclear Regulatory Commission, December 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 Pressurized Water Reactor Power Station. NUREG/CR-0130 Addendum, Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, August 1979.

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

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

8. Technology, Safety and Costs of Decommissioning a Reference Uranium Fuel Fabrication Plant. NUREG/CR-1266, Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, October 1980.

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

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

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

12. Technology, Safety and Costs of Decommissioning Nuclear Reactors at Multiple-Reactor Stations. NUREG/CR-1755, Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, January 1982.

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

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

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

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

ABSTRACT

Safety and cost information is developed for the conceptual decommissioning of two representative licensed nuclear research and test (R&T) reactors. Three decommissioning alternatives are studied to obtain comparisons between costs (in 1981 dollars), occupational radiation doses, potential radiation dose to the public, and other safety impacts. The alternatives considered are: DECON (immediate decontamination), SAFSTOR (safe storage followed by deferred decontamination), and ENTOMB (entombment).

DECON for the reference research reactor is estimated to cost $0.85 million, to require about 1 year for planning and preparation prior to final reactor shutdown, to require about 0.7 years of active decommissioning following reactor shutdown, and to result in radiation doses to decommissioning workers of about 18 man-rem.

SAFSTOR for the reference research reactor with decontamination after 10, 30, or 100 years is estimated to cost $1.64, $2.24, or $4.5 million, respectively. Safe storage is estimated to cost $33,000 per year and would continue until the facility is decontaminated. It is estimated to require about 1 year for planning and preparation prior to final reactor shutdown, to require about 0.5 years to place the facility in safe storage, and to result in accumulated radiation doses to decommissioning workers of about 14 man-rem. Deferred decontamination is estimated to require a time span equivalent to DECON and to result in radiation doses to decommissioning workers of 1.5, 0.11, or <0.01 man-rem after safe storage periods of 10, 30, or 100 years, respectively.

ENTOMB for the reference research reactor after removing the activated reactor vessel internals is estimated to cost $0.56 million, to require about 1 year for planning and preparation prior to final reactor shutdown, to require about 0.5 years of active decommissioning following reactor shutdown, and to result in radiation doses to decommissioning workers of about 17 man-rem.

The costs of continuing care during entombment of the reference research reactor are estimated to be $6,100 per year. These costs would continue until either the radioactivity can be shown to have decayed to unrestricted release levels, or until the facility is dismantled and decontaminated. The costs of dismantling the entombment structure are not analyzed.

DECON for the reference test reactor is estimated to cost $15.6 million, to require about 2 years for planning and preparation prior to final reactor shutdown, to require about 2.1 years of active decommissioning following reactor shutdown, and to result in radiation doses to decommissioning workers of about 322 man-rem.

SAFSTOR for the reference test reactor with decontamination after 10, 30, or 100 years is estimated to cost $17.6, $20.0, or $27.2 million, respectively. Safe storage is estimated to cost $120,000 per year and would continue until the facility is decontaminated. It is estimated to require about 1.5 years for planning and preparation prior to final reactor shutdown, to require about 0.6 years to place the facility in safe storage, and to result in accumulated radiation doses to decommissioning workers of about 118 man-rem. Deferred decontamination is estimated to require a time span equivalent to DECON and to result in radiation doses to decommissioning workers of 86, 6, or <1 man-rem after safe storage periods of 10, 30, or 100 years, respectively.

ENTOMB for the reference test reactor after removing the activated reactor vessel internals is estimated to cost $14.6 million, to require about 2 years for planning and preparation prior to final reactor shutdown, to require about 2.1 years of active decommissioning following reactor shutdown, and to result in radiation doses to decommissioning workers of about 425 man-rem.

The costs of continuing care during entombment of the reference test reactor are estimated to be between $13,000 and $41,000 per year, depending on the security program (if needed) and the requirements of the environmental monitoring program imposed by the amended nuclear license. These costs would continue until either the radioactivity can be shown to have decayed to unrestricted release levels, or until the facility is dismantled and decontaminated. The costs of dismantling the entombment structure are not analyzed.

For both of the reference R&T reactors studied, the safety impacts of the decommissioning operations on the public are found to be small, with the principal impact on the public being the radiation dose resulting from the transport of radioactive materials to a disposal site.

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1.0 INTRODUCTION

This report contains the results of a study sponsored by the Nuclear Regulatory Commission (NRC) to conceptually decommission selected NRC-licensed research and test (R&T) reactors. The primary purpose of this study is to provide information on the available technology, the safety considerations, and the probable costs for the decommissioning of R&T reactors at the end of their operating lifetimes. This information is intended for use as background data and bases in the modification of existing regulations and in the development of new regulations pertaining to decommissioning. It is also intended for use by R&T reactor owners and operators in planning for the decommissioning of their nuclear reactor facilities.

There are 84 non-power R&T reactors in the U.S. that are licensed by the NRC. Of these, 76 are research reactors, 67 of which are currently operational. Two test reactors are operational and six test reactors have been placed in safe storage with an amended nuclear license. The level of activity of the operational facilities ranges from occasional use, to intermittent use, to steady and scheduled use.

Operating licenses for R&T reactors are granted under the provisions of 10 CFR 50.[a] R&T reactors are issued class 104 licenses, licenses for "medical therapy and research and development facilities," described in 10 CFR 50.21(c).[b] A research reactor is defined in 10 CFR 170.3(h) as a nuclear reactor licensed for operation at a thermal power level of 10 megawatts or less, and which is not a testing facility. A testing facility (i.e., a test reactor) is defined in 10 CFR 50.2(r) as a nuclear reactor licensed for operation at: 1) a thermal power level in excess of 10 megawatts, or 2) a thermal power level in excess of 1 megawatt if the reactor is to contain: a circulating loop through the core in which the applicant proposes to conduct fuel experiments; or a liquid fuel loading; or an experimental facility in the core in excess of 16 square inches in cross-section.

(a) Acronym for U.S. Code of Federal Regulations, Title 10, Part 50 (typical).
(b) Acronym for Section 50.21(c) of 10 CFR Part 50, subsection(c) (typical).

Because of the diversity in types and sizes of R&T reactor facilities and in the operational schedules and lifetimes associated with them, the level of effort required to decommission them varies greatly. Necessary actions can range from simple, relatively inexpensive decommissioning activities and administrative procedures to extensive decontamination and disposal activities costing millions of dollars.

This study focuses on one research facility and on one test facility, each representing a significant decommissioning task. It is not practical to include in one study examples of the decommissioning of all classes of R&T reactor facilities. However, by examining selected facilities and some components and operations common to many facilities, this study provides data that will assist the reader in estimating the requirements and costs of decommissioning other facilities not specifically considered.

The Oregon State University TRIGA[a] reactor (OSTR), at Corvallis, Oregon, is the reference research reactor for this study. OSTR is a 1000-kWt, above-ground, open-pool nuclear training and research facility that utilizes a TRIGA-type core and control system. The structures, systems, and components are typical of TRIGA research reactor facilities, which make up 37% of licensed research reactors.

The National Aeronautics and Space Administrations's (NASA) Plum Brook Reactor Facility (PBRF), at Sandusky, Ohio, is the reference test reactor facility for this study. A test reactor and a research reactor are colocated at the PBRF site and are an integral part of the PBRF; both reactors are conceptually decommissioned for purposes of this study.

The test reactor, the Plum Brook Reactor (PBR), is a 60-MWt materials test reactor, light water moderated and cooled, used in testing materials for space flight applications. The research reactor, the Plum Brook Mock-Up Reactor (MUR), is a low-power (100-kWt) swimming pool-type research reactor, used as an experimental tool to assist in the operation of the PBR. Both reactors at the PBRF have been shut down since January 1973. However, in this study, both reactors are conceptually decommissioned as if they had just recently been shut down.

(a) TRIGA trademark registered in U.S. Patent Office.

Three basic approaches to decommissioning are considered in this study: 1) DECON, immediate decontamination leading to release of the facility for unrestricted use; 2) SAFSTOR, safe storage plus deferred decontamination leading to release of the facility for unrestricted use; and 3) ENTOMB, entombment plus decay leading to release of the facility for unrestricted use.

DECON is the most likely decommissioning alternative for the R&T reactor facilities considered in this study because it results in release of the facilities for unrestricted use shortly after cessation of facility operation. DECON of a facility requires that contaminated components either be: 1) decontaminated to levels permitting unrestricted use, or 2) packaged and shipped to an authorized radioactive waste disposal site.

As mentioned earlier, six test reactors have already been placed in a safe storage condition. Where the contained radioactivity is calculated to decay to levels acceptable for unrestricted release within a period of a few decades, SAFSTOR may be an acceptable alternative.

Because of the urban or suburban location of most R&T reactor facilities, there is an incentive to convert these facilities to unrestricted use status in a fairly short time following the termination of nuclear activities. For research reactors, this would probably preclude ENTOMB as a viable decommissioning alternative. It is worthwhile to note that to date no NRC-licensed R&T reactors have been entombed.

The study approach for both R&T reactor facilities is the same. The reference facility is analyzed using data for specific components (the unit-component approach) to provide information about the safety and costs of decommissioning the entire facility. Descriptions of the decommissioning of representative components (e.g., reactor vessel and internals, beam ports, fuel storage areas, exhaust system ductwork) for each reactor type provide data common to that type of reactor.

Sets of work plans are developed for the conceptual decommissioning of the reference R&T reactors via the decommissioning alternatives of DECON, one method of SAFSTOR, and ENTOMB. From these work plans, estimates are developed for the manpower requirements, the major resource and equipment needs, the volumes of

contaminated material packaged for disposal, the costs of accomplishing the work, and the exposure of the decommissioning workers and the public to radiation as a result of the decommissioning efforts. Because widely different work plans and decommissioning techniques can be utilized to achieve the desired decommissioned condition, the results of this study are dependent upon the detailed choices made. Decommissioning techniques are chosen that represent current technology and that conform to the principle of keeping public and occupational radiation doses as low as reasonably achievable (ALARA). The choices of plans and techniques in this study are believed to be realistic and representative of the operations that would be required to safely decommission the reference R&T reactor facilities at a reasonable cost.

The work plans and the scenarios for airborne and/or liquid releases of radioactive materials are used to evaluate the impacts of decommissioning operations on the workers and on the public. Estimates are made of radiation exposure, lost-time injuries, and fatalities for each decommissioning approach studied.

A suggested dose-based methodology is demonstrated for determining the level of radioactive contamination that could remain on an R&T reactor site or in an R&T reactor facility and still allow release of the property for unrestricted use. This methodology utilizes the calculated maximum annual dose to the maximum-exposed individual as the basis for determining these levels. The relationship between dose and contamination level is complex, involving the spectrum of residual radionuclides and their exposure pathways to the maximum-exposed individual.

The operating techniques, safety impacts, and estimated costs developed in this study are sensitive to the specifics of the reference R&T reactor facilities, including assumptions and estimates employed to achieve stated results. For each reference R&T reactor facility, such specifics include the mixtures and the levels of residual radioactive contamination at final plant shutdown, as well as the plant size, design, location, and operating history. Considerable effort was made to obtain factual data for both of the reference

plants; however, in those areas where data were missing or were inadequate, engineering judgement was exercised. These judgements are manifested in the form of assumptions and estimates.

Where estimates are used in this study, they are identified as such and are based on comparable experience and/or engineering judgement. Assumptions and estimates used in this study should be examined carefully before attempting to apply the results of this study to the reference plants as they currently exist or to different nuclear R&T reactors.

The diversity of designs among licensed R&T reactors precludes any reasonable scaling analysis based solely on plant authorized power level. Each particular class of reactor tends to be rather unique and scaling of costs across classes, based on plant authorized power level, cannot be accomplished in any meaningful way. Therefore, only increased radiation levels, different contractual arrangements, and increased waste disposal costs are readily amenable to examination for this study on R&T reactors and are examined briefly to provide guidance in the application of these results to other R&T reactor facilities.

The study results are presented in two volumes. Volume 1 (Main Report) contains the results in summary form. Volume 2 (Appendices) contains the detailed data that support the results given in Volume 1, including unit-component data. The supporting data are presented in a manner that facilitates their use for examining decommissioning actions other than those included in this study.

2.0 SUMMARY

The results of this study sponsored by the Nuclear Regulatory Commission (NRC) to conceptually decommission representative licensed nuclear research and test (R&T) reactors are summarized in this section. The purpose of the study is to provide information on the available technology, the safety considerations, and the probable costs for decommissioning licensed R&T reactors at the end of their useful operating lifetimes.

Decommissioning of a nuclear facility means to safely remove the property from radioactive service and to dispose of residual radioactive materials. The level of any residual radioactivity remaining on the property after decommissioning must be low enough to allow unrestricted use of the property. Three approaches to decommissioning are considered in this study: DECON, SAFSTOR, and ENTOMB. The terms DECON, SAFSTOR, and ENTOMB are relatively new in use. In the past, the nomenclature for describing these alternatives has been inconsistent, with different documents using different terminology when referring to the same decommissioning alternative, thus causing some confusion. Definitions of the major decommissioning alternatives and their pseudoacronyms used in this study are given below:

- DECON means to immediately remove all radioactive material down to residual levels which permit release of the property for unrestricted access.
- SAFSTOR means to fix and maintain the property so that risk to safety is acceptable for a period of storage followed by decontamination and/or decay of radioactivity to levels which permit release of the facility for unrestricted access.
- ENTOMB means to encase and maintain the property in a strong and structurally long-lived material (e.g., concrete) to assure retention until all radioactivity decays to levels which permit release of the property for unrestricted access.[a]

(a) For this study, it is assumed that: 1) the reference R&T reactor's vessel internals are removed and disposed of prior to decommissioning via the ENTOMB alternative, and 2) the radioactivity contained within the entombment structure will decay sufficiently during a 100-year entombment period to permit unrestricted release of the property at the end of that time.

The principal results of the study are given, in brief, in the following paragraphs, with more complete summaries presented in subsequent sections.

Reference Research Reactor - DECON for the reference research reactor is estimated to cost $0.85 million (in 1981 dollars), to require about 1 year for planning and preparation prior to final reactor shutdown, to require about 0.7 years of active decommissioning following reactor shutdown, and to result in radiation doses to decommissioning workers of about 18 man-rem.

SAFSTOR for the reference research reactor with decontamination after 10, 30, or 100 years is estimated to cost $1.64, $2.24, or $4.5 million, respectively. Safe storage is estimated to cost $33,000 per year and would continue until the facility is decontaminated. It is estimated to require about 1 year for planning and preparation prior to final reactor shutdown, to require about 0.5 years to place the facility in safe storage, and to result in accumulated radiation doses to decommissioning workers of about 13 man-rem. Deferred decontamination is estimated to require a time span equivalent to DECON and to result in radiation doses to decommissioning workers of 1.5, 0.11, or <0.01 man-rem after safe storage periods of 10, 30, or 100 years, respectively.

ENTOMB for the reference research reactor, after removing the activated reactor vessel internals, is estimated to cost $0.56 million (in 1981 dollars), to require about 1 year for planning and preparation prior to final reactor shutdown, to require about 0.5 years of active decommissioning following reactor shutdown, and to result in radiation doses to decommissioning workers of about 17 man-rem. Because of the urban environment of the majority of licensed research reactors (including the reference research reactor conceptually decommissioned in this study), ENTOMB is considered to be the least desirable decommissioning alternative. To date, the records indicate that no licensed research reactor has ever been entombed. Entombment of the reference research reactor is only included in this study for completeness.

Costs of continuing care during ENTOMB for the reference research reactor are estimated to be $6,100 per year. These costs would continue until either

the radioactivity can be shown to have decayed to unrestricted release levels, or until the facility is dismantled and decontaminated should an earlier release of the property become necessary.

No detailed estimates of cost and radiation dose are made for dismantlement and decontamination of the entombed reference research reactor facility since the intention assumed in this study is to leave the entombment structure intact until the radioactivity has decayed to release levels.

Reference Test Reactor - DECON for the reference test reactor is estimated to cost $15.6 million (in 1981 dollars), to require about 2 years for planning and preparation prior to final reactor shutdown, to require about 2.1 years of active decommissioning following reactor shutdown, and to result in radiation doses to decommissioning workers of about 322 man-rem.

SAFSTOR for the reference test reactor with decontamination after 10, 30, or 100 years is estimated to cost $17.6, $20.0, or $27.2 million, respectively. Safe storage is estimated to cost $120,000 per year and would continue until the facility is decontaminated. It is estimated to require about 1.5 years for planning and preparation prior to final reactor shutdown, to require about 0.6 years to place the facility in safe storage, and to result in accumulated radiation doses to decommissioning workers of about 112 man-rem. Deferred decontamination is estimated to require a time span equivalent to DECON and to result in radiation doses to decommissioning workers of 86, 6, or <1 man-rem after safe storage periods of 10, 30, or 100 years, respectively.

ENTOMB for the reference test reactor, after removing the activated reactor vessel internals, is estimated to cost $14.6 million (in 1981 dollars) not including any final decontamination, if required; to require about 2 years for planning and preparation prior to final reactor shutdown; to require about 2.1 years of active decommissioning following reactor shutdown; and to result in radiation doses to decommissioning workers of about 425 man-rem.

The costs of continuing care during ENTOMB for the reference test reactor are estimated to range from $13,000 to $41,000 per year, depending on the security program (if needed) and the requirements of the environmental

monitoring program imposed by the amended nuclear license. These costs would continue until either the radioactivity can be shown to have decayed to unrestricted release levels, or until the facility is dismantled and decontaminated, should an earlier release of the property become necessary.

No detailed estimates of cost and radiation dose are made for the dismantlement and decontamination of the entombed reference test reactor facility since the intention assumed in this study is to leave the entombment structure intact until the radioactivity has decayed to release levels.

2.1 STUDY BASES

The major study bases are:

- The study must yield realistic and up-to-date results.
- The study is conducted within the framework of the existing regulations and regulatory guidance.
- The study evaluates existing nuclear R&T reactor facilities.
- The study is based on operating lifetimes estimated to be representative of the two types of reactors selected.
- The estimated radiation dose rates throughout the reference R&T reactor facilities are based on measured data from the reference reactors.
- Current and proven decommissioning technology and techniques are used.
- The financing for decommissioning activities is available as necessary to complete the planned activities without fiscal constraint.
- A nuclear waste disposal facility is in operation and has sufficient capacity.
- For decommissioning activities immediately following plant shutdown, the staff is drawn largely from operating and/or "contract services" personnel familiar with the facility and its systems.
- All material whose radioactivity exceeds unrestricted release levels is removed from the site before the site is released for unrestricted use.

- The performance of decommissioning is assumed to be relatively troublefree, and decommissioning options are evaluated assuming efficient performance of the work.
- The study conforms to ALARA occupational exposure philosophies.
- The costs are in 1981 dollars.

The results obtained in this study are specific to these major bases and to the specific assumptions that are derived from them and stated in the appropriate place in the study. Applying these results to situations where the conditions are different from those in this study could produce erroneous conclusions. In addition, if one wishes to make decommissioning cost estimates for a specific licensed research or test reactor facility based on estimates given for the reference R&T reactor facilities used in this study, it is essential to compare the ancillary facilities carefully, since the number and type of these facilities can strongly influence the total decommissioning cost.

The sensitivity of the study results to increased radiation exposures, increased nuclear waste disposal charges, and different contractural arrangements is examined briefly to provide guidance in the application of these results to other R&T reactor facilities.

2.2 DECOMMISSIONING EXPERIENCE

A review of the documented cases of licensed nuclear R&T reactor decommissionings shows that while the decommissioned R&T facilities were generally small and had operated for relatively short periods of time, the problems encountered tended to be common to all decommissioning undertakings. The review also shows that a wealth of experience exists within the nuclear industry regarding methods and equipment for accomplishing decommissioning, and that there are no major technical impediments to the successful decommissioning of R&T reactors. However, care should be taken in reaching conclusions based on these experiences, since, in many instances, they reflect essentially first-time efforts for a

specific type of research or test reactor and encompass variations in many important factors, such as extent of previous use, power levels, and site characteristics.

2.3 REGULATORY GUIDANCE FOR DECOMMISSIONING

In general, regulations are in place to cover decommissioning of the reference R&T reactors. In some cases (i.e., security, safeguards, quality assurance), the existing regulations do not speak specifically to decommissioning, but they can readily be interpreted as being applicable.

The following suggestions are made for improving present regulations:

- Centralize or provide an index for all regulations that pertain to decommissioning.
- Modify the existing regulations that apply to decommissioning to include reference to such centralized or indexed application.
- Clearly define the financial qualifications and responsibilities of the licensee for decommissioning.
- Specify which of the existing regulations governing allowable public radiation dose take precedence during the decommissioning of all licensed light water reactors.
- More clearly define "high-level waste" (with respect to the highly radioactive reactor vessel components) and the associated disposal requirements.
- Provide a common, identifiable reference for acceptable residual radioactive contamination levels for unrestricted release of materials, structures, and sites (currently under active consideration by the NRC).
- Specify the requirements for license renewal or extension, should such be necessary at the time of decommissioning.

2.4 FINANCING DECOMMISSIONING

In general, NRC regulations require the applicant for an operating license for a research or test reactor to demonstrate the financial resources to cover

the estimated costs of both operating and permanently shutting down the facility. However, the importance of financial assurance for decommissioning was recently recognized by the Congress of the United States in the Uranium Mill Tailings Control Act of 1978, which amends the Atomic Energy Act of 1954, providing explicit authority to the NRC to require an adequate bond, surety, or other financial arrangement by uranium mill licensees to ensure site cleanup and reclamation prior to license termination. Furthermore, the NRC is considering financial requirements within the broader context of an overall re-evalulation of its policies on decommissioning nuclear facilities.

Three principal financing alternatives for decommissioning nuclear R&T reactors are reviewed in this study:

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

A fourth alternative, payment of decommissioning costs from other revenue when the funds are required, is discussed in less detail because it provides less assurance that funds will be available.

The federal government currently has very little direct involvement in decommissioning financing considerations except where the licensed facility is government owned as in the case of the reference test reactor considered in this study. It is recognized that effective planning and preparation is vital to successful completion of decommissioning activities at nuclear facilities. The safety and cost effectiveness of the project could be compromised if planning and preparation are inadequate. Ideally, planning and preparation are scheduled to be completed by the time the reactor is shut down; however, research and test reactor programs have frequently been terminated with little advance notice so that planning and preparation for decommissioning the facilities could not be completed by the time of reactor shutdown. For licensed, government-owned reactors, rapid termination of the test program may virtually rule out DECON as a viable decommissioning alternative since decommissioning funds must be obtained by the operating agency by preparing a budget request and securing approval of the request via the normal channels used to obtain

operating funds. Budget requests need to be prepared well in advance of the planned date of decommissioning to allow adequate time for the approval process. Because a budget request is often initiated 2 or 3 years before the actual expenditure of the funds, it would be necessary to make adequate provision for cost escalation and inflation.

2.5 REFERENCE FACILITIES AND SITES

The reference R&T reactors and their respective reference sites used in this study are described in the following subsections.

Reference Research Reactor and Site

The reactor used as the reference research reactor in this study is the Oregon State University TRIGA Reactor (OSTR), at Corvallis, Oregon. OSTR is a 1000-kWt, above-ground, open-pool nuclear training and research facility that utilizes a TRIGA-type core and control system. The structures, systems, and components are typical of TRIGA research reactor facilities. The reference site used in these analyses is located on the campus of a State University. The city in which the university is located is at the base of the foothills of the Pacific Coast Mountain Range, about 90 km from the coast. The site occupies about 15 hectares in a 122-m square shape. Sufficient descriptive information is presented for both the facility and the site to permit the development of the detailed work plans, the cost estimates, and the safety assessments that are the results of this study.

Reference Test Reactor and Site

The National Aeronautics and Space Administration's (NASA) Plum Brook Reactor Facility (PBRF), at Sandusky, Ohio, is the reference test reactor facility for this study. A test reactor and a research reactor are colocated at the PBRF site and are an integral part of the PBRF; both reactors are conceptually decommissioned for purposes of this study.

The test reactor, the Plum Brook Reactor (PBR), is a 60-MWt materials test reactor, light water moderated and cooled, used in testing materials for space flight applications. The research reactor, the Plum Brook Mock-Up Reactor (MUR),

is a low-power (100-kWt) swimming pool-type research reactor, used as an experimental tool to assist in the operation of the PBR. Both reactors at the PBRF have been shut down since January 1973. Both reactors, however, are conceptually decommissioned in this study as if they had just recently been shut down.

The reference site used in these analyses is typical of a midwestern or middle southeastern river site. This site has been developed for use in a series of studies devoted to the decommissioning of nuclear fuel cycle facilities that is being performed for the NRC by Pacific Northwest Laboratory. Sufficient descriptive information is presented for both the facility and the site to permit the development of the detailed work plans, the costs estimates, and the safety assessments that are the results of this study.

2.6 RADIONUCLIDE INVENTORIES

The levels of radioactivity and dose rates from activated reactor components in the reference R&T reactors, from contamination deposited throughout the plants and from soil surfaces at the reference sites, are either calculated and/or derived from existing data.

Reference Research Reactor Radionuclide Inventory

Radioactive material quantities and resultant radiation doses due to the operation of the research reactor are calculated from the operational parameters expected during the reactor's lifetime. Contamination levels deposited in piping and at locations utilized for radioactive material handling were derived from the available radiation exposure data at the reference reactor and estimates using information from similar facilities elsewhere. After reactor shutdown and for some time to come, ^{60}Co and, to a smaller extent, ^{65}Zn are the principal contributors to radiation dose from the reactor core and vessel. Elsewhere in the facility, ^{60}Co is presumed to produce the major dose from radioactive contamination. Most (>95%) of the radionuclide inventory at the facility is found in the reactor pool. Excluding fuel, this amounts to about 1,500 curies of neutron activation products at time of shutdown. The calculated radiation dose rates of ^{60}Co from reactor core components at the surface of the reactor vessel (1 m from core center) is 200 R/hr. Within the core

itself, dose rates are highly dependent upon geometry factors since a few widely scattered stainless-steel parts contribute to rather large, localized dose rates from ^{60}Co. Dose rates from radioactive contamination away from the reactor proper on equipment and the like do not exceed 2 mR/hr. Within 30 to 50 years, decay will reduce their radioactive content to negligible levels. Although other, long-lived isotopes eventually replace ^{60}Co as the major contributor (∿100 years or more after reactor shutdown), their total quantity becomes insignificant 100 years after reactor shutdown.

Annual atmospheric releases from the reference research reactor within the site boundary and in close proximity outside the site boundary are routinely measured. Based upon the data to date at the reference site, no radionuclide soil contamination has accumulated. It is anticipated that no accumulations greater than levels acceptable for release for unrestricted use will occur during the postulated 40-year normal operating life of the reference plant.

Reference Test Reactor Radionuclide Inventory

The radionuclides that are the princpal contributors to occupational radiation exposure are: immediately after reactor shutdown and during the next 100 years, ^{60}Co; and after 100 years, ^{94}Nb. The total radioactivity present in the activated test reactor structural materials at the time of reactor shutdown is calculated to be about 369,000 curies, including approximately 200,000 curies of tritium in the beryllium reflector segments. The calculated radiation dose rates of ^{60}Co from the activated test reactor components at reactor shutdown range from a maximum of 332,000 R/hr for miscellaneous bolts in the test reactor core assembly to a few mR/hr at the reactor vessel outer surface. The total inventory of radioactivity in the MUR is estimated to be quite small (<2 Ci) and the estimated maximum dose rates are also quite small (<700 mR/hr). Dose rates at locations throughout the test reactor facility range from a few R/hr to a few mR/hr.

The deposition of airborne radionuclides during 12 years of normal test reactor operation is considered to be insignificant because of the relatively small plant size, the absence of any fuel failures, and the extensive use of gaseous radwaste treatment systems. Naturally occurring radionuclides and

those resulting from nuclear weapons-testing fallout are present on the site, but deposition of these latter radionuclides is not quantified in this study. However, low levels of radioactive contamination are anticipated to be present in three areas on the reference site as a result of deposition of waterborne radionuclides. The soil and concrete piping contamination levels in these three areas and associated mixtures of radionuclides are based on a recent (1981) soil surface sample taken from a point of highest concentration. It should be recognized that the data presented in this subsection and in Appendix E of Volume 2 are calculated estimates specific to the reference test reactor (including the MUR) defined for this study. Use of these data in an analysis of any other test reactor should be made with caution and with careful attention to any differences in structural materials, neutron flux levels, and reactor operating histories.

2.7 EXAMPLE ACCEPTABLE CONTAMINATION LEVELS FOR UNRESTRICTED USE OF THE REFERENCE RESEARCH AND TEST REACTOR PROPERTIES

A suggested methodology for determining acceptable residual radioactive contamination levels for unrestricted use of the reference R&T reactor facilities and/or sites is presented in Section 9 of this report. Example acceptable contamination levels are calculated based on the concept that no member of the public will be allowed to receive an annual dose in excess of a limit yet to be established by U.S. regulatory agencies. For the purposes of this study, the example acceptable contamination levels calculated in Section 9 are based on a maximum annual dose to an individual of 10 mrem per year. Example acceptable contamination levels are calculated for the R&T reactor facilities and on the test reactor site. The effect of radioactive decay on these acceptable contamination levels is shown by calculating them at shutdown and at 10, 30, 50, and 100 years of radioactive decay.

For the facilities, the acceptable contamination levels of radioactivity are presented in units of surface activity ($\mu Ci/m^2$). For the test reactor site, soil contamination values are presented in units of radioactivity per gram of soil by assuming mixing to depths of 10 mm and 150 mm. The site

contamination at the test reactor is assumed to be caused by liquids leaked into the Emergency Retention Basin, site ditches, and the soil beneath the two Cold Retention Basins.

A summary of the calculated example radioactive contamination levels that result in an annual dose of 10 mrem per year to the limiting organ of the maximum-exposed individual is given in Table 2.7-1.

TABLE 2.7-1. Summary of Calculated Example Acceptable Residual Radioactive Contamination Levels for the Reference Research and Test Reactors

	Time Exposure Begins (Years After Shutdown)[a]	Limiting Organ	Acceptable Residual Contamination Levels Corresponding to an Annual Dose of 10 mrem/yr: Surface Contamination ($\mu Ci/m^2$)	Soil Contamination: Mixed to 10 mm (pCi/g)	Soil Contamination: Mixed to 0.15 m (pCi/g)
Research Reactor Facility[b]	0	Total Body	0.066	--	--
	100	Lung	0.074	--	--
Research Reactor Site[c]	No reactor-produced site contamination is anticipated (see Section E.1.2.3 of Appendix E).				
Test Reactor Facility[b]	0	Bone	0.18	--	--
	100	Bone	0.22	--	--
Test Reactor Site	0	Bone	0.21	14	0.93
	100	Bone	0.11	7.4	0.49

(a) The time that continuous exposure begins.
(b) In the facility, a determination of acceptable surface contamination levels, based on the mixture of radionuclides, is assumed to be used to help determine the necessary decommissioning procedures.
(c) In any case, to do the final site certification survey before the license termination is approved, a confirmation of site-specific residual radioactive contamination levels would be required based on current acceptable measurement techniques, including the necessary documentation verifying the survey results.

2.8 RADIATION EXPOSURE ESTIMATES

The details of the estimated occupational radiation doses resulting from decommissioning unit components at each of the reference R&T reactors are given in Appendices I, J, and K of Volume 2 for DECON, SAFSTOR, and ENTOMB, respectively. Summaries of estimated total accumulated occupational radiation doses for decommissioning the reference R&T reactors via the DECON, SAFSTOR, and ENTOMB alternatives are presented in subsequent subsections.

Radiation Exposure Estimates for Decommissioning the Reference Research Reactor

Estimates of accumulated occupational radiation dose are 18.34 man-rem for DECON, 16.64 man-rem for ENTOMB, and 13.08 man-rem for placing the facility in safe storage, with an accumulated radiation dose of less than 1 man-rem for surveillance and maintenance during the subsequent 100 years of continuing care. Radiation dose associated with deferred decontamination depends on when the decontamination takes place. Relatively little additional reduction in accumulated occupational radiation dose is estimated to result from deferring the decontamination sequence beyond 30 years, and virtually no additional reduction results from deferment beyond 50 years.

The individual estimates of occupational radiation dose for the various decommissioning alternatives are summarized in Table 2.8-1.

TABLE 2.8-1. Summary of Estimated External Occupational Radiation Doses for Decommissioning the Reference Research Reactor

	Estimated Radiation Dose to Decommissioning Personnel (man-rem)[a]				
		SAFSTOR			
Years After Shutdown	DECON	Preparations	Safe Storage	Deferred Decontamination	ENTOMB
0	18.34	13.08	--[b]		16.64
10	--	--	0.53	1.48	--[c]
30	--	--	0.78	0.11	--
50	--	--	0.80	0.01	--
100	--	--	0.82	<0.01	--

(a) Total dose for safe storage with decontamination deferred for 30 years is the sum of (13.08 + 0.78 + 0.11) man-rem.
(b) Dash means data are not applicable (or calculated).
(c) No post-entombment actions are postulated.

Additional radiation dose is received by the transportation workers and by the general public as a result of transporting the spent fuel and the radioactive materials to disposal sites. These radiation doses are summarized in Table 2.8-2.

TABLE 2.8-2. Radiation Dose from Truck Transport of Radioactive Materials from Decommissioning the Reference Research Reactor

	Radiation Doses from Truck Transport (man-rem)[a]		
	DECON[b]	Preparations for Safe Storage	ENTOMB
Occupational:	2.8×10^{-1}	0	7.0×10^{-2}
Public:	2.7×10^{-2}	0	6.8×10^{-3}

(a) All values are rounded to two significant figures.
(b) For deferred decontamination, these values are reduced in proportion to the decay of ^{60}Co activity during the safe storage period.

Radiation Exposure Estimates for Decommissioning the Reference Test Reactor

Estimates of accumulated occupational radiation dose are 322 man-rem for DECON, 425 man-rem for ENTOMB, and 112 man-rem for placing the facility in safe storage. Based on information relating to the past 8 years of safe storage of the PBRF, and assuming similar decommissioning and continuing care considerations are applied for the reference test reactor used in this study, external radiation exposures for surveillance and maintenance personnel at the reference test reactor during safe storage are reasonably assumed to be at the threshhold levels of detection for personnel monitoring devices. Radiation dose associated with deferred decontamination depends on when the decontamination takes place. Relatively little additional reduction in accumulated occupational radiation dose is estimated to result from deferring the decontamination sequence beyond 30 years, and virtually no additional reduction results from deferment beyond 50 years.

The individual estimates of occupational radiation dose for the various decommissioning alternatives are summarized in Table 2.8-3.

Additional radiation dose is received by the transportation workers and by the general public as a result of transporting the spent fuel and the radioactive materials to disposal sites. These radiation doses are summarized in Table 2.8-4.

TABLE 2.8-3. Summary of Estimated External Occupational Radiation Doses for Decommissioning the Reference Test Reactor

	Estimated Radiation Dose to Decommissioning Personnel (man-rem)[a]				
		SAFSTOR			
Years After Shutdown	DECON	Preparations	Safe Storage	Deferred Decontamination	ENTOMB
0	322	112	--		425
10	--	--	0[b]	86	--[c]
30	--	--	0	6	--
50	--	--	0	<1	--
100	--	--	0	<1	--

(a) Total dose for safe storage with decontamination deferred for 30 years is the sum of (112 + 0 + 6) man-rem.
(b) Based on the negligible radiation exposures reported for the surveillance, maintenance, and security forces during the past eight years of continuing care of the PBRF (see Section J.2.6.2 of Appendix J for details).
(c) No post-entombment actions are postulated.

TABLE 2.8-4. Radiation Dose from Truck Transport of Radioactive Materials from Decommissioning the Reference Test Reactor

	Radiation Doses from Truck Transport (man-rem)[a]		
	DECON[b]	Preparations for Safe Storage	ENTOMB
Occupational:	2.2×10^1	1.2×10^1	1.9×10^1
Public:	2.2×10^0	1.1×10^{-1}	1.3×10^0

(a) All values are rounded to two significant figures.
(b) For deferred decontamination, these values are reduced in proportion to the decay of ^{60}Co activity during the safe storage period.

2.9 DECOMMISSIONING COSTS

The details of the estimated costs of decommissioning unit components at each of the reference R&T reactors are given in Appendices I, J, and K of Volume 2 for DECON, SAFSTOR, and ENTOMB, respectively. In addition, a methodology is developed in Section 13 of this volume for the estimation of decommissioning costs of major reactor components for the reference test reactor. These

data are used in a comparison of test reactor decommissioning costs resulting from three separate studies. One result of this comparison is that very careful analyses of the ancillary structures at a nuclear test reactor facility are necessary, since the number and type of these structures can strongly influence the total decommissioning cost.

Summaries of estimated total costs of decommissioning the reference R&T reactors via the DECON, SAFSTOR, and ENTOMB alternatives are presented in subsequent subsections. All decommissioning costs for the reference R&T reactors are given in terms of 1981 dollars, with 25% contingencies included.

Decommissioning Costs for the Reference Research Reactor

DECON is estimated to cost $0.846 million. The major contributors to the total cost of DECON are summarized in Table 2.9-1. The cost for shipment and disposal of radioactive materials is about 13% of the total decommissioning cost. About 79% of the total decommissioning cost is due to staff labor. Special tools and equipment, license fees, and energy costs constitute about 3, 2, and 2%, respectively, of the total DECON cost.

Other possible costs, which include shipment of irradiated fuel and demolition of the decontaminated facility, total an additional $0.322 million.

Preparing the reference research reactor for safe storage is estimated to cost $0.493 million. The major contributors to the total cost of preparations for safe storage are summarized in Table 2.9-2. The principal cost item is staff labor, contributing about 85% of the total. Miscellaneous supplies, license fees, and storage of radioactive materials and contaminated wastes contribute about 4, 3.5, and 3%, respectively, to the total cost.

The cost of continuing care during safe storage is estimated to be $33,100 per year.

The cost of SAFSTOR for intervals of 10, 30, 50, and 100 years after final reactor shutdown is estimated in constant 1981 dollars to be $1.64 million, $2.24 million, $2.84 million, and $4.5 million, respectively.

TABLE 2.9-1. Summary of Estimated Costs of DECON for the Reference Research Reactor

Cost Category		Estimated Costs ($)[a,b]	Percent of Total
Disposal of Radioactive Materials			
Neutron-Activated Materials	16 610		
Contaminated Materials	60 060		
Radioactive Wastes	9 620		
Total Disposal Costs		86 290	12.8
Staff Labor		530 570	78.4
Energy		13 790	2.0
Special Tools and Equipment		21 150	3.1
Miscellaneous Supplies		6 210	0.9
Nuclear Insurance		4 620	0.7
License Fees		13 950	2.1
Subtotal		676 580	100.0
Contingency (25%)		169 150	
Total, DECON Costs		845 730	
Other Possible Costs			
Spent Fuel Shipment		60 980	
Facility Demolition & Site Restoration		196 750	
Subtotal		257 730	
Contingency (25%)		64 430	
Total, Other Possible Costs		322 160	

(a) 1981 costs used.
(b) The number of figures shown is for computational accuracy and does not imply precision to the nearest $10.

ENTOMB is estimated to cost $0.56 million for the reference research reactor. The major contributors to the total cost of ENTOMB are summarized in Table 2.9-3.

TABLE 2.9-2. Summary of Estimated Costs of Placing the Reference Research Reactor in Safe Storage

Cost Category	Estimated Costs ($)[a,b]	Percent of Total
Disposal of Radioactive Materials[c]	5 530	1.4
Storage of Radioactive Materials and Contaminated Wastes	11 200	2.8
Staff Labor	335 210	85.1
Energy	8 080	2.1
Special Tools and Equipment	2 340	0.6
Miscellaneous Supplies	15 000	3.8
Nuclear Insurance	2 890	0.7
License Fees	13 950	3.5
Subtotal	394 200	100.0
Contingency (25%)	98 550	
Total, Preparations for Safe Storage	492 750	
Other Possible Costs		
Spent Fuel Shipment	60 980	
Contingency (25%)	15 245	
Total, Other Possible Costs	76 225	

(a) 1981 costs used.
(b) The number of figures shown is for computational accuracy and does not imply precision to the nearest $10.
(c) Only includes dry solid wastes.

The principal cost item of ENTOMB is staff labor, contributing 85% of the total. License fees, energy, and supplies contribute about 3, 2, and 2%, respectively, to the total cost.

TABLE 2.9-3. Summary of Estimated Costs of ENTOMB for the Reference Research Reactor

Cost Category	Estimated Costs ($)[a,b]	Percent of Total
Disposal of Neutron Activated Materials	16 610	3.8
Disposal of Radioactive Wastes[c]	6 800	1.5
Staff Labor	378 890	85.2
Energy	9 290	2.1
Special Tools and Equipment	2 340	0.5
Miscellaneous Supplies	5 210	1.2
Specialty Contractor[d]	8 620	1.9
Nuclear Insurance	2 790	0.7
License Fees	13 950	3.1
Subtotal	444 500	100.0
Contingency (25%)	111 130	
Total, Costs of Entombment[e]	555 630	
Other Possible Costs		
Spent Fuel Shipment	60 980	
Facility Demolition & Site Restoration	20 100[f]	
Subtotal	81 080	
Contingency (25%)	20 270	
Total, Other Possible Costs	101 350	

(a) 1981 costs used.
(b) The number of figures shown is for computational accuracy and does not imply precision to the nearest $10.
(c) Only includes dry solid wastes.
(d) For installation of the entombment structure.
(e) The "total" ENTOMB costs also would include the annual surveillance and maintenance service costs of $6,120 times "x" number of years that these services were provided.
(f) Does not include demolition of the Reactor Building and the reactor structure.

The cost of continuing care for ENTOMB is estimated to be about $6,100 per year. It should be recognized that there is no fixed number of years for nucle research reactor facilities to be entombed; it depends on the facility-specific radionuclides and how long they take to decay to unrestricted use levels. For the purposes of this study, all ENTOMB time periods given are for illustration only.

No detailed cost estimates are developed for dismantlement and decontamination of the entombed research reactor since the intent is to leave the structure intact until the radioactivity has decayed to release levels.

Total cost in constant 1981 dollars for each of the decommissioning alternatives for the reference research reactor is summarized in Table 2.9-4.

TABLE 2.9-4. Estimated Total Costs of Possible Decommissioning Alternatives for the Reference Research Reactor

	Decommissioning Costs ($ millions)(a,b) Number of Years After Reactor Shutdown Decontamination is Deferred				
Decommissioning Alternative	0	10	30	50	100
DECON	0.846	--	--	--	--
SAFSTOR					
Preparations for Safe Storage	0.493	0.493	0.493	0.493	0.493
Continuing Care	--	0.314	0.974	1.634	3.284
Deferred Decontamination	--	0.836	0.775	0.716	0.716
Total Cost, SAFSTOR	--	1.643	2.242	2.843	4.493
ENTOMB					
Entombment	0.556	0.556	0.556	0.556	0.556
Continuing Care	--	0.058	0.181	0.303	0.609
Deferred Decontamination(c)	--	--	--	--	--
Total Cost, ENTOMB		0.614	0.737	0.859	1.165

(a) Values include a 25% contingency.
(b) Values are in constant 1981 dollars.
(c) Since the intention is to leave the structure intact until the radioactivity has decayed to release levels, no cost is assigned.

Decommissioning Costs for the Reference Test Reactor

DECON is estimated to cost $15.6 million. The major contributors to the total cost of DECON are summarized in Table 2.9-5. The cost for shipment and disposal of radioactive materials is about 21% of the total decommissioning cost. About 69% of the total decommissioning cost is due to staff labor. Specialty contractors, special tools and equipment, and supplies constitute about 5, 3, and 2%, respectively, of the total DECON cost. The total costs of decommissioning major components at the reference test reactor are estimated by applying the methodology developed in Section 13. For example, the purpose of the ancillary facility identified as the Hot Laboratory Building (HLB) is to contain the seven hot cells and to support the operations and activities associated with the cells. The estimated total cost of decommissioning the HLB is $2 million, or about 13% of the total DECON cost (see Table 13.3-2 for details). Based on the unit component cost data presented in Appendix I of Volume 2, it is estimated to cost approximately $0.8 M of the $2 M total to decommission the seven hot cells within the HLB, which represents about 5% of the total DECON cost. In a similar manner, the total costs of decommissioning the Mock-Up Reactor (MUR) are estimated to be about $0.4 M, which represents about 2.5% of the total DECON cost. Because the reference test reactor is assumed to be federally owned, nuclear insurance premiums are minimal and licensee fees are not applicable as decommissioning costs. However, where applicable for other nuclear R&T reactor facilities, the schedule of fees for license amendments and other approvals required by the license or NRC regulations is given in 10 CFR 170.

Other possible costs, which include shipment of irradiated fuel and demolition of the decontaminated facility, total an additional $3.12 million.

Preparing the reference test reactor for safe storage is estimated to cost $6.7 million. The major contributors to the cost of preparations for safe storage are summarized in Table 2.9-6. The principal cost item is staff labor, contributing about 58% of the total. The cost for shipment and disposal of radioactive materials is about 26% of the total decommissioning cost. Specialty contractors, special tools and equipment, and supplies contribute about 11, 4, and 1%, respectively, to the total cost.

TABLE 2.9-5. Summary of Estimated Costs of DECON for the Reference Test Reactor

Cost Category		Estimated Costs ($ millions)[a,b]	Percent of Total
Disposal of Radioactive Materials			
Neutron-Activated Materials			
Reference Test Reactor	0.131		
Mock-Up Reactor (MUR)	0.004		
Contaminated Materials	2.338		
Radioactive Wastes	0.009		
Total Disposal Costs		2.572	20.7
Staff Labor		8.63	69.3
Energy		0.076	0.6
Special Tools and Equipment		0.361	2.9
Miscellaneous Supplies		0.203	1.6
Specialty Contractors[c]		0.616	4.9
Nuclear Insurance		--[d]	--
License Fees		--[e]	--
Subtotal		12.458	100.0
Contingency (25%)		3.115	
Total, DECON Costs		15.573	
Other Possible Costs			
Spent Fuel Shipment		0.204	
Facility Demolition & Site Restoration		2.289	
Subtotal		2.493	
Contingency (25%)		0.623	
Total, Other Possible Costs		3.116	

(a) 1981 costs.
(b) The number of figures shown is for computational accuracy and does not imply precision to the nearest $1,000.
(c) Includes selected demolition, explosives, temporary radwaste, and environmental monitoring services.
(d) Indemnity fees are currently $100/yr for each license (i.e., the test reactor license and the MUR license) at the reference test facility and are not inlcuded in this study since they represent only a small fraction of 1% of the total decommissioning cost.
(e) Because the reference test reactor is assumed to be federally owned, these fees are not applicable; however, where applicable for other nuclear R&T reactor facilities, the schedule of fees for license amendments and other approvals required by the license or NRC regulations is given in 10 CFR 170.

TABLE 2.9-6. Summary of Estimated Costs of Placing the Reference Test Reactor in Safe Storage

Cost Category	Estimated Costs ($ millions)[a,b]	Percent of Total
Disposal of Radioactive Materials	1.384	25.9
Staff Labor	3.096	57.9
Energy	0.021	0.4
Special Tools and Equipment	0.196	3.7
Miscellaneous Supplies	0.065	1.2
Specialty Contractors[c]	0.585	10.9
Nuclear Insurance	--[d]	--
License Fees	--[e]	--
Subtotal	5.347	100.0
Contingency (25%)	1.337	
Total, Preparations for Safe Storage	6.684	
Other Possible Costs		
Spent Fuel Shipment	0.204	
Contingency (25%)	0.051	
Total, Other Possible Costs	0.255	

(a) 1981 costs.
(b) The number of figures shown is for computational accuracy and does not imply precision to the nearest $1,000.
(c) Includes selected demolition, security preparations, and environmental monitoring services.
(d) Indemnity fees are currently $100/yr for each license (i.e., the test reactor license and the MUR license) at the reference test facility and are not included in this study since they represent only a small fraction of 1% of the total decommissioning cost.
(e) Because the reference test reactor is assumed to be federally owned, these fees are not applicable; however, where applicable for other nuclear R&T reactor facilities, the schedule of fees for license amendments and other approvals required by the license or NRC regulations is given in 10 CFR 170.

The cost of continuing care during safe storage is estimated to be about $120,000 per year.

The cost of SAFSTOR for intervals of 10, 30, 50, and 100 years after final reactor shutdown is estimated in constant 1981 dollars to be $17.6 million, $20.0 million, $21.2 million, and $27.2 million, respectively.

ENTOMB is estimated to cost $14.6 million for the reference test reactor. The major contributors to the cost of entombment are summarized in Table 2.9-7. The principal cost item is staff labor, contributing 74% of the total. The cost for shipment and disposal of radioactive materials is about 14% of the total decommissioning cost. Specialty contractors, special tools and equipment, and supplies contribute about 7, 3, and 2%, respectively, to the total cost.

The cost of continuing care following entombment is estimated to be about $41,000 per year. This could could vary depending on the need for a security system and on the level of environmental surveillance required. It should be recognized that there is no fixed number of years for nuclear test reactor facilities to be entombed; it depends on the facility-specific radionuclides and how long they take to decay to unrestricted use levels. For the purposes of this study, all ENTOMB time periods given are for illustration only.

No detailed cost estimates are developed for decontamination of the entombed test reactor since the intent is to leave the structure intact until the radioactivity has decayed to release levels.

The total cost in constant 1981 dollars for each of the decommissioning alternatives for the reference test reactor is summarized in Table 2.9-8.

2.10 OCCUPATIONAL AND PUBLIC SAFETY

Radiological and nonradiological safety impacts from routine decommissioning tasks and from postulated accidents are identified and evaluated for the reference R&T reactors for DECON, SAFSTOR, and ENTOMB. The safety evaluations include consideration of the radiation dose to the public from routine tasks and postulated accidents, as well as estimates of the lost-time injuries and fatalities associated with industrial and transportation operations. The safety evaluation utilizes current data and methodology, along with engineering judgement when

TABLE 2.9-7. Summary of Estimated Costs of ENTOMB for the Reference Test Reactor

Cost Category		Estimated Costs ($ millions)[a,b]	Percent of Total
Disposal of Radioactive Materials			
Neutron-Activated Materials			
Reference Test Reactor	0.131		
Mock-Up Reactor (MUR)	0.004		
Contaminated Materials	1.352		
Radioactive Wastes	0.087		
Total Disposal Costs		1.574	13.5
Staff Labor		8.63	73.7
Energy		0.076	0.6
Special Tools and Equipment		0.361	3.1
Miscellaneous Supplies		0.202	1.7
Specialty Contractors[c]		0.862	7.4
Nuclear Insurance		--[d]	--
License Fees		--[e]	--
Subtotal		11.706	100.0
Contingency (25%)		2.927	
Total, Costs of Entombment[f]		14.633	
Other Possible Costs			
Spent Fuel Shipment		0.204	
Facility Demolition & Site Restoration		1.783	
Subtotal		1.987	
Contingency (25%)		4.497	
Total, Other Possible Costs		2.484	

(a) 1981 costs.
(b) The number of figures shown is for computational accuracy and does not imply precision to the nearest $1,000.
(c) Includes selected demolition, security preparations, environmental monitoring services, and entombment cap installation.
(d) Indemnity fees are currently $100/yr for each license (i.e., the test reactor license and the MUR license) at the reference test facility and are not included in this study since they represent only a small fraction of 1% of the total decommissioning cost.
(e) Because the reference test reactor is assumed to be federally owned, these fees are not applicable; however, where applicable for other nuclear R&T reactor facilities, the schedule of fees for license amendments and other approvals required by the license or NRC regulations is given in 10 CFR 170.
(f) The "total" ENTOMB costs would also include the annual surveillance and maintenance service costs of about $41,000 (maximum) times "x" number of years that these services are provided.

TABLE 2.9-8. Estimated Total Costs of Possible Decommissioning Alternatives for the Reference Test Reactor

Decommissioning Alternative	Decommissioning Costs ($ millions)(a,b) Number of Years After Reactor Shutdown Decontamination is Deferred				
	0	10	30	50	100
DECON	15.6	--	--	--	--
SAFSTOR					
Preparations for Safe Storage	6.7	6.7	6.7	6.7	6.7
Continuing Care	--	1.1	3.5	6.0	12.0
Deferred Decontamination	--	9.8	9.8	8.5	8.5
Total Cost, SAFSTOR	--	17.6	20.0	21.2	27.2
ENTOMB					
Entombment	14.6	14.6	14.6	14.6	14.6
Continuing Care(c)	--	0.3	1.1	2.0	4.0
Deferred Decontamination(d)	--	--	--	--	--
Total Cost, ENTOMB		14.9	15.7	16.6	18.6

(a) Values include a 25% contingency.
(b) Values are in constant 1981 dollars.
(c) These costs assume a nominal security program is in effect.
(d) Since the intention is to leave the structure intact until the radioactivity has decayed to release levels, no cost is assigned.

necessary, to estimate the required input information and the resulting safety impacts of each task identified for each reactor. The approach used to evaluate all of the safety impacts of each decommissioning operation is believed to result in a realistic yet conservative estimate.

The results of the safety evaluation of routine decommissioning tasks are summarized in Table 2.10-1 for the reference research reactor and in Table 2.10-2 for the reference test reactor. All of the radiation doses to the public are quite small, reflecting the relatively small sizes and small amounts of radioactivity present at the reference R&T reactors.

TABLE 2.10-1. Summary of the Safety Analysis for Decommissioning the Reference Research Reactor

Safety Concern	Source of Concern	Units	DECON	Safe Storage with Decontamination After				ENTOMB
				10 Years	30 Years	50 Years	100 Years	
Public Safety[a]								
Decommissioning Tasks	Atmospheric Releases (Dose to Lungs)[b]	man-rem	5.6×10^{-7}	$<5.6 \times 10^{-7}$	$<5.6 \times 10^{-7}$	$<5.6 \times 10^{-7}$	$<5.6 \times 10^{-7}$	4.0×10^{-7}
	Transportation (Direct Total-Body)	man-rem	2.7×10^{-2}	8.4×10^{-3}	7.1×10^{-3}	7.1×10^{-3}	7.0×10^{-3}	1.4×10^{-2}
	Continuing Care	man-rem	--	Neg.[c]	Neg.[c]	Neg.[c]	Neg.[c]	Neg.[c]
Occupational Safety								
Lost-Time Injuries	Decommissioning Tasks	Total No.	1.1×10^{-1}	1.9×10^{-1}	1.0×10^{-1}	1.0×10^{-1}	1.9×10^{-1}	2.7×10^{-2}
	Transportation	Total No.	3.2×10^{-3}	4.0×10^{-3}	4.0×10^{-3}	4.0×10^{-3}	4.0×10^{-3}	1.6×10^{-3}
	Continuing Care	Total No.	--	1.3×10^{-3}	3.9×10^{-3}	6.6×10^{-3}	1.3×10^{-2}	--
Fatalities	Decommissioning Tasks	Total No.	7.5×10^{-4}	1.2×10^{-3}	1.2×10^{-3}	1.2×10^{-3}	1.2×10^{-3}	1.8×10^{-4}
	Transportation	Total No.	1.9×10^{-4}	2.4×10^{-4}	2.4×10^{-4}	2.4×10^{-4}	2.4×10^{-4}	9.6×10^{-5}
	Continuing Care	Total No.	--	3.0×10^{-4}	9.1×10^{-4}	1.5×10^{-3}	3.0×10^{-3}	--
Radiation Dose	Decommissioning Tasks	man-rem	18.34	15.09	13.97	13.89	13.90	16.64
	Transportation	man-rem	2.8×10^{-1}	8.6×10^{-2}	7.3×10^{-2}	7.3×10^{-2}	7.2×10^{-2}	1.4×10^{-1}
	Continuing Care	man-rem	--	0.53	0.78	0.80	0.82	Neg.[c]

(a) Radiation doses from postulated accidents are not included.
(b) 50-year committed dose equivalent to the lung for a total population within an 80-km radius of the site.
(c) Neg. = Negligible. Radiation doses to the public from routine continuing care tasks are not analyzed in detail, but are expected to be significantly smaller than those from decommissioning tasks.

TABLE 2.10-2. Summary of the Safety Analysis for Decommissioning the Reference Test Reactor

Safety Concern	Source of Concern	Units	DECON	Safe Storage with Decontamination After				ENTOMB
				10 Years	30 Years	50 Years	100 Years	
Public Safety[a]								
Decommissioning Tasks	Atmospheric Releases (Dose to Lungs)[b]	man-rem	1.6×10^{-3}	$<1.6 \times 10^{-3}$	$<1.6 \times 10^{-3}$	$<1.6 \times 10^{-3}$	$<1.6 \times 10^{-3}$	1.0×10^{-3}
	Transportation (Direct Total-Body)	man-rem	2.2	3.5×10^{-1}	1.4×10^{-1}	1.3×10^{-1}	1.2×10^{-1}	1.3
	Continuing Care	man-rem	--	Neg.[c]	Neg.[c]	Neg.[c]	Neg.[c]	Neg.[c]
Occupational Safety								
Lost-Time Injuries	Decommissioning Tasks	Total No.	2.5	3.1	3.1	3.1	3.1	2.5
	Transportation	Total No.	2.6×10^{-1}	4.0×10^{-1}	4.0×10^{-1}	4.0×10^{-1}	4.0×10^{-1}	1.6×10^{-1}
	Continuing Care	Total No.	--	2.6×10^{-3}	2.6×10^{-2}	4.3×10^{-2}	8.6×10^{-2}	--
Fatalities	Decommissioning Tasks	Total No.	1.4×10^{-2}	1.9×10^{-2}	1.9×10^{-2}	1.9×10^{-2}	1.9×10^{-2}	1.4×10^{-2}
	Transportation	Total No.	1.5×10^{-2}	2.3×10^{-2}	2.3×10^{-2}	2.3×10^{-2}	2.3×10^{-2}	9.2×10^{-3}
	Continuing Care	Total No.	--	5.4×10^{-5}	1.6×10^{-4}	2.7×10^{-4}	5.4×10^{-4}	--
Radiation Dose	Decommissioning Tasks	man-rem	322	198	118	112	112	387
	Transportation	man-rem	22	14	12	12	12	19
	Continuing Care	man-rem	--	Neg.[d]	Neg.[d]	Neg.[d]	Neg.[d]	Neg.[d]

(a) Radiation doses from postulated accidents are not included.
(b) 50-year committed dose equivalent to the lung for a total population within an 80-km radius of the site.
(c) Neg. = Negligible. Radiation doses to the public from routine continuing care tasks are not analyzed in detail, but are expected to be significantly smaller than those from decommissioning tasks.
(d) Neg. = Negligible. It is assumed that external radiation exposures for surveillance and maintenance operations at the reference test reactor during continuing care are at the threshold levels of detection for personnel monitoring devices (see Section J.2.6.2 of Appendix J for details).

Lost-time injuries from industrial-type accidents during DECON at the reference research and test reactors are expected to be less than one and three, respectively. Essentially no fatalities are predicted to result from decommissioning tasks at the reference R&T reactors based on previously recorded industrial and transportation accident frequency data.

2.11 COMPARISONS WITH OTHER STUDIES

Studies on the decommissioning of licensed R&T reactors as a class are virtually nonexistent. Historically, it is only when a specific research or test reactor licensee is preparing either for the actual decommissioning of his facility or for an amendment to his existing license (e.g., to permit operation to an increased power level) that the decommissioning of R&T reactors is addressed. A review of the literature has identified two studies on decommissioning test reactors: an earlier study on the reference test reactor (PBRF), and a limited study on the National Bureau of Standards Reactor (NBSR). The earlier PBRF study is incomplete in that it dealt only with activities following the initial cleanup. The NBSR is sufficiently different from the PBRF that to make direct comparisons of the two is of limited value.

2.12 FACILITATION OF DECOMMISSIONING

A number of techniques for facilitating decommissioning are presented and examined for their impact on cost and occupational radiation dose during reactor operation and maintenance, as well as during DECON. It is concluded that the techniques that are most beneficial are those that reduce cost and radiation dose during operations and maintenance, since many more opportunities for reducing cost and dose occur over the operating lifetimes of the R&T reactor facilities than occur during decommissioning. It is suggested that a standard decommissioning closeout data sheet be required to be completed about the same time as the final radiation survey. The proposed standard format should include decommissioning data in sufficient detail to be of subsequent benefit to other R&T reactor licensees whose facilities may be similar in part or in whole, thus

providing the framework for an information data base upon which confident planning and preparation for future R&T reactor decommissionings could be accomplished.

2.13 IMPACTS OF ALTERNATE STUDY BASES

The diversity of designs among licensed R&T reactors precludes any reasonable scaling analysis based solely on plant authorized power level. Each particular class of reactor tends to be rather unique and scaling of costs across classes, based on plant authorized power level, cannot be accomplished in any meaningful way. Therefore, only increased radiation levels, different contractual arrangements, and increased waste disposal costs are readily amenable to examination for this study on R&T reactors.

It is concluded that a threefold increase in the radiation dose rates within the reactor coolant system of the reference test reactor would have little impact on the decommissioning activities, since the annual dose limits for the decommissioning workers would not be exceeded.

Estimated labor costs for DECON are examined for the reference test reactor for both the Owner-Only approach and for the Owner-Contractor approach. The principal impact is from a change in the overhead rates applied to the contractor labor, from 50% to 110% for nonsupervisory staff and from 70% to 110% for supervisory staff. The increased overhead rates increase the estimated labor costs from $8.63 million to $10.91 million, or about 26%. Application of the contractor's fee, together with estimated mobilization/demobilization costs for the decommissioning prime contractor while utilizing the Owner-Contractor approach, results in an overall decommissioning project cost increase of about 36%.

During the past 4 years, the charge per unit volume for burial in a licensed burial ground has increased by over a factor of three. It is likely that these charge rates will continue to increase as operating costs increase and as projected decommissioning costs for burial grounds become better defined. Burial costs comprise 12.5% of the estimated cost of DECON for the reference test reactor. Thus, for every 1% increase in the burial charge, the cost of DECON will increase 0.125%.

2.14 CONCLUSIONS AND RECOMMENDATIONS

Decommissioning of nuclear R&T reactor facilities is technically feasible with present-day technology. Further development of special equipment such as the plasma-arc torch, the arc saw, and sophisticated remote-handling equipment, as well as volume reduction equipment, could lead to reductions in both cost and occupational radiation exposure.

Existing regulations appear to cover decommissioning. However, some modifications and/or additions that speak specifically to the requirements for decommissioning would be helpful. Centralization or an indexing of regulations that apply to decommissioning would also be helpful.

The estimated occupational radiation dose resulting from decommissioning either one of the reference R&T reactors is not prohibitively large. In addition, the impact of decommissioning the reference R&T reactors on the safety of the public is small, with no significant risk to the public identified.

To put the various decommissioning alternatives in perspective, it is useful to examine the estimated costs and occupational radiation doses associated with achieving unrestricted release of the facilities and the site. For the SAFSTOR and ENTOMB alternatives for both the reference reactors, it is assumed that the release takes place about 100 years after final reactor shutdown. The estimated cost and radiation dose for each alternative is given in Table 2.14-1 for the reference research reactor and in Table 2.14-2 for the reference test reactor.

For the reference research reactor, it can be seen from Table 2.14-1 that DECON costs the least but results in the greatest radiation dose. Safe storage with deferred decontamination has a significantly higher cost but a reduced radiation dose. ENTOMB costs about 37% more than DECON and results in about 11% less radiation dose than DECON. The cost of having the property unavailable for unrestricted use for 100 years is not included in these comparisons, since the complexity of estimating the cost is beyond the scope of this study.

Cost estimates for decommissioning of the reference research reactor in this study are rather small in comparison with similar estimates made in

TABLE 2.14-1. Comparison of Costs and Radiation Doses for Decommissioning the Reference Research Reactor Via the Various Alternatives

Decommissioning Alternative	Cost (millions, 1981 dollars)	Occupational Radiation Dose (man-rem)[a]
DECON	0.844	18.62
SAFSTOR	4.492[b,c]	13.91
ENTOMB	1.162[b,d]	16.71

(a) Doses include decommissioning and transportation workers.
(b) Cost includes maintenance and surveillance for 100 years.
(c) cost includes decontamination after 100 years.
(d) No decontamination assumed.

TABLE 2.14-2. Comparison of Costs and Radiation Doses for Decommissioning the Reference Test Reactor via the Various Alternatives

Decommissioning Alternative	Cost (millions, 1981 dollars)	Occupational Radiation Dose (man-rem)[a]
DECON	15.6	344
SAFSTOR	27.2[b,c]	125
ENTOMB	18.7[b,d]	444

(a) Doses include decommissioning and transportation workers.
(b) Cost includes maintenance and surveillance for 100 years.
(c) Cost includes decontamination after 100 years.
(d) No decontamination assumed.

studies of larger commercial power reactors. Irrespective of the absolute size of the overall decommissioning project, a certain minimum number of management and support staff is necessary in order to assure the orderly and expeditious performance of the tasks. Therefore, the smaller the project, the larger is the fraction of total cost related to management and support staff. From an analysis of the staff labor requirements and costs estimated for decommissioning the reference research reactor, it is clear that a considerable cost is attributable to the management and support staff. This cost is time dependent and not particularly sensitive to the dedicated manpower requirements of

each task. In DECON, for example, the management and support staff represent 77% of the overall staff labor costs. Since staff labor, in itself, represents almost 80% of the overall DECON costs at the reference research reactor (see Table 2.9-1), it is clear that overall costs are very sensitive to the length of the schedule for each decommissioning alternative.

For the reference test reactor, it can be seen from Table 2.14-2 that DECON costs the least of the three decommissioning alternatives. DECON results in a larger radiation dose than SAFSTOR but a smaller radiation dose than ENTOMB. Many tasks are identical in both DECON and ENTOMB, and since DECON and entombment are estimated to require about the same total time for decommissioning, similar total radiation doses should be anticipated. However, many of the tasks are accomplished earlier in ENTOMB than in DECON, and since the estimated total dose for each task, regardless of the decommissioning alternative, is corrected for radioactive decay to the midpoint in time for the given task, accomplishing a given task sooner after final reactor shutdown results in a correspondingly higher occupational exposure for that task. In addition, workers installing the entombment cap receive a significant radiation dose. Thus, ENTOMB is estimated to produce the largest occupational radiation dose of the three decommissioning alternatives examined in this study for the reference test reactor and is estimated to cost about 19% more than DECON. The cost of having the property unavailable for unrestricted use for 100 years is not included in these comparisons, since the complexity of estimating the cost is beyond the scope of this study.

The acceptability of disposal of highly activated and/or long-lived radioactive materials by burial in a shallow-land burial facility is under consideration by the NRC. In fact, limits have been promulgated by the NRC in the form of the proposed Low-Level Waste regulation, 10 CFR 61; as published in the Federal Register/Vol. 46, No. 142/Friday, July 24, 1981. Part 61 establishes requirements and concentration limits for the near surface disposal of waste which would include activated and long-lived radioactive materials. Concentration limits for three classes of waste (Classes A, B, or C) are established, with Class C wastes classed as "generally unacceptable" for near surface

disposal. If placement of selected R&T reactor materials in a deep geologic disposal facility is required in the future, R&T reactor decommissioning costs will increase.

If the bulk of the nonactivated, contaminated stainless steel and nonferrous metals can economically be decontaminated to levels sufficiently low to permit unrestricted use, additional savings can be realized. However, the appropriate definitions of the amount of radioactivity that would be permitted on such materials when released for unrestricted use are not presently available.

Certain types of data useful to decommissioning analyses are essentially nonexistent at this time. Measurements on activated stainless steel that has been irradiated for an extended period of time (>10 years) to determine the growth of such long-lived radionuclides as ^{59}Ni and ^{94}Nb would be valuable for confirmation of calculations. Similarly, measurements of the growth of radionuclides in irradiated concrete would be helpful in evaluating the radiation dose rates that might be encountered from the activated biological shield surrounding the reference R&T reactors. In particular, the levels of ^{152}Eu and ^{154}Eu resulting from trace amounts of europium present in the concrete may be important contributors to the total radiation dose rate from the concrete. In addition, studies to determine the actual levels of radioactivity on the soil surfaces surrounding operating R&T reactor facilities would help to characterize in a realistic manner the residual radioactivity that might be present after 12 to 40 years of operation, and would help to quantify the decontamination effort that might be required to release the site for unrestricted use.

Careful attention during the design and construction phase of research or test reactor projects to simplify the problems of eventual decommissioning would be effective in reducing decommissioning costs and occupational dose rates.

3.0 STUDY APPROACH AND BASES

This section contains a description of the study approach taken and the major bases for the results in this study. It should be recognized that the study results are specific to this approach and to these major bases, and any application of different approaches or bases could lead to significantly different results.

Because of the diversity in types and sizes of nuclear research and test (R&T) reactor facilities and in the operational schedules and lifetimes associated with them, the level of effort required to decommission them varies greatly. Necessary actions can range from simple, relatively inexpensive decommissioning activities and administrative procedures to more costly and extensive decontamination and disposal activities. This study focuses on one research facility and on one test facility, each representing a significant decommissioning task.

The study approach for both R&T reactor facilities is the same. The reference facility is analyzed using data for specific components (the unit-component approach) to provide information about the safety and costs of decommissioning the entire facility. Descriptions of the decommissioning of representative components (e.g., reactor vessel and internals, beam ports, fuel storage areas, exhaust system ductwork) for each reactor type provide data common to that type of reactor.

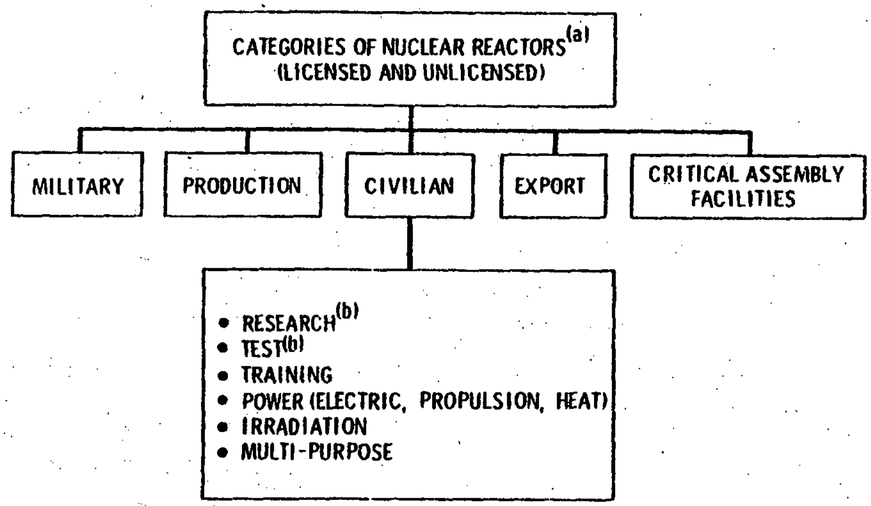
The first step in conducting the study is to select the reference nuclear R&T reactor facilities and to characterize them in sufficient depth to perform engineering and safety analysis of their decommissioning. The selection methodology relies heavily on a practical classification system developed for nuclear reactors from which representative reactors of both R&T reactor types can be selected. This classification system is discussed in Section 3.1; the study approach is discussed in Section 3.2; and the major study bases are discussed in Section 3.3.

3.1 TECHNICAL APPROACH FOR THE SELECTION OF THE REFERENCE R&T REACTORS

The classification system for nuclear reactors in the U.S. is briefly described in this section. This system is used to select the reference R&T

reactors to be conceptually decommissioned in this study. Only those members of the U.S. reactor population that are licensed by the Nuclear Regulatory Commission (NRC) are considered in the selection process.

In general, reactors are classified by the nature of the main reactor components (fuel, moderator, and coolant), by the main design features (nuclear and engineering), and by the purpose for which the reactor is used (research, materials testing). The name given to a reactor type may include descriptive terms indicative of any or all of these characteristics as in the following example: enriched uranium boiling water research reactor. Categories and main classes of licensed and unlicensed nuclear reactors by primary function or purpose are illustrated in Figure 3.1-1. The "CIVILIAN" category shown in the figure, and specifically the classes of R&T reactors, are the main concerns of this study. The R&T reactors that are conceptually decommissioned in this study were selected from these classes.



(a) ALL FACILITIES ARE CAPABLE OF SUSTAINING A NUCLEAR CHAIN REACTION

(b) RESEARCH REACTORS AND TEST REACTORS EACH CONSTITUTE A MAIN "CLASS" WITHIN THE CIVILIAN CATEGORY IN THE CLASSIFICATION SYSTEM FOR NUCLEAR REACTORS. THIS STUDY IS LIMITED SPECIFICALLY TO THESE TWO CLASSES OF LICENSED NUCLEAR R&T REACTOR FACILITIES

FIGURE 3.1-1. Categories and Main Classes of Nuclear Reactors

As part of the selection process, both currently operational R&T reactors as well as shut down R&T reactor facilities are considered as candidates for conceptual decommissioning. The single common denominator for all of the R&T reactors considered for this study is that they are all licensed by the NRC and still all retain a license. Operating licenses for R&T reactors are granted under the provisions of 10 CFR 50. R&T reactors are issued class 104 licenses, licenses for "medical therapy and research and development facilities," described in 10 CFR 50.21(c). The various types of R&T reactors are described in the following subsections, together with the justification for selecting the reference research reactor and the reference test reactor.

3.1.1 Research Reactors

A research reactor is defined in 10 CFR 170.3(h) as a nuclear reactor licensed for operation at a thermal power level of 10 MW or less, and which is not a testing facility as defined by 10 CFR 170.3(m). There are currently 67 operational, licensed research reactors in the United States.[1] The following points are made concerning these facilities:

- The majority (53 reactors) are directly associated with an institution of higher learning - university, college, or institute.
- The remaining 14 reactors are used in private industry or by agencies of the federal government.
- The research reactors are used for training, engineering, scientific purposes, or some combination thereof.
- Research reactors are located in 31 states and the District of Columbia.
- The oldest license (No. R-23) is dated August 26, 1957 and the most recent license (No. R-128) was issued April 14, 1977.
- Nearly all research reactors are submerged in an open pool of deionized water.

The authorized power levels of the research reactors range from 0.0001 kW to 10,000 kW. A summary of the authorized power levels relative to the number of research reactors licensed at each power level is presented in Table 3.1-1.

TABLE 3.1-1. Summary of Operationally Licensed Research Reactors Relative to Their Authorized Power Levels[a]

Authorized Power Level Range (kW)	Number of Research Reactors
0.001 to 0.005	12
0.01 to 0.015	4
0.1	2
10 to 20	7
100	9
200	1
250	10
1 000	12
1 500	2
2 000	4
5 000	3
10 000	1
Total	67

(a) Reference 1, pp. 3-4 and 3-5.

The various types of research reactors currently licensed for operation are shown in Figure 3.1-2. It can be seen that TRIGA[a] and AGN research reactors are the two most dominant types. The authorized power levels of the AGN reactors range from 0.0001 kW to 0.015 kW, while the various TRIGA research reactors are authorized for power levels from 100 kW to 1,500 kW.

As mentioned earlier in Section 1, it is not practical to include in one study examples of the decommissioning of all types of nuclear reactors within a given class of reactor facilities. Because of the diversity in types and sizes of research reactor facilities and in the operational schedules and

(a) TRIGA trademark registered in the U.S. Patent Office.

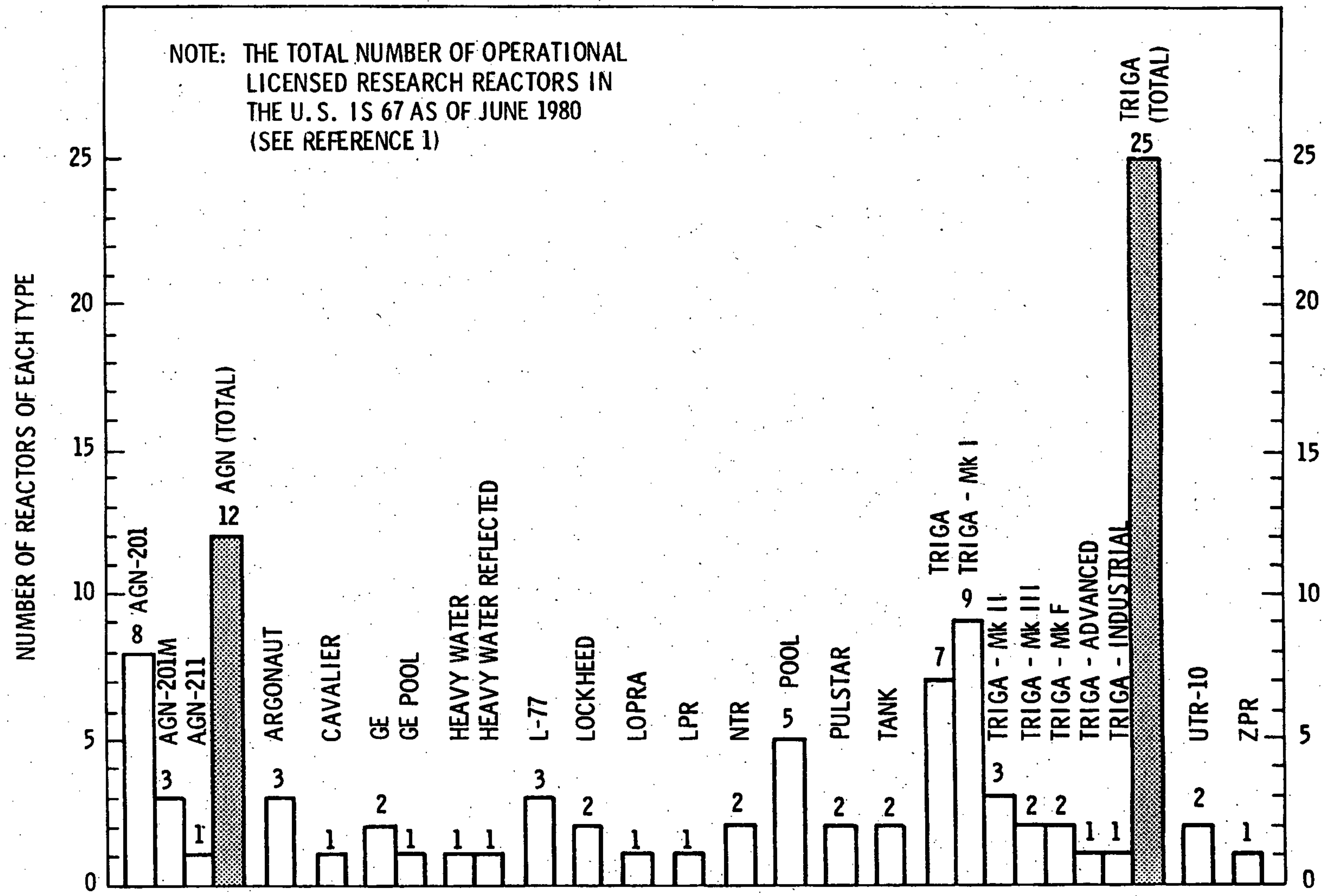


FIGURE 3.1-2. Type and Number of Licensed Research Reactors as of June 1980

lifetimes associated with them, the level of effort required to decommission them varies greatly. Necessary actions can range from simple, relatively inexpensive decommissioning activities and administrative procedures to more costly and extensive decontamination and disposal activities. The 25 licensed TRIGA research reactors shown in Figure 3.1-2 contain many similar characteristics and represent a significant fraction of the total number of licensed research reactors in the U.S. Therefore, this study focuses on a TRIGA research reactor of relatively significant authorized thermal power level that is directly associated with a university as being representative of a significant decommissioning effort. The facility selected as meeting these qualifications is the Oregon State TRIGA Reactor (OSTR) at Corvallis, Oregon. OSTR is a 1000-kWt, above-ground, open-pool nuclear training and research facility that utilizes a TRIGA-type core and control system of the Mark II design. The structures, systems, and components are typical of many TRIGA research reactors.

Currently, there are three models or designs of the TRIGA research reactor. They are designated sequentially as Mark I, Mark II, and Mark III. Brief descriptions of the general characteristics of these three models are included in this section for completeness.

The Mark I and Mark II models have identical reactor cores, reactor vessels, and internal parts. Both models are built to the same size specifications and are capable of up to 2000-kW steady-state operation and square wave and pulsing operation. The specific power levels are determined by the fuel type and quantity used and by the core arrangement. The Mark I model is designed to take advantage of below-ground shielding instead of the large concrete biological shield at the core elevation used in the Mark II and Mark III models. No provisions are made in the Mark I model for any horizontal beam ports or thermalizing columns, since it is anticipated that this region will be underground and inaccessible.

The Mark II model is constructed above ground, with the reactor tank bottom near grade level. It has four beam ports (one tangential) plus two thermal/thermalizing columns, with a small pool irradiation tank adjacent to one of the columns. This model is the reference model used for this study and is discussed in greater detail in Section 8.

The Mark III model is also built above ground. The Mark III reactor tank is oblong and of a larger size than the Mark I or Mark II reactor tank. The reactor core is suspended by an overhead bridge and is moveable in the horizontal plane. It has an elaborate 10-beam port facility on one side as well as one thermalizing column. Across the reactor tank from the ports, in the oblong direction, is a large room. The room is constructed with a minimum of shielding to allow the irradiation of a variety of materials, objects, and/or animals up to the size of a horse. When the reactor core is moved within the vessel to the opposite side, personnel access is possible to the "relieved" experimental facility.

Another research reactor conceptually decommissioned in this study is the Plum Brook Mock-Up Reactor (MUR) colocated at the same site as the reference test reactor described in the subsequent subsection. It is dealt with in the broader context of being an integral part of the reference test reactor.

3.1.2 Test Reactors

A testing facility (i.e., a test reactor) is defined in 10 CFR 50.2(r) as a nuclear reactor licensed for operation at: 1) a thermal power level in excess of 10 MW, or 2) a thermal power level in excess of 1 MW if the reactor is to contain: a circulating loop through the core in which the applicant proposes to conduct fuel experiments; or a liquid fuel loading; or an experimental facility in the core in excess of 16 square inches in cross-section.

Currently there are eight licensed test reactors in the U.S. Table 3.1-2 lists the test reactors by their NRC docket number, thermal power level, location and present licensing status. It can be seen from the table that six of the eight test reactors are in safe storage with an amended nuclear license and two are operational. They range in thermal power level from 6 to 60 MW. It is anticipated that the results of this study will be useful in assisting with the final decommissioning of these facilities.

The Plum Brook Reactor Facility (PBRF), the reference test reactor for this study, is typical of most thermal neutron materials testing reactors built in the mid-1950s. In general, these reactors had relatively short lifetimes of less than 20 years. The PBRF and its associated Mock-Up Reactor

TABLE 3.1-2. Licensed Test Reactors in the U.S.

NRC Docket No./Reactor	Thermal Power	Location	Present Status
50-22/Westinghouse Test Reactor	60 MW	Waltz Mill, Pennsylvania	Amended Nuclear License (NRC)
50-30/NASA Plum Brook Test Reactor	60 MW	Sanduksy, Ohio	Dismantling Order Issued May 26, 1981
50-70/General Electric Test Reactor	50 MW	Alameda County, California	Operational (currently shut down)
50-146/Saxton PWR Test Reactor	28 MW	Saxton, Pennsylvania	Amended Nuclear License (NRC)
50-184/National Bureau of Standards Test Reactor	10 MW	Gaithersburg, Maryland	Operational
50-183/GE EVESR Exp. Superheat Test Reactor	17 MW	Alameda County, California	Amended Nuclear License (NRC)
50-200/B&W BAWTR Test Reactor (pool type)	6 MW	Lynchburg, Virginia	Byproduct License (NRC)
50-231/SEFOR Sodium Cooled Test Reactor	20 MW	Strickler, Arkansas	Byproduct License (State)

(MUR) are also representative of the commingling of a research mock-up reactor being utilized to maximize cost savings during the operating lifetime of its parent test reactor. The PBRF is described briefly in Section 1 and in more detail in Section 8 and Appendix C. As mentioned earlier, both reactors at the Plum Brook site are conceptually decommissioned in this study. This is considered to be a reasonable approach based on their similar operating mission and close proximity (i.e., they are colocated in the same reactor building).

3.2 STUDY APPROACH

The initial effort is to develop plans with which to accomplish the objective of this study, which is to provide an analysis of the technology, safety, and costs of decommissioning reference nuclear R&T reactor facilities at the end of their operating lifetimes. The plan in each case is developed by a staff of personnel with expertise in the pertinent areas of interest in the study. The areas of expertise include nuclear R&T reactor design

and operation as well as the decommissioning techniques of decontamination, radiological and chemical toxicant regulations, radiological and industrial safety analyses, health physics, and cost-benefit estimating and analysis. The study is then carried out by the same staff or by staff with similar backgrounds.

Because of the diversity in types and sizes of R&T reactor facilities and in the operational schedules and lifetimes associated with them, the level of effort required to decommission them varies greatly. Necessary actions can range from simple, relatively inexpensive decommissioning activities and administrative procedures to extensive decontamination and disposal activities costing millions of dollars.

As mentioned earlier, it is not practical to include in one study examples of the decommissioning of all classes of R&T reactor facilities. Therefore, this study selects and focuses on one existing research facility and on one existing test facility, each representing a significant decommissioning task. The reference test facility is placed on a generic site, which is also being used in similar and related decommissioning studies of other fuel cycle facilities. The reference research facility is placed on a generic university campus site to better reflect reality for this particular class of nuclear facility. Detailed descriptions of each selected facility are compiled, including information on plant equipment and material sizes, volumes, and weights (i.e., unit-component data). Predecommissioning conditions for the R&T reactor facilities and sites are defined, including residual radionuclide inventories, radiation dose rates, and radioactive contamination levels.

Three decommissioning alternatives (i.e., DECON, SAFSTOR, and ENTOMB) are considered. Related regulatory guidance is reviewed, summarized, and used as an aid and basis in the study.

Past decommissioning experience of licensed nuclear R&T reactor facilities is reviewed. From this review, a summary of insights from these decommissioning experiences is derived and applied where applicable.

Methods are determined for each reference nuclear facility decommissioning. The methods specified in this study are selected on the basis of engineering

judgment, while maintaining a balance of safety and cost. For each of the selected decommissioning alternatives, tasks and task schedules are developed to conceptually decommission the reference facilities by using the methods specified.

Safety analyses are performed for each of the selected decommissioning alternatives for each of the selected reference reactors. These analyses include postulated radiological and chemical exposures to the workers and the public from normal decommissioning operations and from potential accidents. Nonradiological industrial accidents to workers are also estimated. The safety analyses use established data and methodology to estimate the release mechanisms, dispersion, and pathways and exposure modes of the released materials.

Costs of decommissioning are estimated for labor, materials, equipment, packaging, transportation, disposal, and where applicable, continuing care. The unit cost data used in this study are similar, insofar as possible, to those used in previous pressurized water reactor and boiling water reactor decommissioning studies.[3,4]

Alternatives for financing decommissioning are examined and compared using the costs from this study.

The primary emphasis and first thrust of this study is on the DECON alternative of decommissioning; the SAFSTOR and ENTOMB analyses are outgrowths of the DECON analysis in that they rely largely on data generated for DECON. For DECON, once each of the reference facilities is defined in sufficient detail (including the radiation dose rates and radionuclide inventories at final shutdown) and the radioactive-material packaging and disposal requirements are defined, the analysis proceeds in the following general manner:

1. Define the decontamination, sectioning, and packaging requirements for each piece of contaminated equipment or material.
2. Determine the amenable method and resultant time of disassembly.
3. Specify the staff required to perform the tasks.
4. Determine the schedule and sequence of the tasks.
5. Calculate the resultant costs and assess the safety of the tasks.

Following completion of the DECON analysis, the analyses for the other two decommissioning alternatives are undertaken in a similar manner.

3.3 STUDY BASES

The study is intended to provide decommissioning information useful to regulators, designers, and owner/operators of R&T reactors. The study bases have major impacts on the issues of decommissioning safety, cost, and time. Many aspects of decommissioning may change, depending on the specific design, shutdown conditions, and residual contamination levels at each facility. The bases used in this study must therefore be carefully examined before the results can be applied to different nuclear R&T reactor facilities. These study bases are:

1. The study must yield realistic and up-to-date results. This primary basis is a requisite to meeting the objectives of the study, and provides the foundation for most of the other bases.
2. The study is conducted within the framework of the existing regulations and regulatory guidance. No assumptions are made regarding what future regulatory requirements or guidance might be. It is recognized that future regulatory considerations could have significant impacts on the results of the study.
3. The study evaluates existing nuclear R&T reactor facilities. This is required to meet the study objectives and the primary basis stated earlier. The facilities selected as the references for study were previously described in Section 3.1 and are not repeated here. However, both reference reactors satisfy this condition and are basically typical of their genre, including the fact that they had no fuel element failures during their lifetimes.
4. The estimated radiation dose rates throughout the reference R&T reactor facilities are based on measured data from the reference reactors.

5. Current and proven decommissioning technology and techniques are used. Where developmental techniques are called for, they are in an advanced state of development and are believed to be ready for the specific application.

6. The financing for decommissioning activities is available as necessary to complete the planned activities without fiscal constraint.

7. A nuclear waste disposal facility is in operation. The existence of an operable disposal facility is requisite to most decommissioning alternatives.

8. For decommissioning activities immediately following plant shutdown, the staff is drawn largely from operating personnel familiar with the facility and its systems.

9. All materials whose radioactivity exceed unrestricted release levels are removed from the site before the site is released for unrestricted use.

10. The performance of decommissioning is assumed to be relatively troublefree, and decommissioning options are evaluated assuming efficient performance of the work. A 25% contingency is added to cost totals to account for such things as work delays and unanticipated material and equipment costs.

11. Decommissioning and radiation protection philosophies and techniques applied conform to the principle of keeping public and occupational radiation doses As Low As is Reasonably Achievable (ALARA).

12. Costs are in 1981 dollars.

From these major study bases, more specific bases and assumptions are derived for specific study areas. These specific bases and assumptions appear throughout the report where applicable.

Three plausible alternatives to the major study bases are also analyzed for their impacts on decommissioning costs. These alternatives are: 1) different R&T reactor radiation doses, 2) different contractual arrangements, and 3) increased nuclear waste disposal charges.

REFERENCES

1. U.S. NRC, Operating Units Status Report - Licensed Operating Reactors, Vol. 4, No. 7, July 1980. (NUREG-0020)

2. P. B. Erickson, U.S. Licensed Reactor Decommissioning Experience, Proceedings of the American Nuclear Society Topical Meeting in Sun Valley, Idaho, September 16-20, 1979.

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

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

4.0 DECOMMISSIONING ALTERNATIVES AND SELECTION CONSIDERATIONS

Once a licensed nuclear research or test reactor reaches the end of its useful life, it must be decommissioned (i.e., placed in a condition such that there is no unreasonable risk from the decommissioned facilities to public safety). Decommissioning means to safely remove the property from radioactive service and to dispose of radioactive materials. The level of any residual radioactivity remaining on the property after decommissioning must be low enough to allow unrestricted use of the property. Alternatives for decommissioning are discussed in Section 4.1 and considerations for decommissioning are discussed in Section 4.2.

4.1 DECOMMISSIONING ALTERNATIVES

Three alternatives available for decommissioning nuclear R&T reactor facilities are: 1) DECON, immediate decontamination leading to release of the facility for unrestricted use; 2) SAFSTOR, safe storage plus deferred decontamination leading to release of the facility for unrestricted use; and 3) ENTOMB, entombment plus decay leading to release of the facility for unrestricted use.[a] Before starting decommissioning by any of the three alternatives, the facility operating license may be amended to authorize possession but not operation of the facility.[3]

The general characteristics of the basic decommissioning alternatives are summarized in Table 4.1-1. Each of these alternatives is defined and discussed in the following subsections.

4.1.1 Definition of and Rationale for DECON

DECON means to immediately remove all radioactive material down to residual levels which permit release of the property for unrestricted access. DECON is the only one of the decommissioning alternatives presented here which leads

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

TABLE 4.1-1. Characteristics of the Various Decommissioning Alternatives for Licensed Nuclear R&T Reactors

Alternative	Facility Status	Facility/Site Use
DECON (Immediate decontamination to unrestricted release)	Equipment - removed if radioactive Surveillance Staff - none Security - none Environmental Monitoring - none Radioactivity - removed Surveillance - none Structures - removal optional NRC License - terminated	Facility - Unrestricted Site - Unrestricted
SAFSTOR (Safe storage plus deferred decontamination to unrestricted release)		
Passive	Equipment - some operating[(a)] Surveillance Staff - routine periodic inspections Security - remote alarms Environmental Monitoring - routine periodic Radioactivity - immobilized/sometimes sealed Surveillance - periodic Structures - intact NRC License - amended or transferred[(b)]	All of the facility and most[(c)] of the site are restricted to nuclear use until deferred decontamination is accomplished.
Custodial	Equipment - some operating Surveillance Staff - some required Security - continuous Environmental Monitoring - continuous Radioactivity - confined Surveillance - continuous Structures - intact NRC License - amended or transferred[(b)]	Facility and site are restricted to nuclear use until deferred decontamination is accomplished.
ENTOMB (Entombment plus decay to unrestricted release)	Equipment - none operating Surveillance Staff - none on site Security - hardened barrier; fencing and posting Environmental Monitoring - infrequent Radioactivity - sealed in monolithic structure Surveillance - infrequent Structures - partial removal optional NRC License - amended or transferred[(b)]	Most[(c)] of the facility and some[(c)] of the site are restricted to nuclear use until the confined radioactivity has decayed to unrestricted release levels.

(a) Cold sumps that collect storm water or water from cold-floor drains may remain in service with their water-level alarm monitors active during continuing care.
(b) The NRC amended operating license, allowing the licensee to possess but not operate the facility, is sometimes termed a "possession-only" license.[(3)] In an agreement state the amended nuclear license may be canceled and converted (i.e., exchanged) to a state-regulated byproduct license.
(c) Implies a release of part of the site or the facility for unrestricted use, while maintaining control of the licensed portion that contains radioactive materials above releasable levels.

to termination of the facility license and release of the facility and site for unrestricted use shortly after cessation of facility operations. DECON at a facility requires that contaminated components either be: 1) decontaminated to levels permitting unrestricted use, or 2) packaged and shipped to an authorized radioactive waste disposal site. Demolition and removal of the decontaminated and uncontaminated structure, while not a required part of DECON, is included in this study for completeness.

DECON is the most likely decommissioning alternative for the reference R&T reactor facilities considered in this study because it results in release of the facilities for unrestricted use shortly after cessation of facility operation, thus eliminating long-term security, maintenance, and surveillance needs. However, larger initial commitments of money within a short period of time following final reactor shutdown, higher occupational radiation exposure, and the use of more regulated waste disposal site space than other alternatives are the exchange considerations made for prompt availability of the facility and site for other purposes. An additional consideration is the availability of the facility operations staff that is highly knowledgeable about the facility to form a decommissioning work force.

4.1.2 Definition of and Rationale for SAFSTOR

SAFSTOR encompasses those activities required to place (preparations for safe storage) and maintain (safe storage) a radioactive facility in such condition that the risk to safety is within acceptable bounds and that the facility can be safely stored under the conditions of the amended nuclear license. Since materials having radioactivity levels above unrestricted release levels are still onsite, the amended nuclear license remains in force throughout the SAFSTOR period. SAFSTOR is completed by subsequently decontaminating the facility to levels that permit release of the facility for unrestricted use (deferred decontamination), thus permitting termination of the nuclear license. Some disassembly and disposal of activated components are still required with deferred decontamination, but the personnel radiation exposure and the regulated waste disposal site space requirements are potentially diminished due to

radioactive decay. Deferred decontamination cannot, however, rely on the availability of facility operations staff for personnel familiar with the facility.

Two categories of SAFSTOR are possible:

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

In this study, we consider only passive SAFSTOR, which is referred to as "SAFSTOR." Since both categories of SAFSTOR require some level of continuing care during the holding period, the least expensive method (i.e., passive SAFSTOR) over a lengthy holding period is selected because: 1) it is the SAFSTOR category that results in the lowest continuing care costs regardless of the length of the holding period, and 2) deferred decontamination costs are ultimately lower since comprehensive cleanup and decontamination will have already taken place during the initial preparations for SAFSTOR.

In addition, Regulatory Guide 1.86[3] describes decommissioning monitoring procedures currently considered acceptable by the NRC staff. The Guide states: "adequate radiation monitoring, environmental surveillance, and appropriate security procedures must be established to ensure public health and safety." These decommissioning monitoring procedures apply to both categories of SAFSTOR described above.

SAFSTOR satisfies the requirements for protection of the public while minimizing, in various degrees, the initial commitments of time, money,

occupational radiation exposure, and regulated waste disposal site space. This advantage is offset somewhat by the need to maintain the amended nuclear license, thus contributing to the number of sites dedicated to radioactivity confinement for an extended time period.

Considerations of radiation dose, cost, and the desirability of terminating the license may influence the kind of preparation and the kind and length of the storage period, at the choice of the licensee, with approval of the NRC. A decision to chemically decontaminate contaminated piping systems during the period of preparations for safe storage depends largely on the cost and anticipated length of the storage period. If, for example, the principal cause of high radiation dose rates in a research or test reactor after reactor shutdown is ^{60}Co, a chemical decontamination that achieves a final radioactivity level of one-tenth the original level (decontamination factor of 10) is equivalent to a storage (decay) period of approximately 17.5 years. Similarly, a 50-year period of storage makes possible a large reduction in personnel exposure and a significant decrease in the need for remote or shielded operations during deferred decontamination. In addition, much of the radioactive contamination in the facility will decay to releasable levels during a lengthy ($\geq$110-year) storage period, thus greatly reducing the volume of material requiring disposal and possibly permitting recycle of valuable materials back into commercial channels. Depending on the research or test reactor facility and its operating history, the necessary final actions can range from a radiation survey to show that radioactivity has decayed to acceptable levels, to decontamination and removal of residual radioactive materials. These latter actions, whatever their scale, constitute deferred decontamination.

To terminate the nuclear license, even after a storage period of 100 years, dismantlement of all originally contaminated systems may be required to demonstrate that the facility can be released for unrestricted use. In addition, it is anticipated that any reactor vessel internals that contain ^{59}Ni and ^{94}Nb will have to be removed, packaged, and transported to a regulated waste disposal site.

4.1.3 Definition of and Rationale for ENTOMB

ENTOMB means to encase and maintain property in a strong and structurally long-lived material (e.g., concrete) to assure retention until all radioactivity decays to levels which permit release of the property for unrestricted access. The amount and the half-life of the residual radioactive material in the facility to be entombed determines the time period that the integrity of the structure must be assured. Further, ENTOMB means to include the entire process of first entombing and then continuing some surveillance to assure the integrity of the structure until the encased material is confirmed to have decayed enough to allow unrestricted release. ENTOMB also requires a nuclear license to remain in force. The facility and site preparations include comprehensive cleanup and decontamination outside of and confinement of nonreleasable materials within the encasement structure. Continuing care activities are minimal.

In previous studies,[1,2] we have examined two approaches to ENTOMB: 1) the reactor vessel internals, some of which have extremely long-lived radioactivity, are removed and shipped to a nuclear waste repository, and 2) the reactor vessel internals are left in place. In each case, as much of the radioactive equipment outside the primary containment barrier as possible is consolidated and entombed within. In the first case, because of the relatively short half-lives of the entombed radioactivity, it may be possible, without dismantling the structure, to terminate the amended nuclear license and release the entombment structure for unrestricted use after an extended continuing care period. However, present regulations and regulatory guidance do not allow such action without a comprehensive survey to establish that radioactive contamination is within a level acceptable for releasing the facility for unrestricted use. In the second case, existing regulations require the amended nuclear license to remain in force for an indefinite period of continuing care for as long as the reactor vessel internals are entombed.

According to present regulations, either ENTOMB approach requires dedication of the site as a radioactive waste burial ground. In the second case, with the reactor internals and its long-lived activation products entombed, the security of the site could not be assured for the thousands of years necessary for radioactive decay, so this approach is not viable. In the first case,

with the reactor internals removed, it may be possible to release the site for unrestricted use at some time within the order of a hundred years, if calculations demonstrate that the radioactive inventory has decayed to acceptable residual levels. Therefore, the first ENTOMB approach is the only one examined in this study for conceptually decommissioning the reference R&T reactors via the ENTOMB alternative.

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

The Environmental Protection Agency (EPA) is developing generally applicable environmental protection criteria for management of all radioactive wastes that will impact NRC decommissioning standards and guidelines. In a background report entitled Considerations of Environmental Protection Criteria for Radioactive Waste,[4] the EPA proposes a criterion limiting reliance on institutional controls to a finite period of time. The EPA suggests that the use of institutional control to protect the public from hazards in retired nuclear facilities should be limited to a period of 100 years at most and preferably to less than 50 years. After the allowable institutional care period is over, the site would have to meet radioactive protection levels established for release for unrestricted use.

Extrapolating from the intent of Regulatory Guide 1.86, a nearly identical branch position relating to non-reactor facilities,[5] and the EPA-proposed criteria,[4] it is concluded that any "permanently" entombed structure must be designed to outlast any contained radiological or chemical hazard to man, or be designed perhaps to dilute these hazards to innocuous levels as the structure disintegrates. Unless the structure is to be re-entered later and decommissioned further, potential radiological and chemical hazards should be

reduced to acceptable levels in no more than about 100 years, in order to fulfill the bases for ENTOMB. Taking no credit for the dilution effects of entombment, these criteria and guidance virtually prohibit entombing any nuclear facility containing long-lived radionuclides or toxic chemical elements.

In addition, while it is reasonable to assume that man can design and construct high-integrity, long-lived surface structures, it is also reasonable to assume that any long-term human controls on or responsibility for that facility will ultimately disappear and that the long-lived radionuclides, chemicals, or toxic elements contained therein will ultimately be dispersed into the environment. The ENTOMB alternative also results in the proliferation of decommissioned plant sites containing residual radioactivity. As mentioned earlier in Section 1, no licensed R&T reactors have been entombed to date. ENTOMB is considered to be an especially unlikely choice of decommissioning alternative for university reactors, in particular, where space is at a premium. While the historical data offers some guidance, by itself it does not necessarily preclude ENTOMB as a viable decommissioning alternative for R&T nuclear reactor facilities. Therefore, ENTOMB is included in this study for completeness for both of the reference R&T reactors.

4.2 CONSIDERATIONS IN SELECTION OF DECOMMISSIONING ALTERNATIVES

Many considerations must be taken into account in choosing the appropriate decommissioning alternative for a specific situation. This section, while not purporting to be a complete discussion of all the considerations, discusses five broad, interrelated categories: economic, licensing, societal, safety, and schedule.

4.2.1 Economic

While safety during decommissioning is the principal concern of the NRC, economic matters are a significant consideration to the licensee and/or owner of a nuclear research or test reactor facility. The following factors that control the economy of decommissioning are discussed:

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

4.2.1.1 Property Utilization Potential

The potential use for a deactivated research or test reactor facility site may be a principal economic concern. Particularly for a university research reactor, the need to reuse space may be the paramount factor in deciding the optimum alternative of decommissioning. For a test reactor, the site is certified for industrial purposes, while for both nuclear R&T reactors the structures and systems are licensed for research and testing activities. As such, they represent a significant investment in time and money.

Nuclear R&T reactors are atypical by their very nature; consequently, plans for retrofitting and/or refurbishing of their systems or their reactor cores to meet code requirements to facilitate the reactivation of the facility for another nuclear reactor purpose historically has not been cost effective. Therefore, if reactivation is neither possible nor desirable, potential uses for other purposes could dictate the optimum alternative of decommissioning.

4.2.1.2 Staffing

A sufficient number of properly trained and skilled personnel is a significant cost factor in decommissioning. For decommissioning activities that commence immediately following final reactor shutdown, it is desirable to draw the personnel from the ranks of the plant operating staff. These personnel are very familiar with the structures, systems, radiation work procedures, and specific areas of radiation exposure potential. Specifically, supervisory personnel, health physics personnel, maintenance craft personnel, and personnel trained in conventional decontamination methods and in the

operation of the systems required during decommissioning should be recruited prior to plant shutdown. In general, each of these positions at a test reactor is filled by a highly qualified professional, so offsite recruiting of personnel for the decommissioning planning and preparation is not required. The supervisory personnel are largely responsible for formulating the plans and for making the preparations for decommissioning, and, therefore, should be available to begin these duties approximately 2 years before plant shutdown. The other personnel should be available as necessary to augment the planning and preparation effort, to become trained in the operation of any special decommissioning equipment, and to implement the plans.

On the other hand, the supervisory personnel at university research reactor facilities do not have a captive work force trained in radiation work procedures. Personnel transferred from the university maintenance department or hired from outside labor pools will probably require training in radiation work procedures as well as in special equipment operation, and this will constitute an added expense.

For decommissioning activities performed a significant length of time after final reactor shutdown (e.g., for the six test reactors currently in SAFSTOR), personnel must be selected from elsewhere within the organization or from the outside labor pool. Again, training becomes a cost factor. Alternatively, the job could be contracted with a firm that specializes in decommissioning work.

4.2.1.3 Radioactive Waste Considerations

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

A current major concern of nuclear facility owners is the availability of space in nuclear waste disposal sites.[6] Another concern is the location and accessibility of operable nuclear disposal sites. The cost of shipping decommissioning wastes to disposal sites is determined in part by the distance traveled and in part by the requirements imposed by states through which the radioactive materials must travel.

Although federal agencies dominate the regulatory process in the shipment of radioactive materials, state highway departments regulate gross vehicle weights and dimensions as well as some other aspects of radioactive shipments. Currently, about half of the states have adopted the DOT Hazardous Materials Regulations to cover intrastate radioactive materials shipments. In addition, several states have adopted or proposed additional regulations for other aspects of radioactive materials shipments.[7,8] These aspects include:

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

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

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

4.2.1.4 Planning and Preparation Requirements

The cost of preparing the detailed decommissioning plans, the technical specifications, the safety analyses, and the documentation may be different for each of the decommissioning alternatives and should be considered. For example, a decommissioning plan is required for DECON and ENTOMB,[3] but for the first phase of SAFSTOR (preparations for safe storage), a less comprehensive initial plan is acceptable. A decommissioning plan is required prior to deferred decontamination (the final phase of SAFSTOR).[3]

4.2.1.5 Taxation

Taxation is not a decommissioning consideration for the reference R&T reactors used in this study because they are located on state and federal land, respectively. This is true for the majority of the licensed nuclear R&T reactor facilities. For those few exceptions, the way that the facility is viewed by the local taxing authorities for property tax purposes could be an influential factor both in the choice of the decommissioning alternative and in the time frame for decommissioning. A discussion of taxation considerations is given in Reference 2.

4.2.1.6 License and Insurance Fees

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

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

The cost of nuclear liability insurance depends on the level of coverage required by the NRC as proof of financial protection during decommissioning. If the level must remain the same regardless of the facility condition (which is unlikely), timely termination of the nuclear license would be the prudent alternative.

4.2.1.7 Funding Availability

Regardless of the rate of progress made during decommissioning there are certain fixed costs (i.e., salaries, services, utilities, and maintenance) that must continue once the decommissioning project begins. For example, if insufficient funding were to delay decommissioning activities, these fixed costs, plus the effect of inflation over the delay period, would increase the overall decommissioning cost. Therefore, for these reasons as well as for safety reasons, it is important that sufficient funds are available to complete the planned decommissioning activities as scheduled.

4.2.2 Licensing

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

Termination of a nuclear license is conditional on the removal and proper disposal of radioactive materials that cannot be released for unrestricted use. While the higher occupational radiation exposure from DECON is less desirable than the other alternatives, the requirements and responsibilities of maintaining the license and the problems of increased numbers of sites dedicated to radioactivity confinement may overshadow the exposure aspect and make this alternative desirable. The dynamic nature of government regulations may also make termination of the license desirable, since regulations concerning decommissioning could change over a safe storage or entombment period.

Another aspect of licensing that must be considered is the license duration and the license renewal process and cost. Nuclear reactor licenses are presently subject to a 40-year time limit, at which time they must be renewed. If the nuclear reactor is in safe storage or entombment at the end of the license time limit, the already amended nuclear license may need to be renewed

or extended. The renewal review requirements comprise financial, safety and environmental considerations similar to those for a license amendment. The costs of documenting these considerations and the NRC review costs for each required license renewal must be taken into account when choosing the decommissioning alternative.

4.2.3 Societal

Another consideration is that of public acceptance of the long-term presence of a retired nuclear facility. There is a reasonable probability that, once the facility is shut down, the public may view the facility structures as an eyesore, as a perceived hazard, or as an unproductive use of an otherwise useful site. Thus, pressures may mount for the removal of the retired structures, especially on university sites. While it is beyond the scope of this study to evaluate the likelihood of this concern, the facility owner should sample local public opinion on this question well in advance of setting his plans for decommissioning.

In addition, the NRC presently desires to minimize the number of sites permanently committed to the containment of radioactive materials. Existing regulations allow the various decommissioning alternatives detailed in Section 4.1. It should be recognized, however, that regulations are dynamic in nature and are subject to societal pressures; and, even though new regulations or changes to present regulations may never forbid the use of a particular decommissioning alternative, they could discourage or make impractical its use.

4.2.4 Safety

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

4.2.4.1 Radiation Protection

In decommissioning the reference research reactor, fuel unloading is the prime contributor to the total accumulated occupational radiation dose. ^{60}Co is the prime contributor in decommissioning both the reference test reactor and, to a much lesser degree, its colocated research reactor, since this isotope heavily influences the degree of shielding and remote operations necessary to control external dose rates. In any case, each decommissioning alternative results in a different accumulated occupational radiation dose because of different exposure requirements.

Dose rates at the reference test facility, largely determined by the amount and decay of ^{60}Co, decay to approximately 10% of the original shutdown values after about 17.5 years and to 1% after about 35 years, assuming no decontamination. Therefore, deferring the major decommissioning activity by even 17.5 years can produce a decrease in potential accumulated occupational radiation dose. This depends, of course, on the required decommissioning activities prior to that point in time and those remaining activities necessary to complete the license-termination process. Relatively little reduction in total accumulated occupational radiation dose is assumed to result from deferring decontamination beyond 30 years after placing commercial LWRs in SAFSTOR (Reference 1, p. 11-21 and Reference 2, p. 11-15). This is also assumed to be the case for the reference test reactor.

Radiation safety starts with a health physics radiation protection program under the cognizance of a radiation safety officer and a decommissioning safety committee. Health physics personnel provide complete support and health physics supervision at the site when decommissioning activities are in progress. These services include, but are not limited to, safe work permits, radiological control-zone posting, personnel dosimetry and bioassay, protective clothing and respiratory protective device service, facility and equipment decontamination, personnel decontamination, handling of contaminated injuries, radiation exposure records, liquid effluent and gaseous effluent monitoring and control, environmental surveillance, and all the associated industrial hygiene, safety and health physics tasks. This close attention continues throughout the decommissioning operations to ensure that discharges of gaseous and liquid wastes

to the environs are minimized and that all releases of radioactivity will be not only lower than the limitations proposed for the decommissioning alternative selected, but as low as reasonably achievable (ALARA).

The radiation protection goal is to minimize radiation doses whenever reasonably achievable. All activities where the decommissioning worker must enter radiation zones are planned ahead of time to minimize exposures. When tasks result in significant radiation exposures, a postoperation review of the job is made with the workers to identify how procedures can be changed to reduce subsequent exposures when performing similar tasks in the future. Training reinforces the principles of radiation protection to the worker. The ALARA program is an integral part of the written radiation protection procedures and guides. Personnel are made cognizant of and instructed in management's commitment to implement ALARA, what ALARA means, why it is recommended, and how to implement it on the job.

At universities in particular, where a trained, captive work force is usually not the norm, additional ALARA training and on-going emphasis during decommissioning will probably be required. This additional training will constitute an added expense.

Solid radioactive wastes are packaged and shipped in accordance with applicable NRC and DOT regulations. Containers awaiting shipment may be stored onsite in specified, secure, posted areas. All radioactive waste shipments are by common carrier or contract carrier and exclusive use of vehicle. Disposal is at NRC-licensed commercial disposal sites. Records are maintained of the content and disposition of every waste container leaving the site.

Entry to the reference R&T facilities is controlled by security personnel during operating hours. During non-operating hours the R&T facilities are locked and continuing around-the-clock security surveillance is provided. All personnel entering the reference R&T reactor facilities are admitted under security surveillance and the radiation dosimetry identity badge they are issued must be worn at all times when within the reference facilities. Strict visitor controls are maintained. In addition, heavy equipment and vehicle entries and exits are controlled. No equipment or materials are allowed to be removed

from the reference R&T reactor sites without health physics clearance. All of the above security controls are assumed to remain in effect until all R&T reactor-originated radioactivity is removed from the reference R&T reactor facilities.

4.2.4.2 Industrial Safety

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

The requirements of Title 29, CFR 1910, "Occupational Safety and Health Standards," establish the requirements for employers to provide a safe place to work. Where extensive decommissioning activities involving dismantling is planned, the use of a professional safety engineer for assistance in developing standard operating and working procedures to assure compliance with 29 CFR 1910 is essential.

Decontamination and dismantling work performed within work-site containment envelopes may create a toxic atmosphere that requires the wearing of breathing air supply equipment. The Airborne Radiation Protection Standards of 10 CFR 20 are invoked by 29 CFR 1910. The nonradioactive protection standards included in 29 CFR 1910.1000, "Air Contaminants," defines the airborne limits for the gases, vapors, fumes, dusts, and mist that could be generated in decommissioning.

In general, licensed research reactors are owned by states or private institutions, whereas test reactors are usually owned by government or industry. When the test reactor and the site is owned by the federal government, local and state laws are not necessarily applicable to activities conducted within the confines of the facilities. Usually, however, the operating agency maintains a policy of complying with the intent of state and local laws such as construction standards, elevator, boiler and crane inspection, health and safety standards, and

effluent control limitations. The majority of regulations pertaining to decommissioning activities at all licensed nuclear R&T reactors, however, are those issued by the Nuclear Regulatory Commission, the Department of Transportation, the Labor Department, Occupational Safety and Health Administration, and the Environmental Protection Agency.

4.2.4.3 Environmental Safety

Many of the environmental effects of R&T reactor operation will also be evident during decommissioning, but in most cases at greatly diminished levels. The environmental effects that pertain to decommissioning are radiation exposure, liquid and airborne radioactive release, and solid radwaste disposal. No thermal discharges are anticipated during decommissioning from either the reference research reactor or the reference test reactor.

At final shutdown of the reference R&T reactors, significant volumes of water requiring disposal are anticipated to be present. In each case, some of these volumes are in presumably noncontaminated systems and, after sampling, can be released directly to the environs. Others, notably those contained in the R&T reactor vessels, the reference test reactor spent fuel pool, etc., are contaminated in varying degrees and may require processing through a liquid radwaste treatment system prior to discharge.

For both of the reference R&T reactors, airborne radioactive releases that result from normal decommissioning activities are small. Of the various decommissioning alternatives, SAFSTOR releases the least amount of airborne radioactivity.

DECON generates larger amounts of solid radioactive wastes that require disposal offsite than the other alternatives. ENTOMB produces less waste for offsite disposal, although the entombed structure becomes a waste disposal site, and SAFSTOR (including deferred decontamination) produces the least waste. The principal environmental impact of solid radioactive waste disposal is the land area that must be committed to this activity. In addition, shipping these wastes to the disposal site produces the normal transportation noises, exhaust noises, exhaust fumes, and radiation doses to the drivers and to persons along the transportation routes.

4.2.5 Schedule

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

REFERENCES

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

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

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

4. Considerations of Environmental Protection Criteria for Radioactive Waste, EPA Docket No. PR-30, 40, 50, 70 (43 FR 10370), August 1978.

5. Guidelines for Decontamination of Facilities and Equipment Prior to Release for Unrestricted Use or Termination of Licenses for By-Product, Source, or Special Nuclear Material, U.S. Nuclear Regulatory Commission Draft Guide, November 1976.

6. L. C. Owen, "Current Solid Radwaste Concerns," Trans. Am. Nucl. Soc. 30:557, November 1978.

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

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

5.0 REVIEW OF LICENSED RESEARCH AND TEST REACTORS DECOMMISSIONING EXPERIENCE

The decommissioning of nuclear research and test (R&T) reactor facilities is a relatively well-developed technology in the United States. As of late 1979, forty licensed R&T reactors (34 research reactors and 6 test reactors) have been either decommissioned, were undergoing decommissioning, or were scheduled for decommissioning.[1] Twenty-six of the research reactors have been decommissioned via DECON, while the remaining eight are in safe storage pending authorization to dismantle. All six test reactors are in safe storage, with one having received authorization to dismantle. These experiences demonstrate that the basic technologies for decontamination and dismantlement of these types of nuclear R&T reactor facilities are well-established and that they need only to be modified as necessary to suit site-specific conditions.

The information available about R&T reactor decommissionings is summarized in subsequent subsections, together with brief discussions of the lessons learned and the ongoing experience being developed at other reactor facilities in the United States.

5.1 DECOMMISSIONING EXPERIENCE WITH LICENSED RESEARCH REACTORS

Information on past nuclear research reactor decommissionings that resulted in license termination is presented in Table 5.1-1. Regulatory Guide 1.86 has been used for guidance on surface contamination with activation and soil contamination limits evaluated on a case basis. Experience in dismantling to date indicates that the licensee has been required to show through analysis that radiation exposures to any member of the public would be a small fraction of 10 CFR 20.105 limits for activated materials and soil contamination. The licensee has also been required to demonstrate with cost benefit analysis that the residual radioactivity was as low as reasonably achievable.[1] Research reactors in safe storage with amended nuclear license are listed in Table 5.1-2. Most of the information is derived from References 2, 3, and 4 and from public records located at the NRC Public Document Room, 1717 H Street, N.W., Washington, D.C. Descriptions of selected research reactor decommissionings follow.

TABLE 5.1-1. Dismantled Research Reactors (License Terminated)

Docket No./Reactor	Thermal Power	Location	Years of Operation/ Existence	License No. (Date of Application for Amended License) Date License Terminated	Disposition or Facility Structural Condition
50-1/Illinois Inst. of Technology (Water Boiler Research)	100 kW	Chicago, IL	1956-1967	R-3 (8-12-71) 4-28-72	The reactor was dismantled and shipped to another location. The specifics are not available at this time.
50-4/USN Research Lab, Pool Type w/beam ports & Thermal Column	1 MW	Washington, DC	1956-1970	R-5 (6-17-70) 3-18-71	The reactor was dismantled. The building is currently in non-nuclear use.
50-8/N.C. State (Aqueous Homogeneous) 50-241 (NCSCR-4)	100 W	Raleigh, NC	1959-1963	R-1 (8-23-65) 9-07-66	The reactor was shipped from North Carolina State University, Raleigh, North Carolina to Mississippi State University. It was never reassembled. Mississippi State University has received permission to dispose of it properly.
50-17/Industrial Reactor Labs (pool type)	5 MW	Plainsboro, NJ	1958-1975	R-46 (6-12-75) 11-04-77	When the reactor was decommissioned, all salable items were sold. The reactor was then bulldozed. The radioactive components were buried.
50-43/U.S. Naval Post-Graduate School (AGN-201, Serial 100)	0.1 W	Monterrey, CA	1957-1971	R-11 (--)[(a)] 10-11-72	Moved to California State Polytechnic College, San Luis Obispo. (See Docket No. 50-394, Table 5.1-2.)
50-50/North American Aviation (L-47 homogeneous)	5 W	Canoga Park, CA	1957-1958	R-19 (--) 6-30-58	Model L-47 reactor was dismantled.
50-58/Oklahoma State University (AGN-201, Serial 102)	0.1 W	Stillwater, OK	1957-1974	R-22 (6-26-71) 3-19-74	
50-60/U.S. Navy Hospital (AGN-201M, Serial 105)	5 W	Bethesda, MD	1957-1962	R-27 (--) 6-24-65	The reactor was transferred to Docket No. 50-21, New York University.
50-64/University of Akron (AGN-201, Serial 104)	0.1 W	Akron, OH		R-24 (2-09-67) 10-09-67	The reactor and fuel were transferred to Georgia Institute of Technology and a 4-inch concrete floor was poured over the reactor pad.
50-84/University of California (AGN-201, Serial 112)	0.1 W	Berkeley, CA		R-30 (--) 8-23-66	The reactor was transferred to the University of New Mexico.

TABLE 5.1-1. (Contd)

Docket No./Reactor	Thermal Power	Location	Years of Operation/ Existence	License No. (Date of Application for Amended License) Date License Terminated	Disposition Or Facility Structural Condition
50-98/University of Delaware (AGN-201, Serial 113)	0.1 W	Newark, DL	1958-~1977	R-43 (1-18-78) 2-26-79	
50-101/Gulf United Nuclear (Pawling Lattice Test Rig)(b)	100 W	Sterling Forest, NY	1958-~1971	R-49 (10/73) 6-25-74	
50-106/Oregon State Univ. (AGN-201, Serial 114)	0.1 W	Corvallis, OR	1959-1974	R-51 (--) 03/79	The reactor is crated awaiting shipment to a potential customer.
50-114/William March Rice University (AGN-211, Serial 101)	15 W	Houston, TX	1959-1965	(--) 9-26-67	
50-122/University of Wyoming (L-77), Solution-Type Reactor (UWRR)	10 W	Laramie, WY	1959-1974	R-55 (--) 12-05-74	The reactor was dismantled. The fuel was shipped to Atomics International, Canoga Park, California. Some non-nuclear parts were shipped to Ocala Junior College, Ocala, California. The reactor was housed in an engineering building on campus, which is now being used for non-nuclear purposes.
50-216/Polytechnic Inst., NY (AGN-201M, Serial 105)	0.1 W	Bronx, NY	1957/67-1973	R-105 (--) 12-21-77	The reactor was dismantled. The building is currently in non-nuclear use.
50-135/Walter Reed Medical Center (L-54) Homogeneous Solution (WRRR)	50 kW	Washington, DC	1962-1971	R-85 6-3-71 7-26-72	
50-167/Lockheed, Pool-Type	10 W	Dawsonvile, GA	7-22-60-9-1-60	(--) 9-01-60	The reactor was dismantled and shipped to South America for exhibition purposes.
50-172/Lockheed (Radiation Effects Reactor)	3 MW	Dawsonville, GA	1958-1970	R-86 (4-12-71) 8-31-71	Prior to 1962, the reactor was operated by the Aircraft Nuclear Propulsion Program. On termination of this program, Lockheed took over operation until 1970. The building was destroyed and the reactor was buried.

TABLE 5.1-1. (Contd)

Docket No./Reactor	Thermal Power	Location	Years of Operation/ Existence	License No. (Date of Application for Amended License) Date License Terminated	Disposition Or Facility Structural Condition
50-202/University of Nevada (L-77)	10 W	Reno, NV	1963-1974	R-91 (7-25-73) 12-24-75	Reactor transferred to University of California, Santa Barbara.
50-212/General Dynamics Fast Critical Assembly	500 W	San Diego, CA	1964-1965	R-96 (2-1-65) 3-05-65	
50-227/General Atomic Co. (TRIGA Mark III)	1.5 MW	San Diego, CA	1965-1973	R-100 (3-25-75) 12-10-75	The water and tank are still in use for other radiation experiments. The reactor grid plates and support structure are sitting at the side of the tank. No reactor fuel remains in the tank.
50-235 Gulf General Atomic (APFA)	500 W	San Diego, CA	1965-1967	R-99 (--) 10-22-69	
50-240/Gulf General Atomic (Modified HTGR)	100 W	San Diego, CA	1966-	R-104 (--) 4-02-73	
50-253/Gulf Oil Corp. (APFA III)	500 W	San Diego, CA	1967-1973	R-105 (--) 8-10-73	The General Atomic Company, San Diego, California, operated the reactor as the Accelerator-Pulsed Fast Assembly (APFA-III) during 1967-1973. The equipment was then returned to the Lawrence Livermore Laboratories. Information about the reactor's whereabouts and operating status during 1964-1967 is not available.
50-310/NUMEC and Commonwealth of PA (C-W Reactor)(c)	1 MW	Quehanna, PA	1958-1966	R-72 (--) 12-02-71	The reactor was dismantled and shipped to various locations.

(a) Information not available.
(b) Heavy water moderated and reflected and 1 ft of graphite located outside the aluminum core tank.
(c) C-W is Curtis-Wright Corp.

TABLE 5.1-2. Research Reactors in Safe Storage with Amended Nuclear Licenses

					Decommissioned Facility Data		
Docket No./Reactor	Thermal Power	Location	Years of Operation/ Existence	License No. Present Status	Facility Structural Condition	Maintenance and Surveillance Prog.	Remarks
50-6/Battelle Memorial Institute Pool Type	2 MW	Columbus, OH	1956-1974	R-4 Dismantling Plans Being Developed	The reactor is intact. All reactor-related equipment is removed.	Quartery surveys. Sump effluent is monitored continuously.	Decommissioning Date 10-30-75
50-47/Watertown Arsenal U.S. Army, Pool Type	5 MW	Watertown, MS	1960-1970	R-65 Dismantling Plans Being Developed	The reactor is intact. Fuel is removed. Building is under periodic surveillance and maintenance.		
50-94/Rockwell Inter. Corp. L-77	10 W	Canoga Park, CA	1958-1974	R-40 Dismantling Authorized 9/78.			
50-106/Oregon State Univ. (AGN-201, Serial 114)	0.1 W	Corvallis, OR	1958-1978	R-51 Dismantling Authorized 3/79	The reactor is crated and awaiting shipment to a potential customer.		
50-111/North Carolina State Pool Type	10 MW	Raleigh, NC	1960-1973	R-63 Dismantling Order Issued 6-1-81	The reactor is intact. The fuel is removed and stored onsite. The building is currently being used as a laboratory.		Amended License Requested 12-2-72 & 11-2-73 (Rev.) Granted: 3-18-74
50-129 West Virginia Univ. (AGN-211, Serial 103)	75 W	Morgantown, WV	1959-1972	R-58 Dismantling Order Issued 1-22-80	The reactor is subcritical, with two fuel elements placed in storage. Ten elements remain in the core.		
50-141/Stanford Univ. Pool Type	10 KW	Stanford, CA	1959-1974	Dismantling Authorized			
50-185/NASA MOCK-UP Pool Type (NASA-MUR)	100 kW	Sandusky, OH	1963-1973	R-93 Dismantling Order Issued 5-26-81	Decommissioned by placing in safe storage. All systems, support hardware, etc., remain intact. License amended to possession only.	Routine inspections, maintenance, and security checks to ensure facility is maintained in the required conditions.	
50-394/Calif. Polytechnic State Univ. (AGN-201 Serial 100)[(a)]	0.1 W	San Luis Obispo, CA	1971-1978	R-121 Dismantling Plans Being Developed	Excellent and intact.	General surveys and wipe tests on sealed startup sources are conducted at 6-month intervals.	

(a) California State Polytechnic College, San Luis Obispo, CA, in December 1971, received a permit to relocate AGN-201-100 and operate it on CSPC's Campus. The unit previously was operated starting in 1956 at the Naval Postgraduate School, Monterey, CA (See Docket No. 50-43, same reactor).

5.1.1 Walter Reed Research Reactor, Washington, D.C.

The Walter Reed Research Reactor was dismantled in 1971. The facility was an Atomics International Model L-54 homogeneous-fuel reactor having a maximum operating power of 50 kWt. The reactor was surrounded by a four-story research institute and was housed 6 m below ground with only limited access via elevators. Heavy duty cranes and equipment could not be used.

The aqueous and solid fuel was removed in special containers. Recombiner unit water and decontamination solutions were solidified in vermiculite and shipped in shielded stainless steel drums.

A Darda rocksplitter was used to demolish the thick, dense-concrete biological shield.[5] This tool is a hydraulic device that, when inserted into drilled holes, generates very high lateral pressures to establish fracture planes. Conventional road-surface breakers were then used to separate the concrete. Normal research institute operations continued almost uninterrupted during dismantlement and decontamination. Radioactive materials were removed at night and on weekends.

No information was obtained on costs or on radiological experience. A brief review of the reactor dismantlement is given in Reference 6.

5.1.2 Industrial Reactor Laboratories' Facility, Plainsboro, NJ

The Industrial Reactor Laboratories' pool-type research reactor had a maximum operating power of 5 MWt. The research facility contained activated and/or contaminated beam tube thimbles, pneumatic rabbit system pool extensions, a thermal column, underground primary system piping, a waste evaporator, a catch basin (where contaminated soil had to be removed), waste piping external to the facility proper, laboratory hoods, and hot cells.

Packaged and radioactive waste that was generated during the dismantling project was transported by truck to authorized low-level waste burial sites in Richland, Washington; Barnwell, South Carolina; and Morehead, Kentucky. Forty-eight truck shipments of radioactive waste material ($\sim$680 m^3 weighing 678 Mg) were completed.

The decommissioning to unrestricted use status took approximately 2 years at a cost of less than $1 million (1977 dollars).

5.1.3 Oregon State University's AGN-201 Reactor Facility, Corvallis, OR

The Oregon State University's AGN-201, Serial 114 research reactor had a maximum design operating power of 0.1 W. The room that housed the AGN-201 is approximately 10.7 m long and 9.1 m wide. It is located in the northeastern corner of the Radiation Center Building, adjacent to the TRIGA Reactor Building.[a]

The schedule and the necessary approvals for dismantling were submitted in an application dated March 8, 1979. The AGN-201 dismantling was conducted between June 10 and 20, 1980, and costs to dismantle and transfer reactor components to another university were estimated to be less than $10,000. Currently, the reactor is crated and awaiting shipment to a potential customer.

With the exception of the expected radiation levels detected on the fueled core can and control rods (0.5 to 10 mrem/hr), no radiation levels or radioactivity above normal background levels were detected on reactor components, associated electronic and laboratory equipment, or on floor surfaces in the facility.

5.2 DECOMMISSIONING EXPERIENCE WITH LICENSED TEST REACTORS

Currently there are eight test reactors licensed in the U.S. The test reactors are listed in Table 5.2-1 by their NRC docket number, thermal power level, location and present licensing status. Six of the eight test reactors are in safe storage with an amended nuclear license and two are operational. The operational power levels range from 6 to 60 MW thermal. Descriptions of selected decommissionings of licensed test reactors are given in subsequent subsections.

(a) The Oregon State University TRIGA reactor is the reference research reactor for this study and is described in Section 8 and Appendix B of this report.

TABLE 5.2-1. Test Reactors Licensed in the U.S.

NRC Docket No./Reactor	Thermal Power	Location	Years of Operation/ Existence	Present Status	Disposition
50-22/Westinghouse Test Reactor	60 MW	Waltz Mill, Pennsylvania	1959-1962	Amended Nuclear License (NRC)	Annual survey and structural inspection. Plant container is locked; site under continuous guard.
50-30 NASA Plum Brook Test Reactor	60 MW	Sandusky, Ohio	1961-1974	Dismantling Order Issued, May 26, 1981	Since early-1973 the facility has been maintained in safe storage (see Section 5.2.1).
50-70/General Electric Test Reactor	50 MW	Alameda County, California	1958-1977	Operational (currently shut down)	Not Applicable.
50-146/Saxton PWR Test Reactor	28 MW	Saxton, Pensylvania	1962-1972	Amended Nuclear License (NRC)	See Section 5.2.2 for decommissioning information.
50-183/GE EVESR Exp. Superheat Test Reactor	17 MW	Alameda County, California	1963-1967	Amended Nuclear License (NRC)	See Section 5.2.3 for decommissioning information.
50-184/National Bureau of Standards Test Reactor	10 MW	Gaithersburg, Maryland	1967-	Operational	Not Applicable.
50-200/B&W BAWTR Test Reactor (Open Pool Type)	6 MW	Lynchburg, Virginia	1964-1971	Byproduct License (NRC)	The reactor has been dismantled. The building is in non-nuclear use.
50-231/SEFOR Sodium Cooled Test Reactor	20 MW	Strickler, Arkansas	1969-1972	Byproduct License (state)	See Section 5.2.4 for decommissioning information.

5.2.1 NASA Plum Brook Reactor Facility, Sandusky, OH

The Plum Brook Reactor Facility (PBRF) in Sandusky, Ohio, is owned by NASA and consists of the 60-MWt Plum Brook Test Reactor and the 100-kWt Plum Brook Mock-Up Reactor (MUR). Both reactors have been shut down since January 1973 and all fuel has been removed from the site. As previously described in Section 1, the PBRF is used as the reference test reactor facility for this study.

The Plum Brook Test Reactor is a heterogeneous light water cooled and moderated reactor that used MTR-type fuel. Since 1973 the reactor has been maintained in safe storage. In addition to removing all fuel from the site, all resins were removed, the reactor vessel and all piping systems were drained, and areas with high radiation were shielded and sealed. Fuel storage canals have been cleaned and drained and hot drain systems and sumps have been flushed and kept dry.

Access control has primarily involved the use of existing doors, fences, shielding, intrusion alarms and security personnel. For instance, doors to the Containment Building, subpile room and hot cells are locked and the keys administratively controlled. Radiation surveys and sampling are performed quarterly to verify retention of radioactive material in controlled areas. The integrity of physical barriers is verified by routine security guard checks and monthly inspections.

In 1977 NASA considered a plan for entombing the Plum Brook Test Reactor with monitoring for a limited period of time to assure that entombment structures were adequately retaining the radioactivity. This plan was not pursued, however, in view of the possibility that the license would remain in effect and some monitoring would be required as long as any radioactive material, above levels acceptable for release to unrestricted access, remained onsite.

The MUR is a pool-type reactor that duplicated the Plum Brook Test Reactor in core characteristics but operated at a maximum power level of only 100 kWt. The MUR was used for verifying nuclear characteristics of in-core experiments before they were placed in the test reactor. In addition to removing the fuel, all water has been drained from the reactor pool. The radiation level near

the remaining core components is approximately 100 mR/hr. Access to the pool area is controlled by locked doors and radiation signs.

NASA is now developing plans for dismantlement of both reactors at the facility. Buildings and structures will be retained to the extent allowable but all radioactive material will be removed from the site. The major residual activity is in the reactor vessel and reactor vessel internals of the 60-MW test reactor. NASA estimates that this inventory consists primarily of 156,000 curies of ^{60}Co in the reactor vessel and internals and 7,340 curies of ^{55}Fe in the reactor vessel and internals. The reflector segments and other reactor internals will be detached, removed, and disposed of prior to remotely cutting up the reactor vessel. Dismantling of the 100-kW MUR will involve disposal of much smaller amounts of induced activity in the reactor internals.

5.2.2 Saxton Nuclear Experimental Facility, Saxton, PA

The Saxton plant was a 28-MWt prototype pressurized water power reactor that supplied steam to an existing 10-MWe turbo-generator. The reactor was located in the Saxton Steam Generating Station of the Pennsylvania Electric Company and was operated by the Saxton Nuclear Experimental Corporation (SNEC). The facility was placed in passive safe storage. SNEC was responsible for all decommissioning activities, including those of contractors. These activities were carried out in accordance with written procedures approved by SNEC. Safe storage activities were completed during 1973.

Prior to decommissioning, an extensive planning program was carried out that included:

- performing an assessment to determine the optimum way of decommissioning the plant
- preparing the decommissioning plan
- obtaining AEC approval of the plan.

Safe storage measures taken include intrusion alarms, welded closures, locked doors, and a security fence. The cost to place the facility into safe

storage was estimated to be about \$0.2 million.[7] Additional information of the planning and licensing for the Saxton facility is given in References 7 and 8.

5.2.3 General Electric EVESR Experimental Superheat Test Reactor, Alameda County, CA

Plant deactivation started in May 1967, with the final shipment of test fuel bundles being completed in August 1967. By Decemeber 1967 the reactor was deactivated. Administrative control of the shutdown facility was reported to be similar to that for an operating reactor, with the General Electric Test Reactor personnel providing for control of the EVESR area, since both reactors share a common site.

The only significant source of radioactivity remaining is in the pressure vessel. In April 1970 GE was authorized to remove the following items from those under control of the license: 1) the dump condenser and the miscellaneous equipment building, 2) the gas-fired boiler, 3) the cooling tower, 4) the stack, and 5) the control room. Amendment 16 to the EVESR license, dated October 16, 1969, authorized a modification to the technical specifications to redefine the plant area in order to allow conduct of non-reactor-oriented activities. The facilities and activities requiring continued regulation are now consolidated into one building.

5.2.4 Southwest Experimental Fast Oxide Reactor (SEFOR), Strickler, AR

The General Electric Company's Southwest Experimental Fast Oxide Reactor (SEFOR) was a 20-MWt sodium-cooled test reactor. The application presented to the U.S. Atomic Energy Commission for authority to decommission SEFOR contained the decommissioning plan to be employed. The objective was to place SEFOR in a condition that would permit surveillance requirements to be greatly reduced and, in addition, would permit releasing part of the 640-acre site for unrestricted occupancy.

With respect to regulatory control, the stated objective was to be accomplished in two phases:

Phase I - Decommission SEFOR to the point at which a by-product license could be obtained from the State of Arkansas. This was

considered to be accomplished when the reactor control system was disabled and all the fuel had been transferred from the site.

Phase II - Obtain a by-product license from the State of Arkansas.

Upon completion of Phase I, General Electric obtained the termination of AEC 10 CFR 50 Provisional Operating License DR-15 with simultaneous issuance of a state by-product material license, thereby initiating transfer of regulatory control from the Atomic Energy Commission to the Arkansas State Health Department.[9]

5.3 LESSONS LEARNED FROM PAST DECOMMISSIONINGS

Past R&T reactor decommissionings have demonstrated some of the aspects of the practicality and acceptability of the various decommissioning approaches. This experience contributes to the foundation for the decommissioning of larger commercial power plants. The necessary technology not only exists, but has been safely and successfully applied numerous times to a wide variety of nuclear R&T facilities. Because of the unique sizes, locations, and conditions under which past decommissionings took place, no two had identical problems or conditions. However, the basic approach to any decommissioning alternative remains virtually unchanged (i.e., gathering the manpower, performing the planning and preparation, and implementing the desired decommissioning operations). This fundamental course of events varies only in the numerous plant-specific refinements applied to the various stages of decommissioning. The area of greatest challenge lies in improving job-specific technology, such as remote cutting equipment, and decontamination and volume reduction techniques.

Past R&T reactor decommissionings provide some insight into the socioeconomic impacts on the local communities, the physical impacts on the environment, and the facility design impacts on the facilitation of decommissioning. In addition, required decontamination and decommissioning development needs often are identified. Some of the more universal needs that have been identified are:

- research into special tool development for cost reduction and improved safety (generally, plant specific)
- research into decontamination of soils
- the development of industry-wide acceptable release criteria
- research into reactor vessel installation engineering which makes provisions for future dismantling (i.e., facilitation for removal)
- research into contaminated waste material volume reduction techniques (wide applicability).

Access control at a decommissioned facility in safe storage has usually involved upgrading or minor modification of existing fences, radiation signs, containment buildings, steel doors, and concrete shielding structures and the use of security personnel from adjacent company facilities. Where security personnel are not available from adjacent facilities, intrusion alarm systems, which are continuously monitored, have been installed to detect unauthorized entry. When continuously manned security coverage is not maintained, the NRC has required that access to high-radiation areas be made very difficult. The NRC has accepted the use of combinations of heavy shielding blocks and welded entry portals for the high-radiation areas in combination with the intrusion alarms. Since all fuel, liquids, and easily movable radiation sources have been removed from the site, access control is used primarily for protecting an intruder from serious overexposure.

Erickson indicates in Reference 1 that annual reports received by the NRC for facilities in safe storage state that there has been no evidence of release of radioactivity to the environment or any unauthorized entry into high-radiation areas. The Office of Inspection and Enforcement of the NRC audits the containment of radioactivity with independent radiation surveys and measurements both inside and outside of the facilities. The NRC has uncovered no material migrating to clean areas in a facility or outside the controlled areas. Some facilities do, however, show some evidence of rusting of carbon steel structures such as water tanks and carbon steel containment buildings. To date, this deterioration has not affected the integrity of the retention of radioactive material, which is largely confined to the activated pressure

vessel, pressure vessel internals, and the primary systems. Also, since the primary systems have all been drained and are essentially at atmospheric pressure, a release of radioactive liquid is not likely to occur. The licensee is responsible for maintenance of the facility in a manner to assure that structures are adequate for access control and retention of radioactivity.

The public records clearly show the NRC rapidly reviews and approves decommissioning plans for R&T reactors. In many cases, this quick regulatory action appears to be due to a complete and thorough submittal of information for the license amendment request on the part of the applicant. Often, a properly written dismantling plan replaces the licensee's technical specifications in their entirety. Such a record clearly supports the fact that both parties understand what is required and by whom.

In summary, improvements in decommissioning techniques will occur, as shown by the development and practical use of plasma-arc cutting techniques and the improvements in explosive techniques employed during recent decommissionings. These and other techniques can be expected to be further improved, directly impacting decommissioning costs. Some of the ongoing programs that will impact future licensed R&T reactor decommissionings are described in the following section.

5.4 ONGOING EXPERIENCE AT NUCLEAR REACTOR FACILITIES IN THE U.S.

Radiation field buildup effects on personnel exposure are a recognized problem area that can impede operational maintenance and inspection and can impact decommissioning operations. Efforts currently in progress to reduce radiation level buildup in commercial nuclear power plants include methods for reduction of corrosion product formation in the reactor primary system, methods for cost-effective primary system decontamination, more effective filter and purification systems, and modifications to operational techniques that have a direct influence on radiation fields. The gathering of available data is under way to allow assessment of the overall extent and seriousness of the problem across the nuclear power industry.[10]

Ongoing industrial programs concerning radiation exposure control and decommissioning include:

- concentrated chemical decontamination at Dresden 1 (BWR with steam generator)
- dilute online chemical decontamination at Dresden 2 or Quad Cities 1 and 2 (BWRs)
- steam generator replacement programs at Surry and Turkey Point (PWRs)
- steam generator chemical decontamination at Indian Point 1 (PWR)
- decontamination and cleanup at Three Mile Island, Unit 2 (PWR).

When completed, these programs will yield significant information relevant to decommissioning (e.g., chemical decontamination methods, heavy-equipment removal technology, and associated exposure reduction techniques).

During reactor operations, the radiation levels in many areas are dominated by radiation from internally contaminated piping and equipment, and minimal efforts, if any, are made to keep external surface contamination cleaned up. After many years of operation, these areas may have fairly high radiation levels. For example, at Dresden 1 it is purported that, although chemical decontamination of the test loop was effective, considerable radiation levels were still present from surface contamination on floors and surrounding structures following that effort. The dose rates from the surface contamination were quite high ($\sim$1 R/hr), but prior to loop decontamination it was not controlling. This phenomenon may well be encountered in other decommissionings and may have an effect on the occupational exposures and on the volumes of waste for disposal.

A U.S. Department of Energy (DOE) program is establishing methods, costs, and priorities for the decommissioning of retired, contaminated DOE facilities at Hanford.[11-13] Active programs are under way at Hanford and at other DOE sites to demonstrate the techniques for dismantling and consolidating contaminated equipment and facilities, under the DOE's Surplus Facilities Management Program.

In March 1975, the Peach Bottom End-Of-Life Program, cosponsored by DOE and EPRI, was initiated. The prime objective of the program is to validate specific reactor design codes by comparison with actual measurements at Peach

Bottom 1. Such end-of-life research programs, when appropriately correlated with decommissioning planning, can significantly advance nuclear plant design and fuel development technology.[14]

The NRC is currently sponsoring several Pacific Northwest Laboratory research projects that deal with the following aspects of decommissioning:

- long-lived activation products in reactor construction materials[15]
- characteristic radionuclide contamination throughout LWR power stations
- decontamination as a precursor to decommissioning.[16]

The spin-offs from these diversified efforts to reduce radiation fields will, in many cases, have a direct and favorable impact on R&T reactor decommissionings as well.

REFERENCES

1. P. B. Erickson, U.S. Licensed Reactor Decommissioning Experience, Proceedings of the American Nuclear Society Topical Meeting in Sun Valley, Idaho, September 16-20, 1979.

2. U.S. Nuclear Regulatory Commission Facilities License Application Record, NUREG-0652, March 1, 1980.

3. Nuclear Reactors Built, Being Built, or Planned in the U.S. as of June 30, 1980, DOE/TIC-8200-R42, December 1980.

4. Research, Training, Test and Production Reactor Directory, United States of America, Volumes 1 and 2, First Edition 1980. Published by the American Nuclear Society.

5. "A World's First: Darda Splitter Used for Dismantling a Reactor," Construction, February 21, 1972.

6. B. G. Bass and E. C. Holman, "The Walter Reed Research Reactor Dismantling Project," Trans. Am. Nucl. Soc., 15:897, November 1972.

7. R. J. Reckman and C. R. Montgomery, "Planning and Licensing for the Decommissioning of the Saxton Nuclear Experimental Facility," ASME Publication 73-WA/NE-8, November 1973.

8. Saxton Decommissioning Plan and Safety Analysis Report, AEC Docket No. 50-146/106, Saxton Nuclear Experimental Corporation, General Public Utilities System, Reading, Pennsylvania, April 1972.

9. U.S. Nuclear Regulatory Commission, Report Docket-50231-113, March 1972.

10. S. G. Sawochka, N. P. Jacob, and W. L. Pearl, Primary System Shutdown Radiation Levels at Nuclear Power Generating Stations, EPRI 404-2, Electric Power Research Institute Report by Nuclear Water and Waste Technology Corporation, San Jose, California, December 1975.

11. K. W. Harmon, "PNL Studies of D&D at Hanford," Presented at First Conference on Decontamination and Decommissioning (D&D) of ERDA Facilities, CONF-750827, pp. 345-365, August 1975.

12. J. W. Litchfield and J. C. King, Planning for Decommissioning and Decontamination of Hanford Nuclear Facilities, BNWL-SA-6450, Pacific Northwest Laboratory, Richland, Washington, September 1977.

13. C. W. Manry, et al., Hanford Production and Waste Management Master Plan, ARH-2956, Atlantic Richfield Hanford Co., Richland, Washington, July 1974.

14. E. J. Kohler, K. P. Steward, and J. V. Iacono, "Peach Bottom Decommissioning and Component Removal," Conference on Reactor Operating Experience, Trans. Am. Nucl. Soc., Vol. 26, Suppl. 1, p. 51, August 1977.

15. J. C. Evans, et al., "Long-Lived Activation Products in Reactor Construction Materials," presented at American Nuclear Society Conference on Decontamination and Decommissioning of Nuclear Facilities, Sun Valley, Idaho, September 1979.

16. J. L. Nelson and J. R. Devine, Decontamination Processes for Restorative Operations and as a Precursor to Decommissioning: A Literature Review, NUREG/CR-1915, U.S. Nuclear Regulatory Commission Report by Pacific Northwest Laboratory, May 1981.

6.0 REGULATORY CONSIDERATIONS FOR DECOMMISSIONING

Decommissioning of nuclear research and test (R&T) reactors must be accomplished in compliance with the applicable regulations, guides, and standards. In this section, current regulations, guides, and standards that apply to decommissioning nuclear R&T reactors are cited and the currently developing Nuclear Regulatory Commission (NRC) decommissioning policy is discussed.

Regulations and guidelines for nuclear facility decommissioning are dynamic. National policy relating to decommissioning of LWRs is changing, and new regulations are forthcoming. The NRC is developing a more explicit overall policy for decommissioning nuclear facilities.[1] A comprehensive review and analysis of current regulations related to decommissioning of licensed nuclear facilities was completed by Schilling, et al.,[2] and detailed discussions of the regulations and guides that apply to decommissioning PWRs and BWRs are given in References 3 and 4.

6.1 CURRENT FEDERAL REGULATIONS AND GUIDES

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

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

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

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

A number of other federal regulations contain requirements that must be complied with during the decommissioning of a nuclear facility. The following regulations contain requirements that are applicable to decommissioning nuclear R&T reactors:

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

49 CFR Parts 170-199.	Department of Transportation. Hazardous Material Regulations

The following NRC Regulatory Guides are perceived to provide generic guidance for activities undertaken in decommissioning nuclear R&T reactors:

1.8 Personnel Qualification and Training

1.16 Reporting of Operating Information

1.17 Protection of Nuclear Power Plants Against Industrial Sabotage

1.143 Design Guidance for Radioactive Waste Management Systems, Structures, and Components Installed in Light-Water-Cooled Nuclear Power Plants

4.2 Preparation of Environmental Reports for Nuclear Power Stations

8.2 Guide for Administrative Practices in Radiation Monitoring

8.3 Film Badge Performance Criteria

8.4 Direct-Reading and Indirect-Reading Pocket Dosimeters

8.6 Standard Test Procedures for Geiger-Müller Counters

8.8 Information Relevant to Ensuring that Occupational Radiation Exposures at Nuclear Power Stations will be as Low As Reasonably Achievable

8.9 Acceptable Concepts, Models, Equations, and Assumptions for a Bioassay Program

8.10 Operating Philosophy for Maintaining Occupational Radiation Exposure As Low As Reasonably Achievable

Several American National Standards Institute (ANSI) standards that are perceived as applicable are:

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

ANSI N18.7-1972 Standards for Administrative Control of Nuclear Power Plants

ANSI Z88.2-1969 Procedures for Respiratory Protection

6.2 MAJOR REGULATORY CONSIDERATIONS

At the end of the useful life of nuclear R&T reactors, prompt termination of the NRC license is a desired objective. Removal of the radioactivity to levels permitting unrestricted use of the facility and site is mandatory for full license termination. Present policy and regulatory guidance which addresses nuclear facility decommissioning is not specific enough.(5) The NRC is currently reevaluating its policy on decommissioning of nuclear facilities,(1,6,7) and its draft generic environmental impact statement on decommissioning, issued in January 1981, concluded that the major adverse environmental impact of decommissioning is the commitment of small amounts of land for waste burial in exchange for reuse of the facility for other nuclear or nonnuclear purposes.(5)

6.2.1 Decommissioning Alternatives and Timing

Decommissioning of a nuclear research or test reactor has as its primary objective thorough removal of radionuclides resulting in unrestricted use of the facility at the earliest practical time. In some situations, the potential for reducing the occupational dose as a result of radioactive decay favors a period of safe storage or entombment in the decommissioning process. An upper limit for the period of safe storage or entombment is about 100 years, which is consistent with EPA-recommended policy on use of institutional controls for confinement of radionuclides.(7)

All of the decommissioning alternatives lead to unrestricted access to the facility. DECON results in this unrestricted access shortly after facility shutdown. SAFSTOR defers the release of the facility for unrestricted access until after a final decontamination is made following a period of safe storage. ENTOMB defers unrestricted access until radioactive decay reduces residual contamination to a suitable level while the facility is entombed.

Decommissioning can be accomplished safely and at modest cost shortly after the end of facility operation; therefore, DECON is considered the preferable alternative, especially in regard to research reactors because of their urban locations, since it would restore the facility and site for unrestricted use in a much shorter time than SAFSTOR or ENTOMB. Completing decommissioning and releasing the R&T facilities for unrestricted use eliminates the potential for problems which may result from the increased number of sites used for confinement of radioactively contaminated material.

Timing of the completion of decommissioning of nuclear R&T reactors is dependent upon the decommissioning alternative chosen. For example, the benefit of a period of safe storage or entombment is dependent upon the particular radionuclides contributing to the radiation dose. The radionuclide that controls the radiation dose is termed the critical/abundant radionuclide. According to current policy thinking, the NRC is considering these decommissioning alternatives in terms of three major characteristic critical/abundant radionuclide half-life time limits of 5, 30, and greater than 30 years.[5]

If the critical/abundant radionuclide is 5 years or less, the decommissioning alternatives DECON, SAFSTOR, and ENTOMB would be permissible within appropriate constraints. If the critical/abundant radionuclide has a half-life greater than 5 years but no more than 30 years, only DECON and SAFSTOR would be permissible. For facilities where the critical/abundant radionuclide half-life is greater than 30 years, only DECON would be permissible.[5]

6.2.2 Planning

Decommissioning planning is critical to ensuring that the decommissioning activities are accomplished in a safe, efficient, and timely manner. Initially, a decommissioning plan should be developed prior to commissioning the reactor in order to appropriately facilitate the decommissioning objectives. Although the initial plans do not contain the level of detail required for the final version, they do describe: 1) the decommissioning alternative(s) selected, the cost estimates, and the method of assuring the availability of funds for decommissioning; 2) consideration of facilitation in design and operations for improving health and safety during decommissioning; and 3) the maintenance of records of relevant information.

Final decommissioning plans are submitted to the NRC for review and approval prior to the initiation of any decommissioning activity. For a nuclear power reactor, the NRC review and approval could take on the order of a year.[8] Historically, R&T reactors have had NRC review and approval of their decommissioning plans in considerably less time than 1 year. In any case, the final plans include: 1) a detailed description of the decommissioning alternative selected, including plans to protect health and safety, plans for waste disposal, and plans for a final termination radiation survey; 2) detailed schedules; 3) administrative controls; 4) proposed specifications on controls and limits for procedures and equipment used; and 5) details of the training program for employees and contractor personnel.

Additional planning is necessary as the license termination process proceeds, since the formal requirements of the licensee will be reduced. Once the non-operating status of the research or test reactor facility is recognized by the NRC, the requirements (as applicable) of 10 CFR 30, Licensing of By-Product Material; 10 CFR 40, Licensing of Source Materials; and, 10 CFR 70, Special Nuclear Material remain a prime concern. That is, control of by-product material such as the activated pressure vessel; control of source material such as nuclear instrument calibration sources; and control of special nuclear material such as fresh or irradiated fuel assemblies must be maintained as long as each category of material remains onsite. The specific controls which are to be maintained are addressed in revisions to the research or test reactor's technical specifications. The specification requirements applicable only to an operating reactor facility are, in turn, deleted.[9]

6.2.3 Financial Assurance

Assurance of the availability of funds ensures that decommissioning can be accomplished in a safe and timely manner and that lack of funds does not result in delays in decommissioning that may cause health and safety problems to the public. A preliminary review of the current NRC considerations on assuring the availability of funds for decommissioning was reported by R. S. Wood.[10] There are several possible funding mechanisms for providing a reasonable degree of assurance that funds are available for decommissioning

at the time of cessation of R&T reactor operations (see Section 7, Financing of Decommissioning). Guidance on what funding mechanisms provide adequate assurance is given in the following classification of funding alternatives that may be used singly or in combination.

1) Prepayment into an account segregated from other company funds prior to reactor startup.

2) Decommissioning insurance, surety bonds, letters of credit, and lines of credit that guarantee that decommissioning costs will be paid.

3) Annual deposit of a prescribed amount of funds into a sinking fund that is segregated from other company funds. Decommissioning insurance or other mechanisms listed in 2), above, may also be required because premature shutdown could result in an insufficient collection of funds.

6.2.4 Residual Radioactivity Levels for Unrestricted Use

The allowable residual radioactivity contamination level for unrestricted access to a decommissioned nuclear research or test reactor and its site has a major impact on decommissioning activities and costs. Conti reported a review of residual activity limits for decommissioning in 1979.(11)

The EPA has the responsibility for setting residual radioactivity levels which are considered safe for release of a facility for unrestricted access. Due to the variety of facility types and radionuclides involved it is not feasible to set a single dose limit that would be valid under all conditions for all facilities. Based on these considerations, the NRC has made the following recommendations:(7)

1. A residual radioactivity level for permitting release of a nuclear facility for unrestricted use should be consistent with ALARA. Guidance in establishing such a level is best expressed in terms of a value which bounds the dose for the majority of nuclear facilities. This value is determined to be 10 mrem/yr whole-body dose equivalent, but could be lower for specific facilities.(7) The 10 mrem/yr level is chosen recognizing that it may be impractical and unnecessary in some cases to meet the

5 mrem/yr level, mentioned in Reference 6, because of cost-benefit considerations and problems in detectability, sampling, and/or exposure patterns.

Discussions with EPA indicate that the 10 mrem/yr level would not be considered unreasonable. For a few situations, it is expected that residual levels will be above the 10 mrem/yr range. For these special situations, case-by-case analysis in terms of cost and benefit effectiveness will be required to establish appropriate levels.

2. Such dose rates and allowable contamination levels should be based on realistic dose assessment methodology. Realistic dose assessment recognizes, for example, that individuals do not spend all their time indoors, that building shielding should be accounted for, and that particulate resuspension diminishes due to weathering and decay.

REFERENCES

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

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

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

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

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

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

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

8. N. G. Wittenbrock, Technology, Safety and Costs of Decommissioning Nuclear Reactors at Multiple-Reactor Stations, Prepared by Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, January 1982.

9. W. J. Manion and T. S. LaGuardia, An Engineering Evaluation of Nuclear Power Reactor Decommissioning Alternatives, AIF/NESP-009, November 1976.

10. R. S. Wood, Assuring the Availability of Funds for Decommissioning Nuclear Facilities, Draft Report, NUREG-0584, Rev. 2, U.S. Nuclear Regulatory Commission, October 1980.

11. E. F. Conti, Draft Residual Activity Limits for Decommissioning, NUREG-0613, U.S. Nuclear Regulatory Commission, October 1979.

7.0 FINANCING OF DECOMMISSIONING

Alternative approaches of providing funds for the decommissioning of research and test (R&T) reactors are discussed in this section. Only alternative financial mechanisms for insuring the availability of adequate funds are discussed. Legal-institutional issues, such as who should collect the funds and how they should be administered, are outside the scope of this study and are not considered.

The federal government has, until the present, had little direct involvement in regulating the financing of decommissioning. The NRC's policy on assuring funding for decommissioning reactors is codified in Section 50.33(f) of 10 CFR Part 50. This regulation requires applicants for reactor operating licenses to furnish the commission with sufficient information to demonstrate that they can obtain the funds needed to meet both the costs of operating the plant as well as the estimated costs of permanently shutting down the facility and maintaining it in a safe condition. The NRC is, however, currently considering financial requirements within the broader context of an overall reevaluation of its policies on decommissioning nuclear facilities.[1-4]

R&T reactors encompass a wide diversity in types and sizes of facilities with a broad range of operational schedules and operating lifetimes. The level of effort required to decommission these reactors varies greatly, and decommissioning costs can range from a few thousand dollars for a small research reactor to several million dollars for a large test reactor. These reactors are owned and operated by agencies of the federal government, by colleges and universities that may be either state funded or privately owned, and by private industry. This diversity in ownership considerations and in decommissioning funding requirements may require a broad range of approaches for assuring the funding of decommissioning costs.

7.1 DECOMMISSIONING FINANCING FOR PUBLICLY OWNED FACILITIES

Of the 67 NRC-licensed, operational research reactors in the United States, 53 reactors (79%) are directly associated with a college, university, or technical institute. Most of these educational institutions are state-owned.

The 14 remaining research reactors are operated by private industry or by agencies of the federal government. Thus, the majority of research reactors are owned and operated by state and federal agencies. Two of the eight NRC-licensed test reactors (the Plum Brook Test Reactor and the NBS Test Reactor) are operated by agencies of the federal government. The other six are privately owned. Funds for the decommissioning of publicly owned R&T reactors would be paid out of general tax revenues, either at the state or federal level.

Decommissioning funds for federal- or state-owned R&T reactors would be obtained by the operating agency by preparing a budget request and securing approval of the request via the normal channels used to obtain operating funds. Budget requests would need to be prepared well in advance of the planned date of decommissioning to allow adequate time for the approval process. Because a budget request is often initiated 2 or 3 years before the actual expenditure of the funds, it would be necessary to make adequate provision for cost escalation and inflation.

It is important for members of state legislatures and for administrative officials of educational institutions involved in the procurement of research reactors to recognize that the purchase price of a reactor is only the first cost element that must be considered. The second cost element is the annual operating budget, and the third cost element is the cost of decommissioning at the end of reactor operating life. The money needed to decommission a university research reactor (approximately $10,000 to $1,000,000, depending on the size and the operating history of the reactor) would normally constitute only a small fraction of the total annual operating budget of the institution, but might constitute a major fraction of the annual equipment budget.

7.2 DECOMMISSIONING FINANCING FOR PRIVATELY OWNED FACILITIES

Since privately owned facilities could not draw upon tax revenues to pay for decommissioning, other approaches must be considered. Three alternatives of providing funds for decommissioning privately owned R&T reactors are considered in this section. These alternatives are:

1. payment of anticipated decommissioning costs into an account prior to the start of reactor operations

2. creation of a decommissioning fund during the operating lifetime of a reactor by periodic payments into a reserve fund

3. use of a performance bond to ensure the payment of decommissioning costs when the reactor ceases operation.

All of these alternatives provide some assurance that decommissioning funds will be available when needed. Preliminary evaluation by NRC staff[(2)] has indicated that these alternatives, used singly or in combination, appear satisfactory to implement financial assurance for decommissioning.

A fourth alternative would be the payment of decommissioning costs when incurred without any prior provision for assuring the availability of the necessary funds. This alternative provides the least degree of assurance that decommissioning costs will be borne by the licensee. The authors of this report believe this alternative is not generally acceptable, and it is not further discussed.

7.2.1 Prepayment of Decommissioning Costs

Under this alternative, the present value of anticipated decommissioning costs (and long-term care costs, if applicable) would be paid into a trust fund prior to the start of reactor operations. The fund could cover the total estimated cost of decommissioning or it could be invested so that the principal plus accumulated interest over the life of the plant would be sufficient to pay anticipated decommissioning costs. Adjustments might have to be made over the projected life of the facility to accommodate variations in such factors as the trust fund earnings rate, the rate of inflation, the lifetime of the facility, and increases in estimated decommissioning costs.

The principal advantage of this alternative is that it provides a high degree of assurance that decommissioning funds will be available when needed. Prepayment will probably be the only satisfactory alternative to cover costs associated with the long-term surveillance phase of the SAFSTOR decommissioning alternative.[(2)] Assuming that appropriate adjustments are made to the fund from time to time, sufficient money should be available for decommissioning,

even if the facility ceases operation prematurely. (As noted in Section 7.2.2 the operating lifetimes of R&T reactors are subject to several variables, and are normally much shorter than the 40-year operating lifetime assumed for commercial power reactors.)

The prepayment alternative is probably the most expensive alternative for the licensee of an R&T reactor because of the early date at which funds are removed from his use. Normally, the licensee can, over the long run, earn more from his own equity capital structure than by investing in high-grade corporate or government bonds. If debt funds are used to prepay the present value of decommissioning costs, the borrowing capacity of the licensee is reduced and consequently his available supply of funds for capital investment is reduced. Decommissioning alternatives that allow greater use of his own capital would be preferred by a reactor licensee, but these alternatives are generally somewhat less secure than the prepayment alternative.

7.2.2 Periodic Payments Into a Reserve (Sinking) Fund

This alternative contemplates that periodic (e.g., annual) payments be made to a reserve fund during the operating life of a research or test facility to generate enough income to pay anticipated decommissioning costs (and long-term care costs, if applicable). The funds in the reserve account could be placed permanently outside the control of the facility licensee and could be invested in high-grade securities, in federal debt obligations, or in other assets. Payments to the reserve fund might require periodic adjustment to account for changes in factors affecting fund requirements. Factors which change with time and could affect fund requirements include the rate of inflation, the rate of return on investment, estimated decommissioning costs, and the expected operating lifetime of the reactor.

A major difficulty with use of the funded reserve to ensure decommissioning funds for R&T reactors is the difficulty of estimating operating lifetimes for these facilities. Experience has shown that these reactors have relatively short lifetimes compared to those of power reactors and that planned research and test programs may be cancelled on short notice when changes occur in program emphasis.

If the sinking fund alternative is chosen, several options might be used to reduce the risk of unavailability of funds in the event of premature closure. These include one or more of the following:

- an initial cash payment to the fund prior to facility operation
- higher annual sinking fund payments in real dollars (i.e., constant dollars) during the first few years of operation
- a decommissioning assurance insurance pool
- a bond posted by the licensee prior to facility operation

The initial cash payment option provides that an initial cash payment is made to the decommissioning fund prior to reactor startup. The size of the cash payment could be flexible and might depend on the financial resources of the licensee, the probability of premature closure, the extent of anticipated decommissioning problems, the anticipated operating life of the facility, and other factors. An initial payment of 10 to 20% of the total estimated cost (in year of startup dollars) might be required.

Under the option of requiring higher annual sinking fund payments during early years of facility operation, the payments in constant dollars would initially be higher than the average annual cost and then would decline with time. The precise sliding scale could be determined at the time of reactor licensing. This option could also be used in conjunction with an initial cash payment.

An insurance pool is an additional approach to decommissioning fund assurance. Under this arrangement, licensees of nuclear reactors would make payments to a decommissioning fund assurance pool administered by the nuclear industry, the insurance industry, or the federal government. The administrator of the pool would be obligated to pay decommissioning costs if a licensee defaulted on performance. The fund would also assure the availability of decommissioning funds in the event of premature closure of a facility. Setting the appropriate premiums would be difficult. The insurance option is discussed in Reference 4. The concept needs further study to determine its feasibility.

The use of a bond posted by the licensee to assure the availability of funds for decommissioning is discussed in Section 7.2.3.

7.2.3 Use of a Performance Bond

If decommissioning costs are not prepaid by one of the financing alternatives previously described, then performance bonds may be used to ensure the availability of decommissioning funds. Performance bonds may take several forms that include:

- a bond issued by a fidelity or surety company
- a letter of credit or line of credit issued by a recognized financial institution
- a personal bond secured by collateral.

Basically, a performance (or surety) bond guarantees that funds equal to the face value of the bond will be paid in the event that the bond purchaser defaults. A surety company, of course, will try to minimize its risk by carefully evaluating the financial health of the bond purchaser and only issuing a bond in cases where default is highly unlikely. The bond purchaser must, therefore, demonstrate an ability to pay the costs of decommissioning.

Surety bonds are apparently not available in the amounts (∿$50 million) and for the terms (∿40 years) needed to ensure the decommissioning of nuclear power reactors.[4] However, such bonds may be available in the amounts and for the time periods needed to ensure the decommissioning of R&T reactor facilities. This area requires further investigation. The cost of surety is usually about 1 to 2% per year of the face value of the bond,[a] and would be in addition to the cost of any provisions the reactor licensee would have to make for decommissioning funds (since the surety company would pay only in the event of default by the licensee). If the licensee is able to obtain a bond, he may have to provide substantial collateral. The Conference of Radiation Control Program Directors task force found that surety companies are reluctant to issue bonds for large amounts unless secured by 100% collateral.[5]

Although a surety bond theoretically provides a high degree of assurance that funds for decommissioning will be available, in reality this may not be the case. Bonds of this type are usually renewed annually and may contain a

(a) The cost of a letter of credit would probably be only about 0.5% per year.

short-term (i.e., 30-day) cancellation clause. If a licensee began to experience financial difficulties, the surety company might decline to renew the bond. An additional problem is that even if a long-term bond can be obtained, its degree of assurance is only as good as the surety company. Surety companies, can become financially incapacitated just as any other company can. Finally, the guaranteed amount of the bond would have to be readjusted periodically to cover revised decommissioning cost estimates. If the bonding company does not agree ahead of time to automatic adjustment of its guarantee, the usefulness of the bond is again substantially decreased.

The performance bond could be used in conjunction with the reserve fund described in Section 7.2.2 to provide funds for decommissioning and to assure the availability of adequate funds in the event of premature closure of a facility. A performance bond that decreased in face value with increasing time could be used to ensure the availability of funds until the reserve account reached a predetermined value.

7.3 PROVISIONS FOR CONTINGENCY COSTS

This section provides a brief description of the issues associated with contingency cost protection for R&T reactor decommissioning. Contingency costs here do not refer to ordinary cost overruns incurred during decommissioning, which can be handled by building a reasonable contingency factor into the funding mechanism. Rather, the concern is with unexpected factors, such as corrective action needed for unexpected radionuclide releases or unanticipated requirements caused by changing regulations, or by unanticipated rates of inflation.

The important issue is who should bear the risk if decommissioning costs exceed available funds. This issue should be covered by the nuclear license or by the contract agreement used to set up the decommissioning fund. In general, it is appropriate that the licensee bear the overrun, primarily because the licensee benefited from facility operation and has ultimate responsibility for decommissioning regardless of previous decommissioning cost estimates or prior financial arrangements. Moreover, the licensee will want to complete

decommissioning to ensure against future liability. If a sufficient decommissioning fund is not available, the licensee still has decommissioning responsibility, regardless of the cost.

If a non-government licensee is financially incapacitated at the time of the decommissioning cost overruns, the burden of these excess costs may fall on the state and/or federal government. This possibility should encourage regulatory agencies to be diligent in licensing and in monitoring licensee facilities to correct operating practices that may aggravate decommissioning problems, as well as to prevent changing regulations that may cause large decommissioning cost overruns. This possibility might also encourage the development of decommissioning insurance pools as protection against unanticipated decommissioning costs.

7.4 SUMMARY

R&T reactors may be publicly owned (i.e., owned by agencies of the federal government or by state-funded colleges and universities) or they may be privately owned.

Decommissioning of publicly owned R&T reactors will be paid out of general tax revenues. It is important for federal and state agencies and legislative bodies to be cognizant of the magnitude of funding requirements for decommissioning these reactors.

Among the options considered for decommissioning fund assurance for privately owned R&T reactors, two options need further study. One of these options is the decommissioning assurance insurance pool. An insurance pool could assure the availability of decommissioning funds in the event of premature closure of a facility, or it could assure the availability of funds in the event of licensee default. The insurance pool option is not presently available and needs further study to determine its feasibility.

The second option needing additional study is the use of surety bonds to guarantee the availability of decommissioning funds. Such bonds are apparently not available in the amounts and for the time periods needed to ensure the decommissioning of commercial nuclear power reactors, but they may be

available in the amounts and for time periods needed to ensure the decommissioning of nuclear R&T reactors. To be useful, the amount of the bond should be readjusted periodically to cover revised decommissioning cost estimates. Thus, the possibility of a surety company agreeing to automatic adjustment of its guarantee should also be investigated.

REFERENCES

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

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

3. G. D. Calkins, Plan for Reevaluation of NRC Policy on Decommissioning of Nuclear Facilities, NUREG-0436, Revision 1, Supplement 2, U.S. Nuclear Regulatory Commission, Washington, DC, March 1981.

4. R. S. Wood, Assuring the Availability of Funds for Decommissioning Nuclear Facilities, NUREG-0584, Revision 2, U.S. Nuclear Regulatory Commission, Washington, DC, October 1980.

5. Task Force Report on Bonding and Perpetual Care of Licensed Nuclear Activities, Conference of Radiation Control Program Directors, Little Rock, Arkansas, April 5, 1976.

8.0 CHARACTERISTICS OF THE REFERENCE RESEARCH AND TEST REACTORS

This section contains brief descriptions of the characteristics of the reference research and test (R&T) reactors, summarizing the detailed information contained in Appendices A, B, D, and E for the reference research reactor, and in Appendices A, C, D, and E for the reference test reactor. Included are descriptions of the sites and facilities at the reference R&T reactors. Also included are estimates of the radiation dose rates, the surface contamination levels, and the radionuclide inventories at both reference reactor facilities at the time of final reactor shutdown.

Individual features of the reference R&T reactor sites vary from those of any specific R&T reactor sites. However, it is believed that the use of reference sites rather than specific sites results in more meaningful overall analyses of potential impacts associated with decommissioning nuclear R&T reactor facilities. A site-specific assessment will be required for the safety analysis and for the environmental report submitted with the request for a license amendment prior to actively decommissioning a specific research or test reactor facility.(1)

8.1 THE REFERENCE RESEARCH REACTOR SITE AND FACILITY

The reference site and the licensed research reactor facility are described briefly in this subsection, based on the detailed information contained in Appendices A and B in Volume 2, which is developed from information contained in Reference 2.

8.1.1 The Reference Research Reactor Site

The reference research reactor is assumed to be located on a university campus in an urban environment. The reference site is representative of a university site in a northwestern location.

The city in which the university is located is at the base of the foothills of the Pacific Coast Mountain Range, about 90 km from the coast. The site contains about 1.5 hectares in a 122 m square shape. The population of the city is

about 45,000, including the university students. Another town of 24,000 population is located 19 km northeast of the reactor. Two larger cities, 50 km from the reactor, have populations of 90,000 and 150,000. About 90 km north of the reactor is a large city of 525,000.

The main industry in the city is the state university, with emphasis on research and development. Local industries include sawmill design and manufacture, plywood manufacture, paper pulp products, fiberglass products, concrete products, and food processing. The surrounding countryside is primarily farm land and federal- and state-owned forests. Agriculture is a significant economic factor in the area, and includes beef cattle, dairying, seed crops, row crops, flax, berries, nuts, and fruits.

8.1.2 The Reference Research Reactor Facility

The reference research reactor for this study is the Oregon State University TRIGA Reactor (OSTR), at Corvallis, Oregon. OSTR is a 1000-kWt, above-ground, open-pool nuclear training and research facility that utilizes a TRIGA-type core and control system. The structures, systems, and components, described briefly in this subsection, are typical of TRIGA research reactor facilities. Additional information is contained in Appendix B of Volume 2, based primarily on the OSTR Safety Analysis Report,[2] and on other reactor-specific documents referenced in Appendix B.

8.1.2.1 Reference Research Reactor

The reference research TRIGA reactor is illustrated in Figure 8.1-1. The components of interest are: the reactor tank; the core structure and reflector; and the beam tubes, thimbles, and auxiliary equipment contained within the reactor tank.

Reactor Tank. The aluminum tank that serves as the reactor vessel has an outside diameter of 2 m, a depth of 6.3 m, and a minimum thickness of 6.4 mm. The aluminum tank is pierced by the four beam tubes, the thermal column, and the thermalizing column.

Core Structure. The core assembly is a right-circular cylinder, 1.1 m in diameter and 0.6 m high, consisting of a compact, concentric array of cylindrical

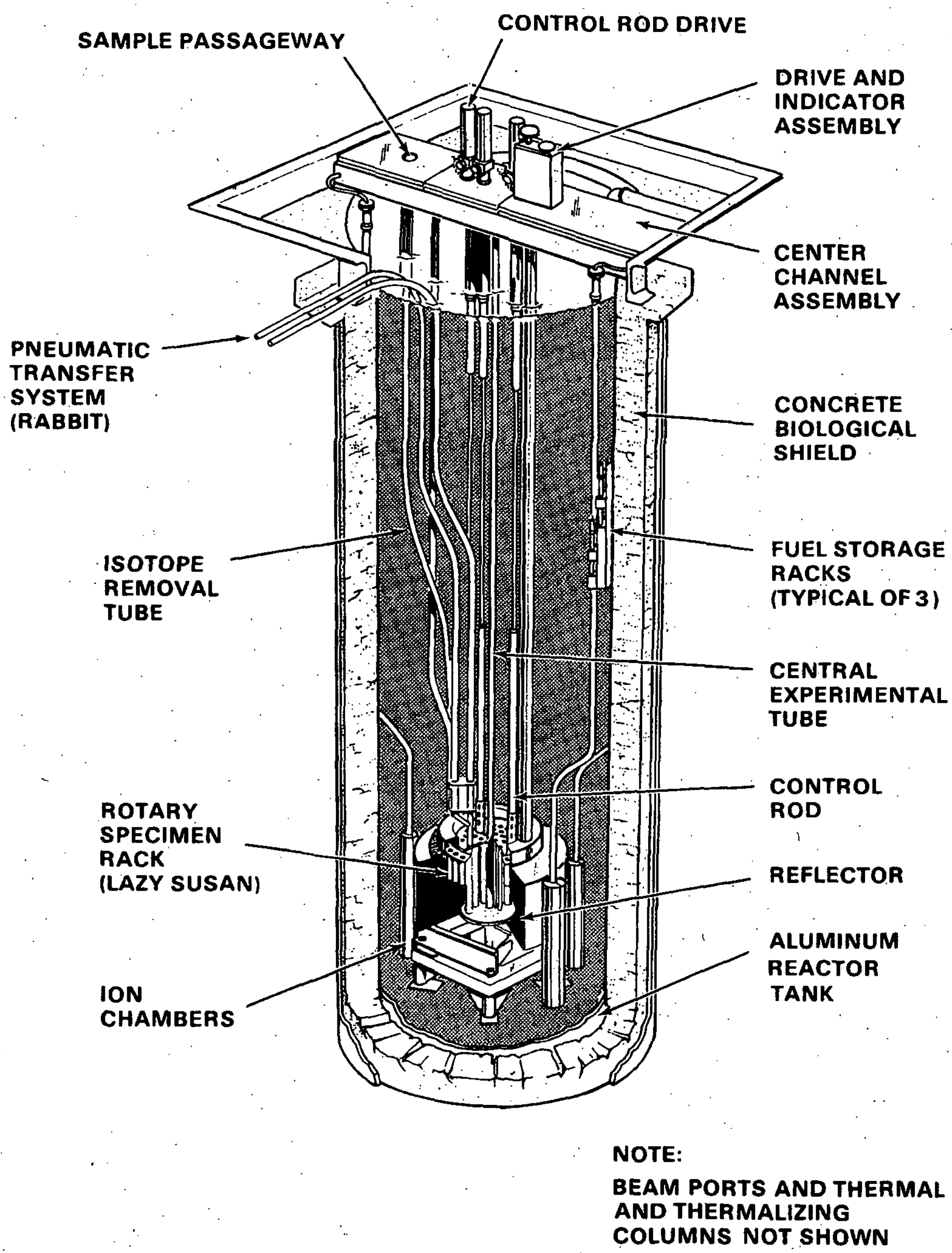


FIGURE 8.1-1. Cutaway View, Reference Research Reactor

fuel elements, a central thimble, a neutron source, and control rods, all positioned vertically between two grid plates fastened to the reflector assembly. The reactor core and the reflector assembly surrounding and supporting the core are situated upon an aluminum pedestal about 0.46 m above the bottom of the vessel. The reflector rests on a platform that raises it 0.6 m above the vessel bottom. The internal arrangements of the reactor are shown in Figure 8.1-2.

8.1.2.2 Major Structures

Major structures which comprise the reference research reactor facility include: the Reactor Building, housing the TRIGA reactor and the support area including the control room; the Cooling Tower; the Annex; the Heat Exchanger Building; the Pump House; and the Radiation Center Building, housing the Waste Processing and Storage Room. Collectively, these structures form a Radiation Center Complex. A security fence surrounds the Reactor Building and its supporting facilities. The arrangement of the structures on the reference research reactor site is illustrated in Figure 8.1-3, including identification of major structures/areas anticipated to require decontamination activities.

Reactor Building. The Reactor Building, shown in section view in Figure 8.1-4, houses the reactor room, which contains the reactor structure, fuel storage pits, and a large support area, and serves as a confinement structure for the reactor. The Reactor Building is a concrete structure, rectangular in plan and elevation. The building superstructure consists of precast-prestressed exterior wall panels and poured-in-place pilasters, a structural steel roof frame with metal deck and insulating concrete fill, and a structural steel interior floor frame with metal-formed concrete slabs. The maximum exterior dimensions of the Reactor Building are a 18.3 m wide by 23.2 m long and 13 m high.

The reference research reactor is built on an independent 0.75-m-thick concrete foundation pad. There are two walkways leading to the upper two levels of the structure. A cantilevered platform surrounded by metal railings is provided for personnel and equipment at the top of the reactor shield. A metal stairway and railing extends from the floor to the cantilevered platform at the top of the shield structure. The research reactor vessel is surrounded by a concrete biological shield, as shown in Figure 8.1-5.

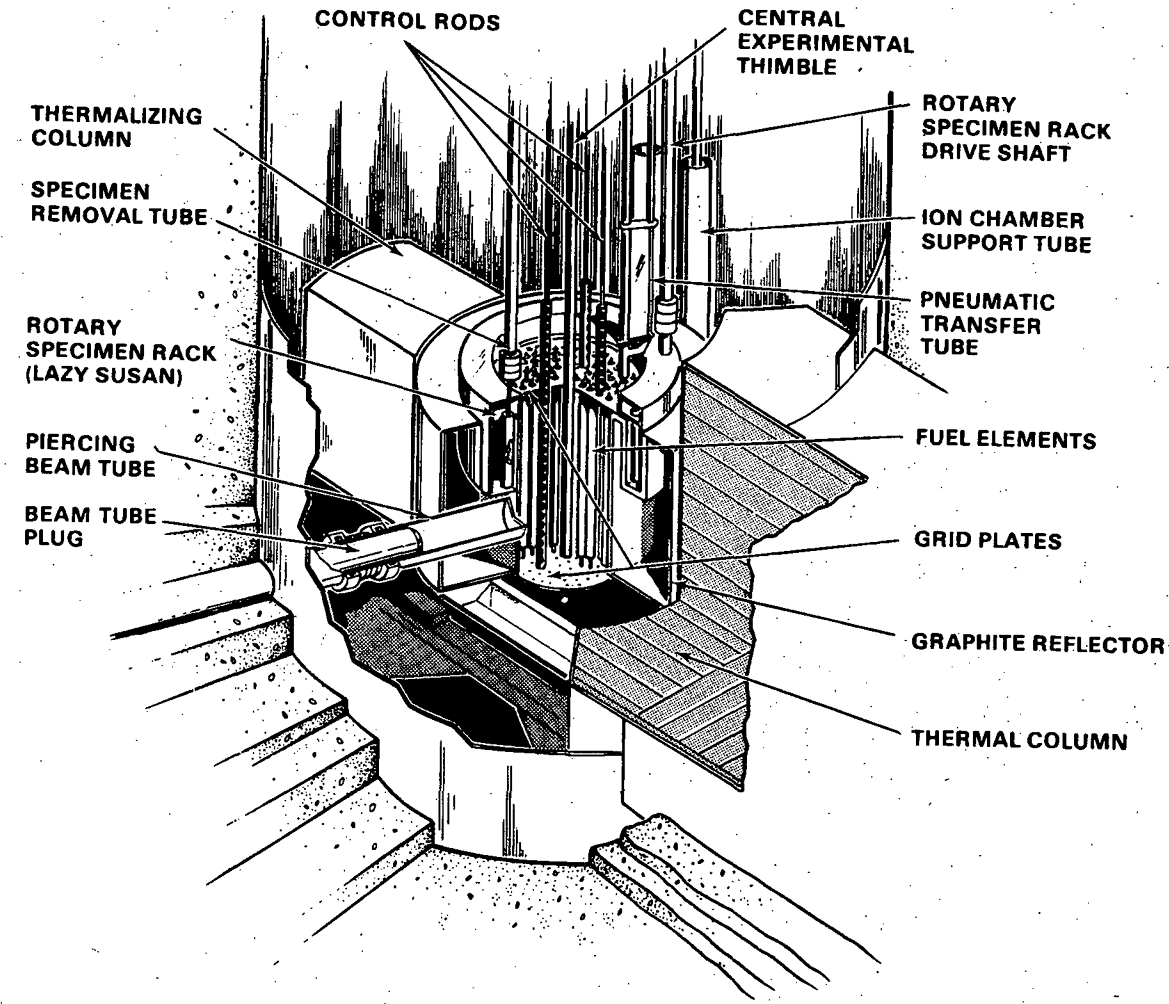


FIGURE 8.1-2. Cutaway View of the Reference Research Reactor Core Structure

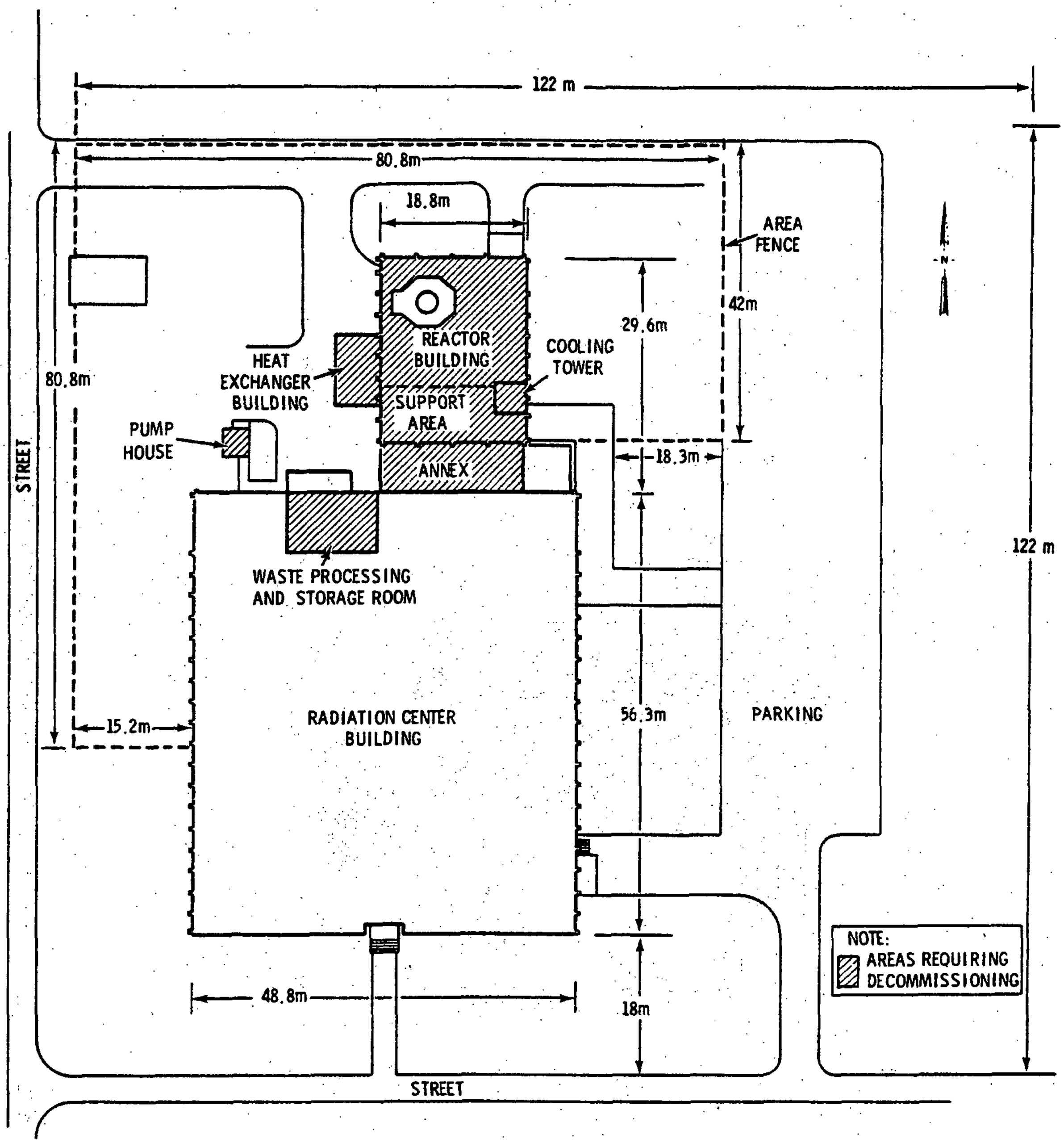


FIGURE 8.1-3. Site Layout of the Reference Research Reactor Facility

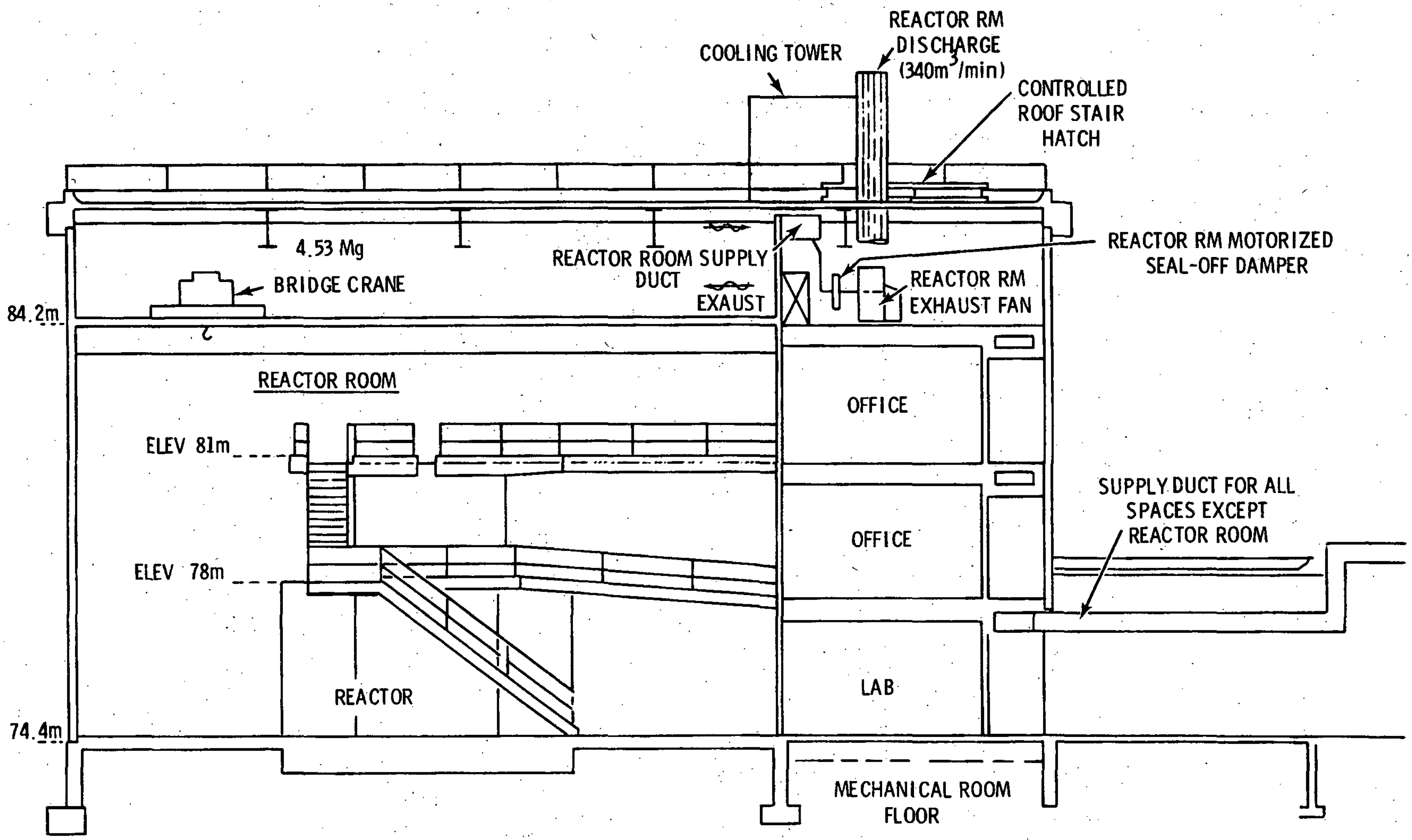


FIGURE 8.1-4. Reactor Building--Section View Looking West

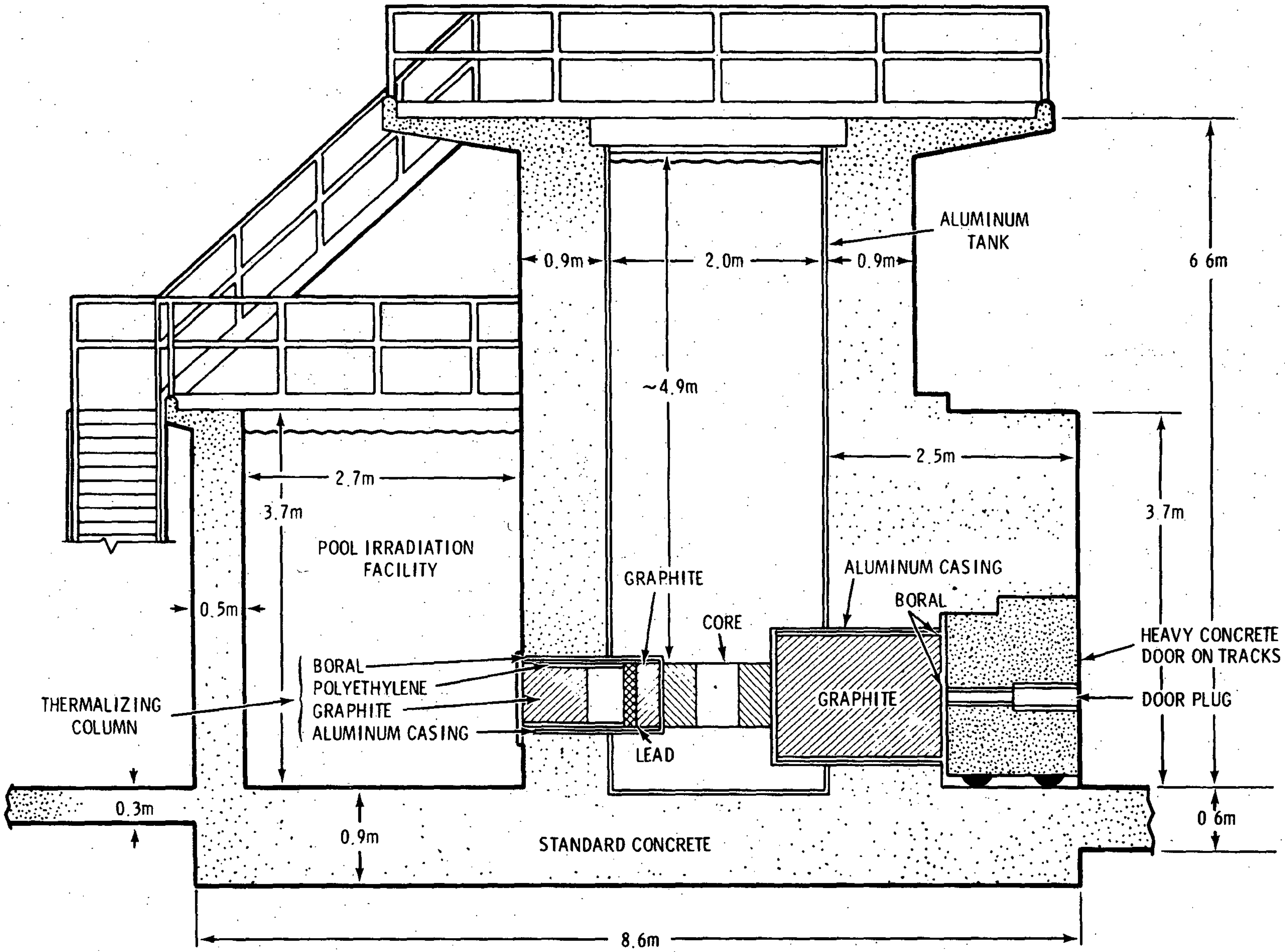


FIGURE 8.1-5. Vertical Section View of the Reference TRIGA Reactor Looking North

Several areas within the Reactor Building are allocated for offices, mechanical areas, laboratories (for the handling and processing of radioactive materials), and the Control Room. These areas and their respective roles during operation of the reference research reactor facility are described in detail in Appendix B of Volume 2.

Cooling Tower. A cooling tower structure (see Figure 8.1-4) is located on the Reactor Building roof at elevation 81.3 m. It is used to cool the secondary water from the reactor coolant heat exchanger. The tower is approximately 2.7 m wide by 3.7 m long by 3 m high and rests on two I-beams placed on the roof. The tower is made of galvanized steel, weighs 3.8 Mg, and has a filled working weight of 5.8 Mg. Two heaters are incorporated into the system to prevent the water from freezing during cold weather.

Annex Building. A single-story building connects the Radiation Center and the Reactor Building (see Figure 8.1-3). A hot laboratory area and hot cell are located in this annex.

Heat Exchanger Building. The Heat Exchanger Building contains equipment for operation of three water pumping systems used in reactor operations and an air compressor system for transient rod operation. The three pumping systems are the water purification system, the primary water pumping system, and the secondary water pumping system. The first two systems are expected to be contaminated and to require decommissioning activities. These systems are discussed in detail in Section B.3.3.1 of Appendix B.

Pump House. A sheet-metal Pump House, approximately 2.6 m square and 3 m high, is located about 3 m from the northwest corner of the Radiation Center Building (see Figure 8.1-3). The Pump House (with associated piping and valves) is above an underground liquid retention tank whose capacity is 11.1 m^3. Liquid wastes from contaminated areas of the Reactor Building, the Annex, and the Radiation Center Building are collected in this retention tank.

Radiation Center Building. The Radiation Center Building is a single-story concrete building (see Figure 8.1-3), located south of and connected to the Annex. It incorporates a large attic loft area which contains an HVAC system that is shared with the Annex and support area of the Reactor Building.

The Waste Processing and Storage Room, a 7-m by 10-m by 3-m-high area within the Radiation Center Building and adjacent to the Reactor Building, is used for solidification of liquid waste and solid-waste storage (see Figure 8.1-3). It is a single-story garage-type structure with a concrete floor and sheet-metal exterior walls.

8.1.3 Radiation Dose Rate and Surface Contamination Data for the Reference Research Reactor Facility

The radiation dose rate at a specific work site has an important influence on the time needed to complete each decommissioning task. In addition, the degree of concrete contamination determines how much surface will require removal and how much contaminated rubble will require disposal. The dose rates and the concrete surface contamination levels that are assumed to be present in the reference research reactor at final shutdown are described briefly in subsequent subsections.

8.1.3.1 Estimated Radiation Dose Rates at Shutdown in the Reference Research Reactor Facility

Radiation dose survey information was obtained from the operational and shutdown levels of the reference research reactor and the 1-MW Texas A&M TRIGA reactor, located at College Station, Texas. A compilation of routine radiation monitoring data from the reference research reactor is summarized in Table 8.1-1. These data are in agreement with the information from the Texas A&M reactor. Results from 5 years of operation were used to assess the radiation dose rates during operation, shutdown, and after extended periods of shutdown.

In general, radiation dose rates were found to be rather low due to the low power level of the reactor. Even during operation, few areas exist in which restriction of personnel activities are necessary due to radiation exposure. Health physics personnel have observed that after a short period following reactor shutdown only few specific components away from the reactor proper have significant radiation levels.

TABLE 8.1-1. Annual Summary of Radiation Levels and Contamination Levels Observed During Routine Radiation Surveys for the Year July 1, 1979 Through June 30, 1980, at the Reference Research Reactor[3]

Location	Direct Radiation Levels (mRem/hr) (βγ+neutrons) Average	Maximum	β-γ Contamination Levels (dpm/100 cm^2)[a] Average	Maximum
Reactor Top	<1	143	≤370	≤370
Sampling Handling Area	<1	143	≤370	≤370
Reactor Room Floor	<1	120	≤370	≤370
Beam Port Facilities	<1	96	≤370	≤370

Demineralizer Tank	Outside Shield Avg.	Outside Shield Max.	Inside Shield Avg.	Inside Shield Max.	Outside Shield Avg.	Outside Shield Max.	Inside Shield Avg.	Inside Shield Max.
	<1	3	39	150	--[b]	--	--	--

(a) No contamination was found at the designated locations during the entire reporting period. The 370 dpm/100 cm^2 value given in this table is the normal background counting rate for the portable survey meters routinely used in the field to screen for radioactive contamination.
(b) No data available.

8.1.3.2 Estimated Concrete Surface Contamination Levels at Shutdown in the Reference Research Reactor Facility

It should be recognized that to date no significant surface contamination has been observed at the reference research reactor (see Table 8.1-1). Several assumptions and postulations are made throughout this study concerning the eventual use of radioactive material storage and handling facilities that will, by their nature, result in some surface contamination. In addition, certain areas are not accessible for routine inspection by health physics personnel and, in selected situations, these areas are also postulated to contain surface contamination on the concrete. Estimates of the quantities of contaminated concrete waste materials expected throughout the reference research reactor are summarized in Table 8.1-2, based on the assumptions contained in Section D.1.1 of Appendix D.

TABLE 8.1-2. Summary of Postulated Quantities of Contaminated Concrete Waste Material in the Reference Research Reactor Facility

Location	Estimated Surface Area (m^2)	Percent of Area Assumed Contaminated	Rubble Volume[a] (m^3)
Reactor Building			
Inner Surface of Reactor Structure	31	100	4.6
Reactor Top	9.4	20	0.1
Fuel Storage Pits (3 each)	0.5	100	0.1
Annex			
Hot Cell	13.5	100	8.5[b]
Hot Lab	40	10	0.2
Hot Lab Sump	15	100	0.8
HX Building			
Floor	54	10	0.3
Sump	15	100	0.8
Pump House			
Concrete Floor Pad	60	10	0.4
Sump	15	100	0.8
Waste Storage Room			
Concrete Floor Pad	38	10	0.2
Sump	15	100	0.8
Total Waste Volume			17.6 m^3

(a) Based on a contamination thickness of 0.05 m.
(b) Rubble volume includes entire concrete structure of cell.

8.1.4 Radionuclide Inventories at the Reference Research Reactor

The radionuclide inventories at the time of final reactor shutdown (excluding the irradiated spent fuel) are of two types: 1) neutron-activated components in and surrounding the reactor core, and 2) surface contamination from activated

corrosion products deposited inside certain piping and equipment systems and on some structural surfaces. This section presents a summary of the information contained in Section E.1 of Appendix E in Volume 2.

Details of the calculational methods used for estimating the radionuclide inventories at the reference research reactor are presented in Section E.1.4 of Appendix E in Volume 2. The radioactivity levels present in the neutron-activated portions of the reference research reactor have been calculated to facilitate making estimates of shielding and packaging requirements, disposal costs, and potential personnel radiation exposure rates for the removal and disposal of these materials from the reference reactor. It should be recognized that the data presented in this section and in Section E.1 of Appendix E are calculated estimates specific to the reference research reactor defined for this study. Use of these data in an analysis of any other research reactor should be made with caution and with careful attention to any differences in structural materials, neutron flux levels, and reactor operating histories.

The inventory of longer half-life radionuclides that remains to be dealt with during decommissioning is dependent on the constituents of the construction materials in the core vicinity. Neutron activation products from stainless steel contribute heavily to the long-term radionuclide inventory, while those from aluminum alloys are much less significant. Aluminum alloys are used extensively in the reactor zones where activation products are produced. By comparison, stainless steel represents only 6.6% by weight of the materials within these zones.

The following subsections contain summaries of the radionuclide inventories and the total radioactivity in, and selected dose rates from, the neutron-activated components.

8.1.4.1 Radionuclide Inventories in Neutron-Activated Materials

For the purposes of this study, it is estimated that reactor operation is intermittent over a postulated 40-year operational lifetime, representing little over 5% of the available time. This estimate is based on the reference research reactor's 5-year operating history to date. The postulated 40-year lifetime is consistent with previous decommissioning studies in this series.

Radioactive material is produced in the structural components in and around the reactor vessel because of interactions with neutrons produced in the reactor fuel during operation. A summary of materials found in the highest neutron flux zones of the reference test reactor used in this study is presented in Table E.1-1 in Appendix E. Essentially the same elemental composition is present in the materials of the reference research reactor, thus the types of neutron activation products that are produced in these materials are assumed to be similar for both types of reactors. The reference radionuclide inventories calculated for the neutron-activated materials in the reference research reactor at final reactor shutdown are presented as follows: Table 8.1-3 for stainless steel (reference radionuclide inventory 1), Table 8.1-4 for aluminum (reference radionuclide inventory 2), and Table 8.1-5 for biological shield concrete (reference radionuclide inventory 3). Two elements stand out as being particularly important with respect to their impact on the radiological dose to personnel, their disposal requirements, and their potential impact on public safety during decommissioning of the reference research reactor. These are: cobalt in stainless steel, contributing to the production of ^{60}Co; and zinc in aluminum alloys, producing ^{65}Zn.

TABLE 8.1-3. Reference Radionuclide Inventory 1, Neutron-Activated Stainless Steel(a) in the Reference Research Reactor

Radionuclide	Radioactivity Concentration at Shutdown (Ci/m^3)	Fractional Radioactivity at Decay Times of: Shutdown	10 Years	30 Years	50 Years	100 Years
^{14}C	9.22×10^{0}(b)	1.75×10^{-5}	1.75×10^{-5}	1.74×10^{-5}	1.74×10^{-5}	1.73×10^{-5}
^{51}Cr	1.27×10^{5}(b)	2.41×10^{-1}	--(c)	--	--	--
^{54}Mn	1.61×10^{4}(d)	2.09×10^{-2}	3.49×10^{-6}	2.15×10^{-5}	1.27×10^{-7}	--
^{55}Fe	2.52×10^{4}(d)	4.76 x 10-2	3.63×10^{-2}	2.15×10^{-5}	1.27×10^{-7}	--
^{59}Fe	2.41×10^{3}(b)	4.56×10^{-3}	--	--	--	--
^{58}Co	1.03×10^{5}(e)	1.28×10^{-1}	--	--	--	--
^{60}Co	2.88×10^{5}(e)	5.45×10^{-1}	6.33×1^{-2}	4.56×10^{-3}	3.28×10^{-4}	4.58×10^{-7}
^{59}Ni	5.59×10^{1}(d)	1.06×10^{-4}	1.06×10^{-4}	1.06×10^{-4}	1.06×10^{-4}	1.06×10^{-4}
^{63}Ni	6.40×10^{3}(d)	1.21×10^{-2}	1.14×10^{-2}	9.82×10^{-3}	9.07×10^{-3}	6.41×10^{-3}
^{93m}Nb	1.02×10^{-2}(b)	2.25×10^{-8}	1.35×10^{-8}	4.88×10^{-9}	1.76×10^{-7}	1.38×10^{-10}
^{94}Nb	1.32×10^{-1}(b)	2.50×10^{-7}	2.50×10^{-7}	2.50×10^{-7}	2.50×10^{-7}	1.38×10^{-7}
^{95}Nb	1.06×10^{1}(b)	2.00×10^{-5}	--	--	--	--
Totals	5.61×10^{5}	1.00	1.11×10^{-1}	1.45×10^{-2}	9.52×10^{-3}	6.53×10^{-3}

(a) Grid plate inserts and hardware.
(b) Not calculated, inferred by analogy with ^{59}Ni activity as calculated in Reference 4.
(c) Indicates a value of less than 1×10^{-10}.
(d) Based upon ratio of radionuclide to ^{60}Co observed in the reference test reactor calculation (see Section E.2 in Appendix E).
(e) Calculated from neutron exposure.

TABLE 8.1-4. Reference Radionuclide Inventory 2, Neutron-Activated Aluminum[(a)] in the Reference Research Reactor

Radionuclide	Radioactivity Concentration at Shutdown (Ci/m^3)	Fractional Radioactivity at Decay Times of: Shutdown	10 Years	30 Years	50 Years	100 Years
^{46}Sc	9.80×10^{-2} (b)	1.74×10^{-4}	--(c)	--	--	--
^{54}Mn	3.90×10^{0} (b)	6.93×10^{-3}	1.15×10^{-6}	--	--	--
^{55}Fe	2.77×10^{2} (b)	4.93×10^{-1}	3.74×10^{-2}	2.22×10^{-4}	1.31×10^{-6}	--
^{60}Co	1.36×10^{-1} (b)	2.42×10^{-4}	6.48×10^{-6}	4.68×10^{-6}	3.37×10^{-7}	4.70×10^{-10}
^{63}Ni	3.37×10^{-2} (b)	6.00×10^{-5}	5.67×10^{-5}	4.94×10^{-5}	4.30×10^{-5}	3.04×10^{-5}
^{65}Zn	2.81×10^{2} (d)	5.00×10^{-1}	1.62×10^{-5}	--	--	--
Totals	5.62×10^{2}	1.00	3.75×10^{-2}	2.76×10^{-4}	4.46×10^{-5}	3.04×10^{-5}

(a) Averaged over grid plates for 2.03 EFPY of operation, from Reference 5.
(b) Based upon ratio of radionuclide to ^{65}Zn observed in the reference test reactor calculation (see Section E.2 in Appendix E).
(c) Indicates a value of less than 1.0×10^{-10}.
(d) Calculated from neutron exposure.

TABLE 8.1-5. Reference Radionuclide Inventory 3, Activated Biological Shield Concrete in the Reference Research Reactor[(a)]

Radionuclide	Radioactivity Concentration at Shutdown (Ci/m^3)	Fractional Radioactivity at Decay Times of:[(b)] Shutdown	10 Years	30 Years	50 Years	100 Years
^{39}Ar	5.4×10^{-4}	1.1×10^{-3}	1.1×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	8.8×10^{-4}
^{41}Ca	9.8×10^{-5}	2.0×10^{-4}	2.0×10^{-4}	2.0×10^{-4}	2.0×10^{-4}	2.0×10^{-4}
^{45}Ca	4.9×10^{-2}	1.0×10^{-1}	2.3×10^{-8}	--(c)	--	--
^{54}Mn	2.4×10^{-3}	4.8×10^{-3}	1.0×10^{-6}	--	--	--
^{55}Fe	4.2×10^{-1}	8.6×10^{-1}	6.6×10^{-2}	3.9×10^{-4}	2.3×10^{-6}	--
^{60}Co	9.3×10^{-3}	1.9×10^{-2}	5.2×10^{-3}	3.7×10^{-4}	2.7×10^{-5}	3.7×10^{-8}
^{59}Ni	1.7×10^{-5}	3.4×10^{-5}	3.4×10^{-5}	3.4×10^{-5}	3.4×10^{-5}	3.4×10^{-5}
^{63}Ni	2.0×10^{-3}	4.0×10^{-3}	3.8×10^{-3}	3.3×10^{-3}	2.8×10^{-3}	2.0×10^{-3}
Totals	4.9×10^{-1}	1.0	7.7×10^{-2}	5.3×10^{-3}	4.1×10^{-3}	3.1×10^{-3}

(a) The radionuclides listed include only those whose half-life and/or initial concentration result in a significant contribution after one years' decay and/or one-hundred years' decay.
(b) Based on data from Table 7.3-5 of Reference 6.
(c) Indicates a value of less than 1.0×10^{-10}.

In addition, significant quantities of ^{14}C are produced in the graphite moderator material near the reactor core. While ^{14}C contributes little to the external dose rate since it is a weak beta emitter, the potential for contamination of larger volumes of materials must be considered in the waste disposal process. Because of its long half-life (5730 years), the quantity of ^{14}C (see Table 8.1-6) will remain essentially constant during the decommissioning alternatives considered in this study.

TABLE 8.1-6. Activated Carbon Inventory Present During Decommissioning Tasks in the Reference Research Reactor

Carbon Component	Mass (mg)	Volume (m^3)	Total Activity[(a)] ^{14}C (Ci)
Reflector	5.90×10^{-1}	3.6×10^{-1}	1.02×10^{0}
Dummy Fuel Elements	1.96×10^{-2}	1.21×10^{-2}	6.67×10^{-2}
Thermal Column (within vessel)	1.1×10^{0}	6.8×10^{-1}	1.89×10^{-3}
Thermal Column (outside vessel)	2.71×10^{0}	1.69×10^{0}	2.69×10^{-8}
Thermalizing Column (within vessel)	1.39×10^{-1}	8.57×10^{-2}	2.69×10^{-3}
Thermalizing Column (outside vessel)	3.67×10^{-1}	2.27×10^{-1}	2.52×10^{-11}
Total			1.09×10^{0}

(a) Calculated from the neutron flux exposure.

8.1.4.2 Total Radioactivity in Neutron-Activated Components

The levels of radioactivity in selected neutron-activated stainless steel, aluminum, and carbon components and in concrete are listed in Table 8.1-7. The estimated total radioactivities in all of the neutron-activated stainless steel, aluminum, and carbon components are 1.42×10^{3} Ci, 3.65×10^{1} Ci, and 1.09×10^{0} Ci, respectively. The activated stainless steel components of the core contain about 97% of the total radioactivity in the neutron-activated components.

TABLE 8.1-7. Estimated Radioactivity in Selected Neutron-Activated Components of the Reference Research Reactor[a]

Component	Estimated Mass (Mg)	Estimated Radioactivity (Ci)
• Stainless Steel		
Rotary Specimen Rack Hardware	1.7×10^{-2}	2.19×10^{2}
Grid Plate Inserts and Hardware	4.8×10^{-3}	2.75×10^{2}
Control Rods (3 each)	9.0×10^{-3}	5.46×10^{2}
• Aluminum		
Reactor Vessel (core zone)	1.3×10^{-1}	6.16×10^{-5}
Reactor Vessel (above core)	6.2×10^{-2}	1.89×10^{-9}
Reflector Platform	1.2×10^{-1}	1.0×10^{0}
Reflector and Shroud	3.4×10^{-1} 1.0×10^{-1}	1.73×10^{1} 1.18×10^{-1}
Grid Plates	2.6×10^{-2}	4.91×10^{0}
Safety & Grid Adapter Plates	1.2×10^{-2}	2.84×10^{0}
Dummy Fuel Elements	8.5×10^{-3}	1.27×10^{0}
Rotary Specimen Rack	5.8×10^{-2}	4.98×10^{0}
Central Thimble (in core)	3.6×10^{-3}	1.16×10^{0}
Thermal Column (in vessel)	2.1×10^{-1}	1.53×10^{-2}
• Carbon		
Reflector	5.9×10^{-1}	1.02×10^{0}
Dummy Fuel Elements	1.96×10^{-2}	6.67×10^{-2}
Thermal Column (within vessel)	1.1×10^{0}	1.89×10^{-3}
Thermalizing Column (within vessel)	1.39×10^{-1}	2.69×10^{-3}
• Concrete	1.09×10^{1}	2.3×10^{0}

(a) These data are summarized from Tables E.1-2, E.1-3, E.1-4, and E.1-7 in Appendix E.

8.1.4.3 Dose Rates from Selected Neutron-Activated Components

The radiation dose rates from neutron-activated components are of concern in determining waste transportation and disposal requirements. Computed dose

rates for selected components at the time of final reactor shutdown are presented in Table 8.1-8. Only those radionuclides in reference radionuclide inventories 1 and 2 that significantly contribute to the dose rates (either at shutdown or after a long decay time) are included.

TABLE 8.1-8. Calculated Radiation Dose Rates from Selected Neutron-Activated Components in the Reference Research Reactor[(a)]

Radial Distance from Axial Centerline of the Core, cm	Component	Calculated Radiation Dose Rate from Selected Radionuclide (R/hr)	
		^{60}Co (gamma)	^{65}Zn (gamma)
10	Grid Plate Inserts and Hardware	1.76×10^{5}	--
9	Control Rods (3 each)	1.91×10^{5}	--
30	Rotary Specimen Rack Hardware	4.01×10^{4}	--
100	Reactor Vessel (core zone)	--	4.35×10^{-5}
60	Reflector Platform	--	1.87×10^{0}
43, 68	Reflector and	--	1.13×10^{1}
	Shroud	--	2.72×10^{-1}
12	Grid Plates	--	5.34×10^{1}
12	Safety & Grid Adapter Plates	--	5.48×10^{1}
22	Dummy Fuel Elements	--	3.46×10^{1}
30	Rotary Specimen Rack	--	2.27×10^{1}
0	Central Thimble (in core)	--	7.56×10^{1}

(a) These selected data are identical to those presented in Tables E.1-2 and E.1-3 in Appendix E.

8.1.5 Surface Contamination in the Reference Research Reactor Facility

Surface contamination is expected to be found on equipment and in work areas designated for handling radioactive materials, such as the hot cell, the terminus of the rabbit facility, and the fuel storage facilities. In addition, materials in contact with the reactor water may contain deposited radionuclides carried through the recirculating system. Little information is available about the accumulation of surface contamination at the reference research reactor;

however, radiation survey information indicates that it is very low. This confirms the expectation that in the absence of fuel failures, surface contamination is not a significant factor in a research reactor that operates at a relatively low power level (∼1 Mw). This subsection presents the known data, judgements, and quantitative calculations used to estimate the contamination levels in piping, equipment, and other reactor areas.

8.1.5.1 Internal Contamination on Reactor Cooling System Surfaces

A thin surface layer of material is deposited from the ionic species in the reactor water onto internal components of the reactor primary water cooling and purification system. (This system is shown in Figure B.3-9 and is described in Section B.3.3.1 of Appendix B.) In addition, neutron-activated particulate corrosion products add to this surface layer by deposition and absorption.

The composition and amount of radioactivity found on these internal surfaces at the time of facility shutdown are dependent on several reactor design parameters. These design parameters and their anticipated effects on internal surface contamination are discussed in Section E.1.2.1 of Appendix E.

Fission products may enter the primary water recirculation system by occasional leaks in fuel elements. Because of the high structural integrity of the fuel elements and the low operating power levels, it is postulated that this occurs only rarely during the 40-year operating life of the reference research reactor. By careful monitoring of the radioactivity levels at the demineralizer, prompt corrective action is assumed to have prevented any long-term introduction of fission products into the reactor water. From the postulated low frequency of this occurrence and its short duration in comparison with the normally occurring corrosion products, it is postulated that the radiation dose from fission product surface contamination in the primary water recirculation system comprises less than 2% of the dose that results from activated corrosion product adsorption and deposition.

The major contributor to radiation dose from neutron-activated corrosion products is ^{60}Co (see Tables E.1-2, E.1-3, and E.1-4 in Appendix E for details). The levels of surface contamination inside equipment and piping are calculated

based on dose rates measured at the reference research reactor. The estimates are doubled to approximate the projected radionuclide accumulation to the end of the reference reactor's operational life. For dose rates in the 1 mR/hr range from stainless steel equipment or piping whose wall thickness is conservatively estimated to be no greater than 12.5 mm (the maximum thickness anticipated for any equipment or piping at the reference research reactor), the ^{60}Co internal surface contamination level is estimated to be 7×10^{-2} mCi/m^2.

8.1.5.2 Contaminated Surfaces of the Hot Cell, the Storage Pits, and the Pneumatic Transfer System Terminus

Several pieces of equipment at the reference research reactor are designed to handle high levels of radionuclides. These are: the hot cell facility, the fuel storage pits, and the hoods at the pneumatic transfer system terminus. The anticipated radionuclide inventories associated with these units are described briefly in the following paragraphs.

Hot Cell Facility. The hot cell contains equipment for remote maintenance and decontamination and is used to prepare failed fuel for transfer to the onsite fuel storage facilities. It is equipped with shielding windows and manipulators. The hot cell is presumed to have had light use compared to typical hot cells in the nuclear industry, since no actual use has been made of the reference hot cell facility after 6 years of reactor operation. For the purposes of this study, a "light-use" hot cell is postulated to have been in service at the reference research reactor during its operating lifetime. Such a hot cell is described as one of several used in a reference nuclear fuel reprocessing plant.(7) Although small amounts of fission products are expected in the residual surface contamination of this hot cell, only the major items of concern are estimated.(7) These estimates are given in Table 8.1-9. The ^{137}Cs value is in good agreement with the lower limit of contamination estimated for hot-cell work when handling this isotope.(8) Contamination can be expected to be minimized in a low-service facility.

Storage Pits. It is postulated that three of the five radioactive material storage pits will see service during the operating lifetime of the reference research reactor. Although used for fuel elements and high-level

TABLE 8.1-9. Estimated Inventory of Major Radionuclides in the Hot Cell at the Reference Research Reactor

Radionuclide	Radionuclide Inventory (Ci)
^{90}Sr, ^{90}Y	4
^{134}Cs	3
^{137}Cs	3
Total Actinides	<1
Total	10

radioactive sample storage, no manipulative activity (such as that carried out in the hot cell) is associated with these storage pits. No actual data are available on the radionuclide inventory within these areas; however, they are postulated to contain approximately 10% of the inventory estimated for the hot cell, or about 1 Ci.

Pneumatic Transfer System Terminus. There are two fume hoods located in Room R-3 (see Figure B.2-1a in Appendix B) that contain surface contamination. They are used as the receptor point for the pneumatic transfer system (rabbit facility), which produces radionuclides by moving materials from the hood to the reactor core. As such, it is a radionuclide manufacturing facility and can be considered to contain materials and quantities similar to those described in the non-fuel-cycle reference facility.[8] The total radionuclide inventory for both hoods is presented in Table 8.1-10. Each hood found in the reference research reactor has a surface area of approximately 5 m^2.

TABLE 8.1-10. Estimated Radionuclide Inventory in the Contaminated Hoods at the Pneumatic Transfer System Terminus

Nuclide	Radionuclide Inventory (Ci)
^{3}H	4.5×10^{-1}
^{14}C	4.5×10^{-5} to 4.5×10^{-4}
^{125}I	4.5×10^{-8} to 4.5×10^{-7}
^{137}Cs	4.5×10^{-4} to 4.5×10^{-3}
Transuranics	4.5×10^{-8} to 4.5×10^{-7}

8.1.5.3 Surface Contamination on the Reference Research Reactor Site

It is postulated that no radioactivity is present on the grounds surrounding the reference research reactor site. Normal operation of this reactor does not result in deposition of radionuclides in the immediate site vicinity. Should internal monitoring information indicate the accidental release of fission products, the reactor ventilation system is designed to shut down, seal, and isolate the reactor room until cleanup is complete. In any event, immediate external cleanup would take place due to the very close proximity of public lands. Therefore, it is assumed that this cleanup would preclude the presence of site contamination at the time of decommissioning.

8.2 THE REFERENCE TEST REACTOR SITE AND FACILITY

The reference site and the licensed test reactor facility are described briefly in this subsection, based on the detailed information contained in Appendices A and C, respectively, of Volume 2.

The reference site described for the test reactor uses some information, namely the meteorological parameters and population distributions, taken from Appendix I of the ALAP study[9] for the river site in the year 2000. Ecological information is derived from the environmental statement for an operating nuclear power plant.[10] The remainder of the information is obtained from a variety of sources.

8.2.1 The Reference Test Reactor Site

A reference site, described briefly in this subsection, is used in assessing the public safety aspects of decommissioning the reference test reactor by various alternative methods. The reference test reactor is assumed to be located on a rural site, which is the same as the generic site described in the BWR[4] and PWR[6] decommissioning studies. The charactieristics of the reference site are representative of existing and potential nuclear reactor sites in the midwestern or middle southeastern United States. The detailed information supporting this abbreviated site description is found in Appendix A of Volume 2.

Individual features of an actual site for a given nuclear facility may vary from those of the reference site. However, it is believed that this generic approach will result in a more meaningful overall analysis of potential impacts associated with most nuclear reactor facilities. Site-specific assessments would be required for individual test reactors.

The 4.7-km^2 reference site is a rectangle 2 km by 2.35 km in dimension, with a river of moderate size running through one corner. The plant facilities are located inside a 0.12-km^2 fenced portion of the site. The minimum distance from the point of plant airborne releases to the outer site boundary is 1 km.

The reference site is located in a rural area with a relatively low population density. About 80% of the land in the vicinity of the site is farmed. High population densities are located at distances of 10 to 80 km, and gradually reducing population densities are encountered out to 180 km. The closest moderately large city, population 40,000, is about 30 km distant. The nearest large city, with 1.8 million inhabitants, is about 50 km away. The total population in a radius of 80 km is 3.52 million.

The climate at the site is typical for internal continental areas, with wide temperature variations and moderate precipitation. Meteorology information used in this study is averaged from 16 nuclear reactor sites, with an annual average atmospheric dispersion factor ($\overline{\chi}/Q'$) of about 5×10^{-8} sec/m^3 at the closest site boundary.

In this study, deposition of airborne radionuclides during 12 years of normal test reactor operation is considered to be insignificant because of the relatively small plant size, the absence of any fuel failures, and the extensive use of gaseous radwaste treatment systems. Naturally occurring radionuclides and those resulting from nuclear weapons testing are present on the site, but deposition of these latter radionuclides is not quantified in this study. However, low levels of radioactive contamination are anticipated to be present in three areas on the reference site as a result of deposition of waterborne radionuclides. The three areas are: 1) the contaminated drainage ditches, 2) the Emergency Retention Basin, and 3) the soil beneath the two Cold

Retention Basins. Descriptions of these areas are given in Section C.4, Appendix C (Volume 2) and are not repeated here. Estimates of the maximum contamination levels on the reference site at plant shutdown are given in Section 8.2.5.3.

8.2.2 The Reference Test Reactor Facility

The National Aeronautics and Space Administration's (NASA) Plum Brook Reactor Facility (PBRF), at Sandusky, Ohio, is the reference test reactor facility for this study. A test reactor and a research reactor are colocated at the PBRF site and are an integral part of the PBRF; both reactors are conceptually decommissioned for purposes of this study.

The test reactor, the Plum Brook Reactor (PBR), is a 60-MWt materials test reactor, light water moderated and cooled, used in testing materials for space flight applications. The research reactor, the Plum Brook Mock-Up Reactor (MUR), is a low-power (100-kWt) swimming pool-type research reactor, used as an experimental tool to assist in the operation of the PBR.

The principal plant systems and structures are described briefly in this section. More detailed information is found in Appendix C, which is based primarily on References 11 through 15.

8.2.2.1 Nuclear Test System

The nuclear test system of the reference test reactor is illustrated in Figure 8.2-1. The principal components and systems of interest are the test reactor vessel (containing the nuclear core and experimental beam tubes) and the reactor water recirculation systems.

Test Reactor Vessel and Internals. The test reactor vessel, shown in Figure 8.2-2, is a vertical, cylindrical ASME code pressure tank with a welded hemispherical bottom head and an elliptical top head that is flanged and gasketed so that it can be removed. A hatch is also provided to facilitate changing fuel elements and inserting or withdrawing experiments. The reactor vessel is fabricated of A-201 steel, and internal surfaces that are in contact with primary coolant are clad with type 304 stainless steel. The approximate dimensions of the vessel are 9.5 m in height and 2.7 m in outside diameter. The mass of the vessel is approximately 35.5 Mg, including all appurtenances that are welded to the vessel.

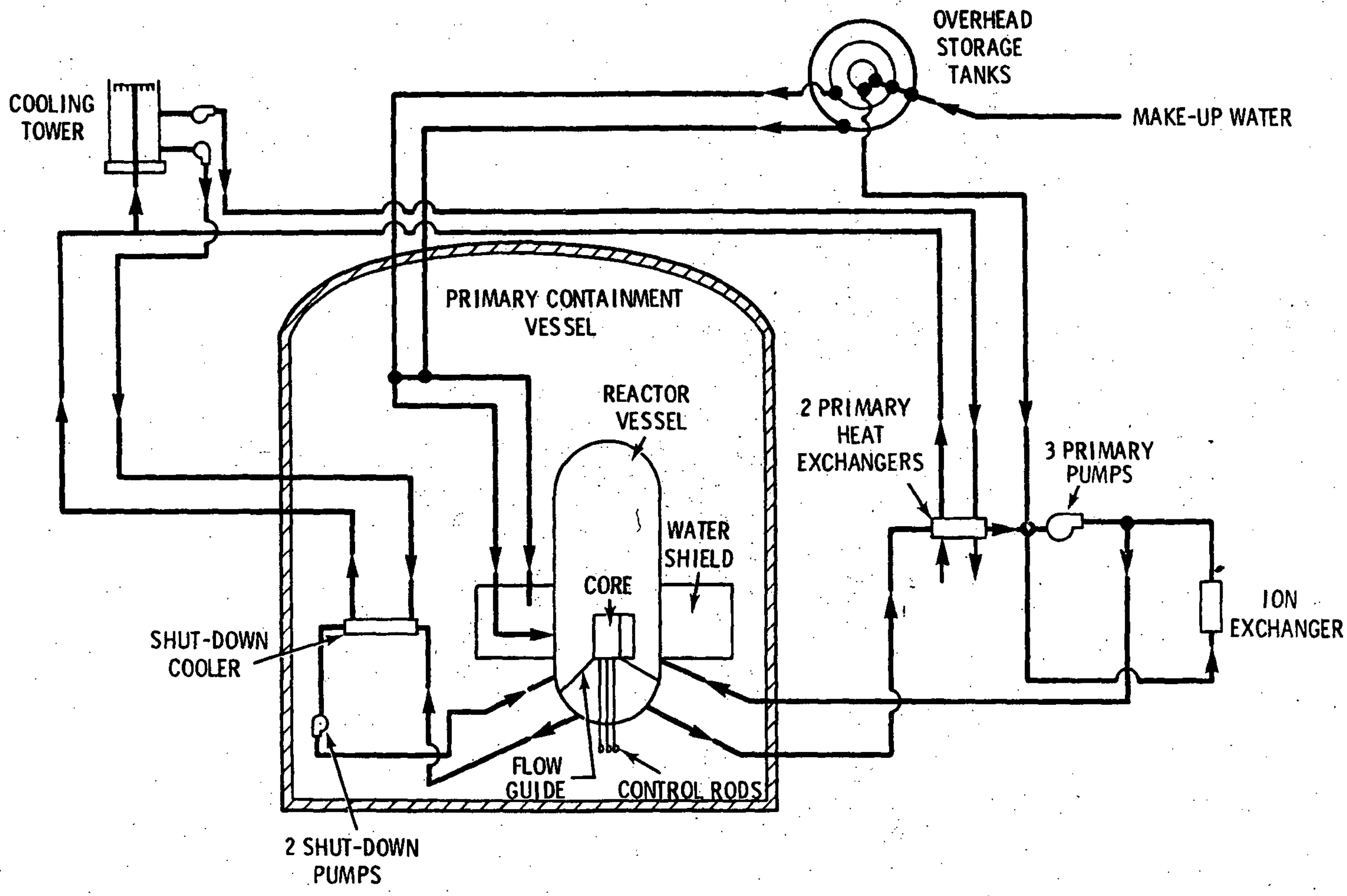


FIGURE 8.2-1. Nulcear Test System of the Reference Test Reactor

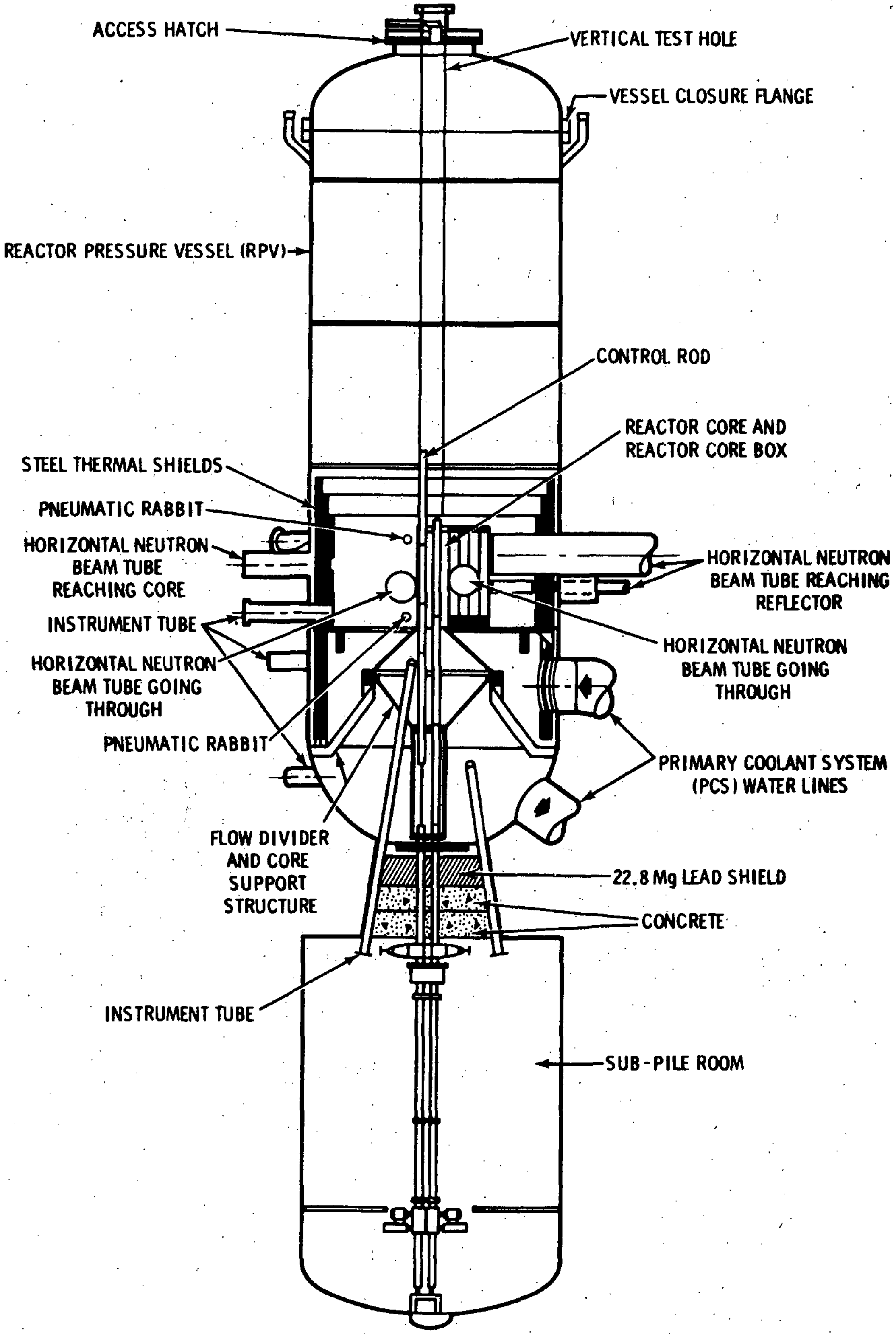


FIGURE 8.2-2. Test Reactor Vessel and Internals

The major test reactor internal components are the core (fuel, control rods, and in-core nuclear instrumentation), the core support structure (including the upper and lower flow guides, control rod drive box, and orifice plate), the thermal shields, the horizontal and vertical test holes, the horizontal beam holes, the thermal column, and the rabbit tubes.

Test Reactor Water Recirculation Systems. The primary cooling water system (refer to Figure B.2-1) is subdivided into four loops: 1) the main loop which circulates through the reference test reactor, 2) the bypass cleanup loop, 3) the instrument and test hole cooling loop (not shown in Figure 8.2-1), and 4) the shutdown loop.

The main loop is a closed loop containing 98.4 m^3 of deionized water. The bypass cleanup loop is a secondary loop on the main loop and is used to control the purity of the water in this system. There are two mixed-bed deionizers with an auxiliary heat exchanger and two pumps for circulation during shutdown. The instrument cooling loop is a secondary loop on the main and shutdown loops which supplies cooling water to instrument thimbles and experimental test holes within the reactor vessel. The shutdown loop is an auxiliary loop on the reactor vessel which circulates the water through a heat exchanger and two pumps during reactor operation and cooldown and provides sufficient capacity for decay-heat removal after shutdown. Flow from the shutdown loop also supplies the instrument cooling loop.

8.2.2.2 Mock-Up Reactor (MUR)

The Mock-Up Reactor (MUR) is located in Canal H, inside the Reactor Building but outside of the Primary Containment Vessel. The location of the MUR in relation to the reference test reactor is illustrated in Figure 8.2-3. The two reactors are connected via a system of canals to facilitate the transfer of irradiated experiments or specimens.

The MUR is used as an experimental tool to assist in the operation of the reference materials test reactor. It is a realistic physical and neutronic mock-up of the test reactor core, including the major beam tubes. A vertical section view of the MUR is shown in Figure 8.2-4. The MUR is controlled from an enclosed control room which overlooks the canal. Full access to the core can

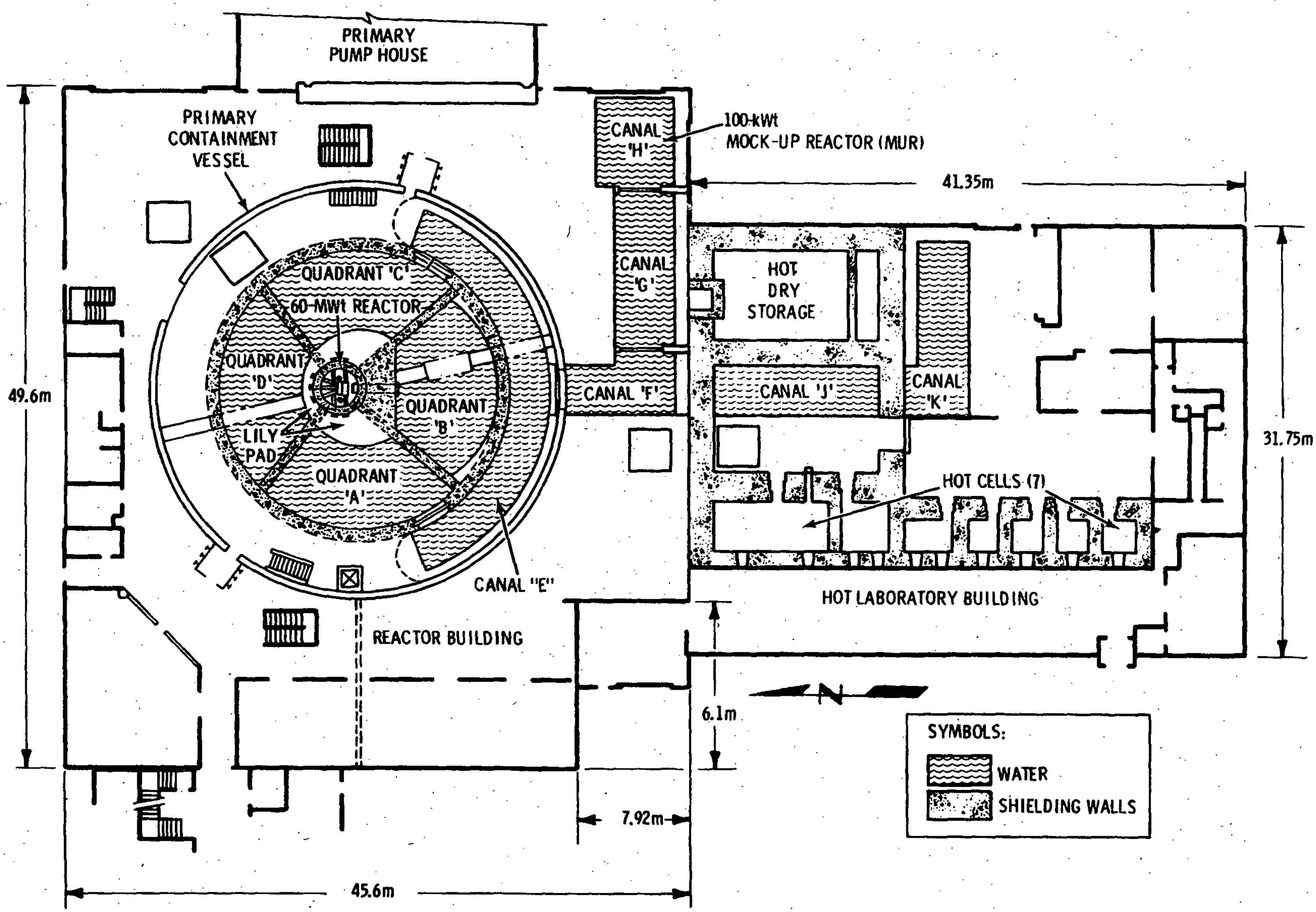


FIGURE 8.2-3. Reactor Building and Hot Laboratory Building Canal System--Plan View

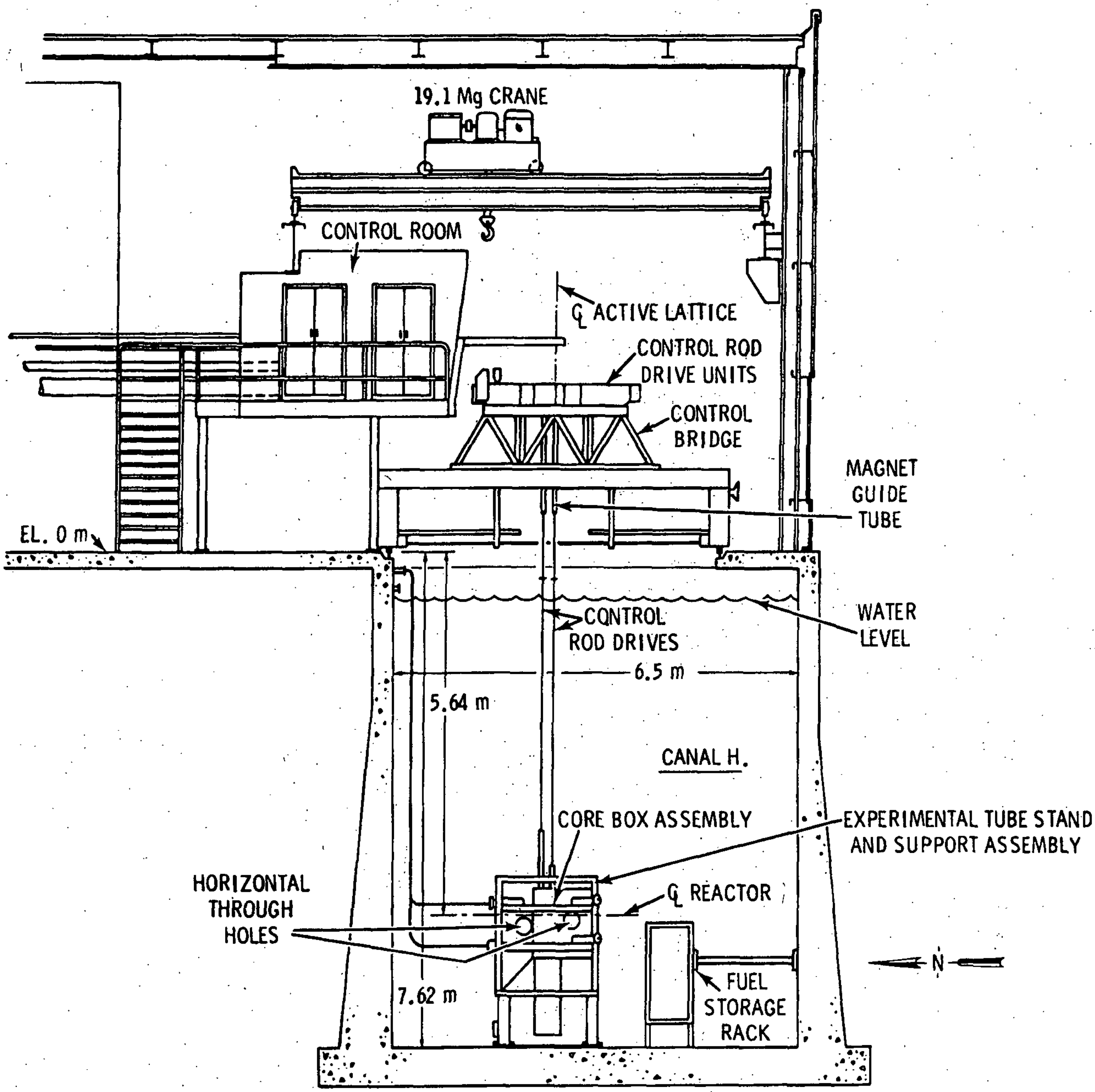


FIGURE 8.2-4. MUR--Vertical Section View

be achieved by moving the submerged instrumentation clear of the core, unlatching the control rods, and then moving the control bridge to another section of the pool. The entire core box with beryllium, beam tube mock-ups, flow guide, rod box, and support frame is estimated to weigh less than 4,550 kg.

8.2.2.3 Facility Structures

The arrangement of the structures on the reference test reactor facility site is illustrated in Figure 8.2-5, including identification of major

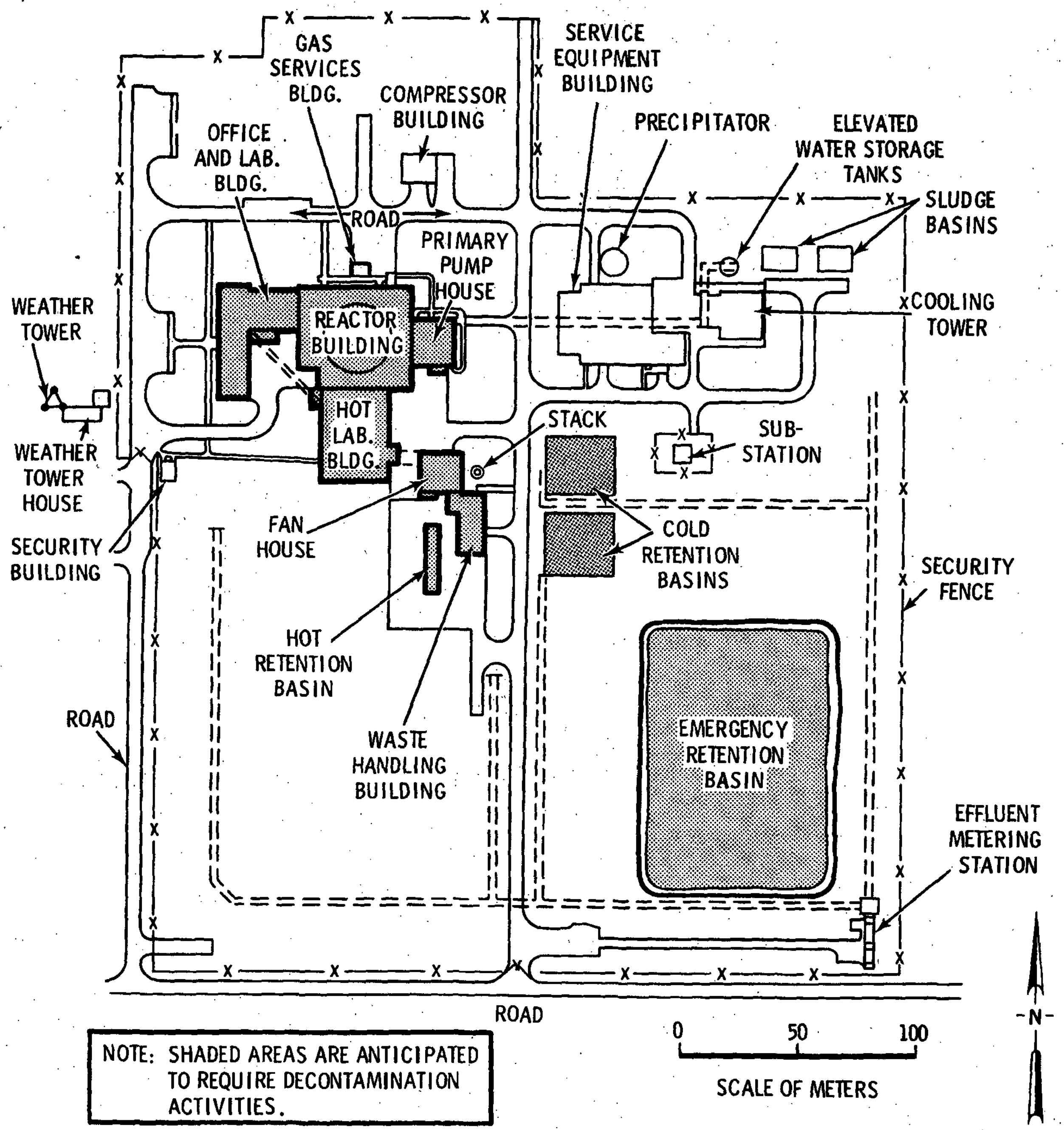


FIGURE 8.2-5. Site Layout of the Reference Test Reactor Facilities

structures/areas anticipated to require decontamination activities. The structures of primary interest during decommissioning are: the Reactor Building, housing the test reactor and the MUR; the Hot Laboratory Building with seven hot cells; the Primary Pump House; the Office and Laboratory Building; the Fan House; the Hot Retention Area; the Cold Retention Area; the Emergency Retention Basin; and the Waste Handling Building. These structures and areas contain radioactive materials that require special handling during decommissioning. The other structures, if removed, are conventionally demolished.

Reactor Building. The Reactor Building, shown in section view in Figure 8.2-6, is a flat-roofed, metal-frame building, 45.6 m by 49.6 m, which completely surrounds the containment vessel (CV). The primary structural unit of the Reactor Building is the CV itself, which houses the test reactor and the quadrant pools (refer to Figure 8.2-3). The CV has a diameter of 30.5 m, a height above grade of 16.8 m, and extends 17.1 m below grade.

Hot Laboratory Building. The Hot Laboratory Building (HLB) is a combination concrete and mill-type structure measuring approximately 31.2 m by 41.5 m, attached to the south wall of the Reactor Building. Transfer of irradiated materials and equipment from the Reactor Building to the HLB is via canal (see Figure 8.2-3). The HLB houses seven hot cells, controlled (and generally clean) work areas, an office, a manipulator repair shop, a decontamination room, and storage and repair shop areas.

A Hot Pipe Tunnel (HPT) is located directly under the row of hot cells. It contains the contaminated drain pipes from the low-level chemistry laboratories in the Office and Laboratory Building, and from the Hot Laboratory Building itself. In addition, the HPT contains contaminated air-handling systems piping. The role of the HPT in relation to contaminated air-handling systems is discussed in detail in Section C.5.2 of Appendix C.

Other Contaminated Structures and Areas. Ten of the 21 structures/areas (refer to Figure 8.2-5) at the reference test reactor facility have major radiological involvement. The two buildings with the largest involvement are described in previous paragraphs. The remaining structures and areas to be decontaminated and dismantled are described briefly in the following paragraphs.

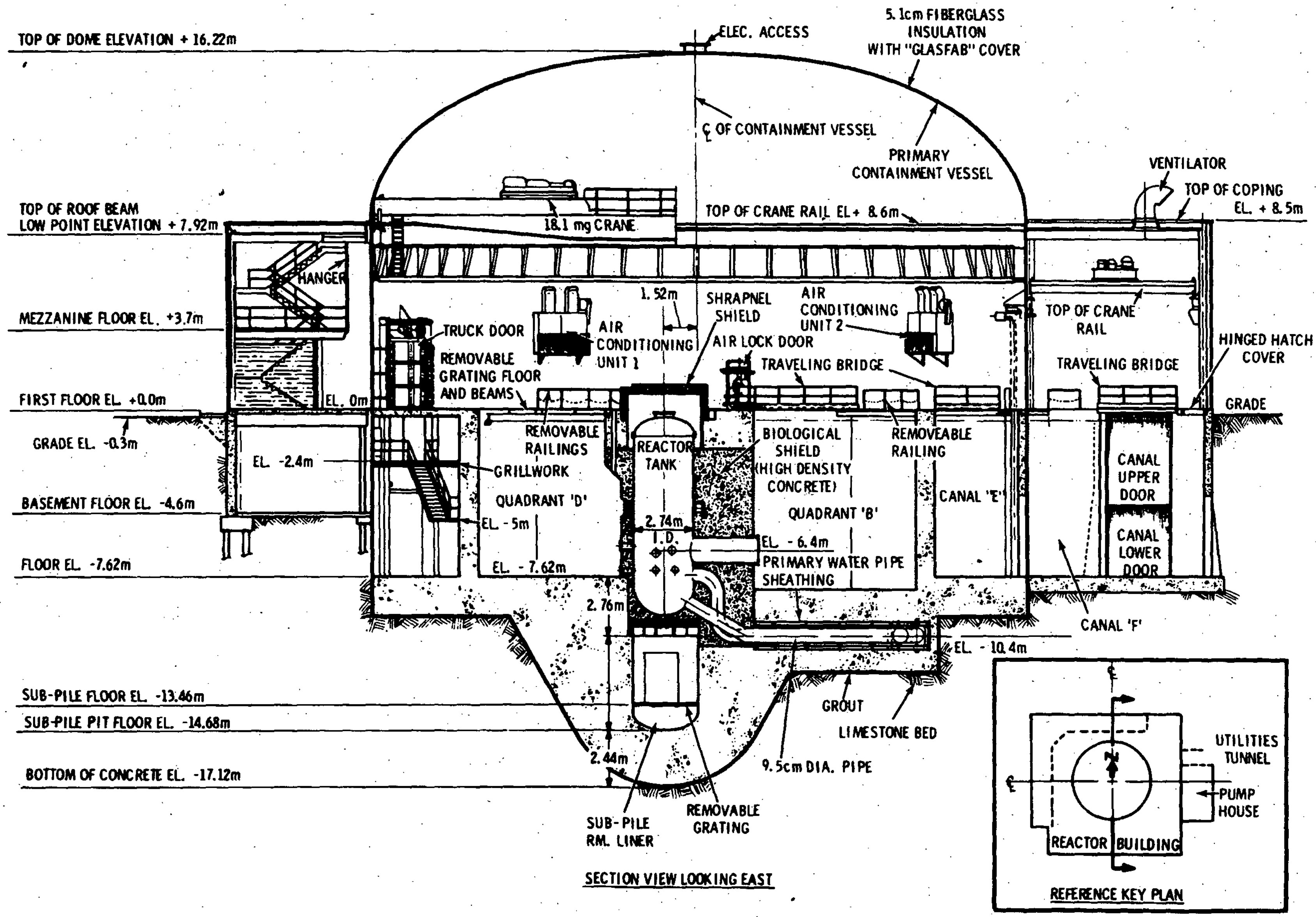


FIGURE 8.2-6. Reactor Building--Section View

Primary Pump House. The Primary Pump House is attached to the east side of the Reactor Building and shares a thick concrete shield wall. The overall outside dimensions are approximately 21.3 m by 22.1 m by 6.1 m high.

The outer north and east walls are of mill-type construction on a concrete slab floor. The shielded portion of the building, which is inside this shell, is 16.8 m by 15.9 m. The concrete walls are 1.2 m thick. The building has six internally shielded cells which house the primary heat exchanger, three primary process water pumps, deionizer tanks, and a tank room for process water additives. The roof of the shielded area is a 1.1-m-thick concrete slab. On the south side, outside the building, are two hot spent resin pits approximately 2.5 m in diameter.

Office and Laboratory Building. The Office and Laboratory Building (OLB) is attached to the west side of the Reactor Building and consists of one basement level and two floors above grade. It houses offices, electronics repair shops, health physics offices, a first aid facility, and low-level radiochemistry laboratories. There are 22 OLB laboratory hoods that exhaust to the building roof. A utility tunnel connects the hot sump in the basement of the Office and Laboratory Building to the Hot Laboratory Building.

Fan House. The Fan House is located to the southeast of the Reactor Building. The building is approximately 17.1 m by 19.1 m by 4.7 m high. It consists of two levels, a basement level and a first-floor level. It is of light mill-type construction, except for the concrete shielding walls of the deionizer room.

The Fan House contains the CV ventilating compressors, tanks, and monitoring system and ventilating fans, both feed and discharge, for the reference test reactor facility. It also houses various waste cleanup deionizers, filters, and sumps. These facilities have low-to-moderate levels of surface and internal contamination.

Hot Retention Area. The Hot Retention Area is located south of the Fan House and contains a rectangular concrete pit 13.7 m wide, 27.4 m long, and covered by 1.2 m of earthen shield. Within the pit are eight tanks, each with a capacity of 240 m^3 and fed with waste liquids from the hot drain system.

Immediately north of the concrete pit are four 28.4-m^3 tanks. These tanks are interconnected and are fed by return waste water from the waste cleanup system. Liquid from these tanks may be transferred to the Cold Retention Area, into the quadrant and canal system, or diluted with uncontaminated waste water for disposal. These tanks are anticipated to contain low-to-moderate levels of internal contamination after draining.

Cold Retention Area. The Cold Retention Area is located east of the Fan House and consists of two 1,900-m^3 tanks. The tanks are 5.5 m deep with above-grade covers approximately 28.6 m square. These tanks are used primarily for storage of water pumped from the quadrant and canal water system.

Emergency Retention Basin. The Emergency Retention Basin is a 37,800-m^3 above-ground earthen-diked basin, approximately 130 m by 96 m, located at the southeast corner of the reference site. It provides for the emergency storage of water for the facility. Very low radioactivity levels exist in this area. This area is decontaminated by soil removal.

Exhaust Stack. The exhaust stack is a 30.5-m-high, 1.5-m-diameter, vertical steel pipe with a concrete support stand and a vortex plenum at the base. The air flowing through the exhaust stack is monitored and contamination levels are recorded at the Fan House. In this study, the exhaust stack is assumed to be contaminated.

Waste Handling Building. The Waste Handling Building is located south of the Fan House. It includes a boiler room annex on the northwest corner of the building. The Waste Handling Building is of mill-type construction and measures approximately 31 m by 15.4 m by 6.2 m high. The boiler room annex is about 7.9 m by 3.3 m by 4.7 m in height.

The Waste Handling Building contains the liquid waste evaporator system with associated boiler, condenser, sumps, filters, and pumps. It also contains contaminated laundry equipment, a gantry room, waste packaging equipment, and waste storage facilities. The facilities have low-to-moderate levels of surface and internal contamination.

Auxiliary Structures. The remaining structures of the reference test reactor facility, described briefly here, are assumed in this study to be uncontaminated with radioactive material (refer to Figure 8.2-5).

Service Equipment Building. The Service Equipment Building, east of the Primary Pump House, contains the raw-water processing equipment, three large air compressors, electrical control equipment, two steam boilers, and two diesel electric generators for emergency electrical power. It also houses the health physics radiochemistry/analytical laboratory. No radiological involvement of any significance takes place in this building.

Cooling Tower. The cascading flow-type cooling tower is about 24.5 m by 21.3 m by 13.1 m high. The redwood plates are highly impregnated with the various water conditioners--algacides, fungicides, and corrosion control chemicals--used to treat process water. The main structural material is steel frame with process water distribution manifolds.

Security Building. This building is located off the west perimeter fence boundary. It is 8.2 m by 6.1 m and is 2.8 m high. It is of frame construction and houses the security personnel who control vehicular and personnel access to the facility.

Gas Service Building. This building is located just north of the Reactor Building. It is 6.1 m by 7.6 m and is 3 m high. It is of steel construction and contains storage of specialty gases in steel cylinders.

Compressor Building. This building is located due north of the primary pump house. It is 12.8 m by 15.2 m and is 3.7 m high. It is of steel construction.

Weather Tower and Building. A three-sided, steel meteorology tower and an associated single-story instrument building are located on the extreme west side of this facility, outside of the perimeter fence and near the main entrance. The collapsible installation tower is 3 m by 3 m by 46 m high.

Effluent Water Monitoring Station. This facility is located in the extreme southeast corner of the reference facility site. It consists of a series of

flumes through which flow all facility surface and waste water collected by a series of open ditches and covered culverts. A small structure at the site houses the monitoring instruments. It is of steel construction and is 3.7 m by 3.7 m by 2.4 m high.

Water Tower. The water tower, located to the east of the Service Equipment Building and north of the Cooling Tower, is 56.8 m high. Two storage tanks, one directly above the other, are visible. The upper stainless steel tank contains an inner stainless steel tank. The tanks are supported by a tubular steel frame resting on a structural concrete foundation.

Substation. An electrical substation is located east of the Cold Retention Basins. It occupies an area of approximately 7.5 m by 7.5 m.

Sludge Settling Basins. Two concrete-lined sludge basins are located northeast of the cooling tower. They are approximately 9.1 m by 15.2 m, and are used as part of the reference facility's water treatment capability.

8.2.3 Radiation Dose Data and Surface Contamination Data for the Reference Test Reactor Facility

The radiation dose rate at a specific work site has an important influence on the time needed to complete each decommissioning task. In addition, the degree of concrete contamination determines how much surface will require removal and how much contaminated rubble will require disposal. The dose rates and the concrete surface contamination levels that are assumed to be present in the reference test reactor facility at final shutdown are described briefly in subsequent subsections.

8.2.3.1 Estimated Radiation Dose Rates at Shutdown in the Reference Test Reactor Facility

A final radiation survey was made when the reference test reactor was placed in safe storage in 1973. The radiation dose rates and contamination levels measured both at that time and again in 1978 are given in Table D.2-1 in Appendix D and are not repeated here.

A methodology for establishing a useful data base of radiation dose rates and surface contamination levels for conceptually decommissioning the reference

test reactor facility as though it had only recently shut down is developed and discussed in Section D.2.1 of Appendix D. Based on the assumptions presented in Section D.2.1, a new set of dose rate data is generated to provide the bases for conceptually decommissioning the reference test reactor facility. These modified estimates are given in Table 8.2-1, together with data for additional locations identified at the reference test reactor facility as a result of communications with former operating personnel of the facility.

8.2.3.2 Estimated Concrete Surface Contamination Levels at Shutdown in the Reference Test Reactor Facility

Measured concrete surface contamination level data (1973 and 1978) were obtained from Reference 13 and corrected for decay to shutdown conditions (see Section 8.2.3.1). These data are presented in Table 8.2-1, together with the estimated radiation dose rates used for conceptually decommissioning the reference test reactor facility. Additional information on the makeup of the surface contamination affecting radiation dose rates in the plant is contained in Section E.2.2 of Appendix E. With the exception of the buried contaminated concrete piping discussed in Section C.4 of Appendix C, the estimated quantities of contaminated concrete waste material expected throughout the reference test reactor facility are summarized in Table 8.2-2, based on the assumptions contained in Section D.2.1 of Appendix D. No concrete surface contamination is assumed in the other buildings and structures at the reference test reactor site.

8.2.4 Radionuclide Inventories at the Reference Test Reactor

The radionuclide inventories at the time of final reactor shutdown (excluding the irradiated spent fuel) are of two types: 1) neutron-activated components in and surrounding the reactor core, and 2) surface contamination from activated corrosion products deposited inside certain piping and equipment systems and on some structural surfaces. This section presents a summary of the information contained in Section E.2 of Appendix E in Volume 2.

Details of the calculational methods used for estimating the radionuclide inventories at the reference test reactor (including the MUR) are presented in

TABLE 8.2-1. Estimated Radiation Dose Rates and Surface Contamination Levels Used for the Conceptual Decommissioning of the Reference Test Reactor Facility

Location	Estimated Dose Rate (R/hr)/ Type of Measurement	Estimated Smearable Contamination (d/m/100 cm^2)[a]
Reactor Building and Containment Vessel		
Reactor Tank with Internals and Water Shield	$\sim$0.030 - 0.150/general field[b]	--[c]
Reactor Tank, Empty	$\sim$0.060/contact[d]	--
Sub-pile Room	0.020 - 0.100/general field	0.2 to 1.6 K[e]
Maximum (roof)	0.250	--
Quadrants	0.010 - 0.020/general field	0.1 - 20 K
RT Shielding	0.300 - 0.700	--
Canals E&G, Empty	<0.010 - 0.20/general field	0.25 - 29 K
Drains	0.080 - 2.0	--
Canal F, Empty	0.020 - 0.030/general field	2.2 - 126 K
Drain	1 - 2	--
Canal H, Full	<0.001/general field	--
When Empty	<0.010/general field	--
MUR	<0.010 - 0.700/contact[f]	--
Drain	1.0 - 2.0	
Hot Laboratory Building		
Behind Cells	0.005 - 0.010/general field	1.5 - 1000 K
Decontamination Room No. 23	<0.005	--
Repair Shop Room No. 22	0.002 - 0.005	--
Sump, Maximum	0.6	--
Cell Drains	1 - 2/contact	--
Cell 1	1 - 1.5/general field	1.0×10^8 K
Cell 2	1 - 1.5/general field	1.0×10^8 K
Cell 3	$\sim$0.5/general field	5×10^6 K
Cell 4	$\sim$0.5/general field	3×10^6 K
Cell 5	$\sim$0.5/general field	1×10^6 K
Cell 6	$\geq$0.5/general field	2×10^7 K
Cell 7	$\sim$0.3/general field	4×10^5 K
Cell Manipulators	1 - 2	--
Canal J and K, Empty	0.020 - 0.030/general field	2.2 - 126
Hot Drain	1 - 2	--

TABLE 8.2-2. (contd)

Location	Surface Area (m^2)	Percent of Area Assumed Contaminated	Rubble Volume[b] (m^3)
Decontamination Room 23	12	100	0.6
Repair Shop Room 22	30	100	1.5
Sump	25	100	1.3
Fan House			
Sump Room	25	100	1.3
Resin Pit	13	100	0.7
Pipe Trench	18	50	0.5
Deionizer Room	15	100	0.8
Waste Handling Building			
Decontamination Room 17	38	50	1
Evaporator Room 18	38	100	1.9
Laundry	21	25	0.3
Sumps	25	100	1.3
Equipment Room 8	270	25	3.4
Primary Pump House			
Resin Pit	21	100	1.1
Sump	25	100	1.3
Primary Pump Rooms	48	100	2.4
Degassier Room	14	100	0.7
Deionizer Room	24	100	1.2
HX Room	100	50	2.6
Hot Retention Area			
Floor Area (including sumps)	424	50	11.5
Cold Retention Area			
Floor Area	1252	100	191[e]
Emergency Retention Basin	--[f]	--	--

TABLE 8.2-2. (contd)

Location	Surface Area (m^2)	Percent of Area Assumed Contaminated	Rubble Volume(b) (m^3)
Office and Laboratory Building			
Sumps	50	50	1.3
Utility Tunnel	27	50	0.7
Miscellaneous	∿25	50	0.6
Total			603.3

(a) Does not include contaminated concrete piping (see Section C.4 of Appendix C for details).
(b) Based on a contamination thickness of 0.05 m; does not include a packing factor.
(c) Includes the drain area.
(d) Does not include that portion of the canal formed by the metal containment vessel wall.
(e) Includes the total basin area for both basins, which is formed by the 0.15-m-thick concrete base slabs.
(f) Included for completeness; negligible amount of contaminated concrete assumed.

Section E.2 of Appendix E in Volume 2. The radioactivity levels present in the neutron-activated portions of the reference test reactor have been calculated to facilitate making estimates of shielding and packaging requirements, disposal costs, and potential personnel radiation exposure rates for the removal and disposal of these materials from the reference reactors. It should be recognized that the data presented in this section and in Appendix E are calculated estimates specific to the reference test reactor (including the MUR) defined for this study. Use of these data in an analysis of any other test reactor should be made with caution and with careful attention to any differences in structural materials, neutron flux levels, and reactor operating histories.

The quantities of radioactivity and the radiation dose rates are significantly greater in the reference test reactor facility than in the reference research reactor facility because of the generally higher neutron flux levels

TABLE 8.2-1. (contd)

Location	Estimated Dose Rate (R/hr)/ Type of Measurement	Estimated Smearable Contamination (d/m/100 cm^2)[a]
Hot Pipe Tunnel	0.5 - 1.5/general field	6 - 40 K
Maximum at Drain Line	15	
Primary Pump House (PPH)	0.010/general field	0.1 - 9 K
Maximum at Valves and HXs	0.6 - 10	
Pumps	0.050/general field	--
Sumps	0.020/general field	--
Resin Pit (So. side of PPH)		
Tanks, Full	2 - 5/contact	--
Tanks, Empty	≥0.020/general field	--
Waste Handling Building		
Evaporator Sump	0.120 - 0.140/general field	--
Evaporator, Maximum	0.4	--
Cold Retention Area	0.002 - 0.010	2 - 18 K
Hot Retention Area		
Inside Tank No. 1	~0.100/general field	0.1 - 3.6 K (minimum range)
Inside Tanks No. 2 through 8	~0.010 - 0.015/general field	1.4 - 46 K (maximum range)
Fan House		
Pipe Trench and Resin Pit	≤0.010/general field	--
Resin Pits (SW of Fan House), Empty	≤0.010/general field	--

(a) Disintegrations per minute per 100 square centimeters of surface surveyed.
(b) "General field" refers to the radiation field not emanating specifically from one discrete source or direction in a room or area, although a specific source may be the sole contributor to the radiation measurement. General field readings are taken at least 1 m from any surface.
(c) Indicates data not available.
(d) "Contact" means a dose rate at the closest approach to a given surface (a surface dose rate), including the necessary corrections for geometry and source size made in the field by the health physics technician.
(e) 0.2 to 1.6 K stands for 200 to 1,600 d/m/100 cm^2 (typical).
(f) See Section E.2.1.2 for details.

TABLE 8.2-2. Summary of Estimated Quantities of Contaminated Concrete Waste Material in the Reference Test Reactor Facility[a]

Location	Surface Area (m^2)	Percent of Area Assumed Contaminated	Rubble Volume[b] (m^3)
Reactor Building and Containment Vessel			
1st Floor	2416	100	123.2
Reactor Well Cavity	21	100	1.1
Quadrant "A"	335	100	17.1[c]
Quadrant "B"	353	100	18.0[c]
Quadrant "C"	335	100	17.1[c]
Quadrant "D"	297	100	15.1[c]
Underwater Beam Room	93	100	4.7
Canal "E"	366[d]	100	18.7[c]
Dry Annulus	1022	100	52.1
Sumps (4)	~50	100	2.6
Experiment Decontamination Room	34	20	0.3
Lily Pad	15	100	0.8
Canal F	170	100	8.7[c]
Canal G	222	100	11.3[c]
Canal H (including MUR)	193	100	9.8
Pump Room Area 22	67	50	1.7
Hot Laboratory Building			
Hot Cells 1-7	581	40	11.9
Hot Dry Storage	340	50	8.7
Canal J	282	100	14.4
Canal K	300	100	15.3
Off-gas Cleanup Room	170	100	8.7
Valve Pit	17	100	0.9
Hot Pipe Tunnel	307	50	7.8
Hot Handling Room 17	56	50	1.4
Hot Work Area Room 16	112	50	2.9

and longer integrated exposure of materials to neutrons. Available data on the quantities and levels of radioactivity in neutron-activated materials for the reference test reactor are presented in Section E.2.1 of Appendix E; and for the MUR in Section E.2.1.2. A limited amount of information is available on the radionuclides and contamination levels throughout the reference test reactor facility. This information is presented in Section E.2.2 of Appendix E.

The following subsections contain summaries of the radionuclide inventories and the total radioactivity in, and selected dose rates from, the neutron-activated components.

8.2.4.1 Neutron-Activated Materials in the Reference Test Reactor Facility

Radioactive material is produced in two locations in the reference test reactor facility. The principal source is the test reactor, and the second and much lesser source is the MUR. The characteristics of the principal radionuclides produced by neutron activation in the reactor components are described in Section E.2.1.3 and are not repeated here.

Neutron-Activated Materials in the Reference Test Reactor. The reference test reactor was operated over a 12-year period, accumulating a total of 98,000 MWd, with a nominal level of 60 MW, for a total of 1633 EFPD, or 4.47 EFPY. A 12-year plant operating lifetime is considered conservative based on the operating lifetimes of the eight NRC-licensed test reactors in existence. Currently (see Section 3), seven of the eight licensed test reactors are shut down. The average operating lifetime of these seven test reactors was about 8.4 years, with the reference test reactor above average at about 12 years.

Based on this operating history and on detailed neutron flux information, NASA consultants calculated the types and quantities of radionuclides that should be present in the neutron-activated reactor materials at the end of operating life, using the methodology described in Appendix A of Reference 11. These calculations are straightforward production-removal calculations performed over the cyclic power history of the reference test reactor for the principal constituents of the reactor core structure. The reference

radionuclide inventories calculated for neutron-activated materials in the reference test reactor at final reactor shutdown are presented as follows: Table 8.2-3 for stainless steel (reference radionuclide inventory 1), Table 8.2-4 for aluminum (reference radionuclide inventory 2), Table 8.2-5 for biological shield concrete (reference radionuclide inventory 3), and Table 8.2-6 for beryllium (reference radionuclide inventory 4).

In the case of stainless steel, several radionuclides likely to be present were not calculated directly but were inferred from other calculations made for stainless steel in a previous decommissioning study.[4] Three of these additional radionuclides, ^{51}Cr, ^{59}Fe, and ^{95}Nb are of significance only immediately following reactor shutdown. However, ^{14}C, ^{93m}Nb, and ^{94}Nb are long-lived and are important even after extended safe storage periods.

<u>Neutron-Activated Materials in the Mock-Up Reactor</u>. The MUR operated for a total of 0.198 MWd, with a maximum power level of 100 kW, for a total of

TABLE 8.2-3. Reference Radionuclide Inventory 1, Neutron-Activated Stainless Steel[a] in the Reference Test Reactor

Radionuclide	Radioactivity Concentration at Shutdown (Ci/m^3)	Fractional Radioactivity at Decay Times of: Shutdown	10 Years	30 Years	50 Years	100 Years
^{14}C(b)	2.97×10^{0}	1.75×10^{-5}	1.75×10^{-5}	1.74×10^{-5}	1.74×10^{-5}	1.73×10^{-5}
^{51}Cr(b)	4.10×10^{4}	2.41×10	--(c)	--	--	--
^{54}Mn	3.56×10^{3}	2.09×10^{-2}	3.49×10^{-6}	--	--	--
^{55}Fe	8.10×10^{3}	4.76×10^{-2}	3.63×10^{-2}	2.15×10^{-5}	1.27×10^{-7}	--
^{59}Fe(b)	7.75×10^{2}	4.56×10^{-3}	--	--	--	--
^{58}Co	2.18×10^{4}	1.28×10^{-1}	--	--	--	--
^{60}Co	9.27×10^{4}	5.45×10^{-1}	6.33×10^{-2}	4.56×10^{-3}	3.28×10^{-4}	4.58×10^{-7}
^{59}Ni	1.80×10^{1}	1.06×10^{-4}	1.06×10^{-4}	1.06×10^{-4}	1.06×10^{-4}	1.06×10^{-4}
^{63}Ni	2.06×10^{3}	1.21×10^{-2}	1.14×10^{-2}	9.82×10^{-3}	9.07×10^{-3}	6.41×10^{-3}
^{93m}Nb(b)	3.82×10^{-3}	2.25×10^{-8}	1.35×10^{-8}	4.88×10^{-9}	1.76×10^{-9}	1.38×10^{-10}
^{94}Nb(b)	4.25×10^{-2}	2.50×10^{-7}	2.50×10^{-7}	2.50×10^{-7}	2.50×10^{-7}	2.50×10^{-7}
^{95}Nb(b)	3.40×10^{0}	2.0×10^{-5}	--	--	--	--
Totals	1.70×10^{5}	1.00	1.11×10^{-1}	1.45×10^{-2}	9.52×10^{-3}	6.53×10^{-3}

(a) Averaged over the upper flow guide, for 4.47 EFPY of operation, from Reference 11.
(b) Not calculated, inferred by analogy with ^{59}Ni activity as calculated in Reference 4.
(c) Indicates a value of less than 1×10^{-10}.

TABLE 8.2-4. Reference Radionuclide Inventory 2, Neutron-Activated Aluminum[(a)] in the Reference Test Reactor

Radionuclide	Radioactivity Concentration at Shutdown (Ci/m^3)	Fractional Radioactivity at Decay Times of: Shutdown	10 Years	30 Years	50 Years	100 Years
^{46}Sc	1.96×10^{1}	1.74×10^{-4}	--[(b)]	--	--	--
^{54}Mn	7.78×10^{2}	6.93×10^{-3}	1.15×10^{-6}	--	--	--
^{55}Fe	5.53×10^{4}	4.93×10^{-1}	3.74×10^{-2}	2.22×10^{-4}	1.31×10^{-6}	--
^{60}Co	2.72×10^{1}	2.42×10^{-4}	6.48×10^{-5}	4.68×10^{-6}	3.37×10^{-7}	4.70×10^{-10}
^{63}Ni	6.74×10^{0}	6.00×10^{-5}	5.67×10^{-5}	4.94×10^{-5}	4.30×10^{-5}	3.04×10^{-5}
^{65}Zn	5.61×10^{4}	5.00×10^{-1}	1.62×10^{-5}	--	--	--
Totals	1.12×10^{5}	1.00	3.75×10^{-2}	2.76×10^{-4}	4.46×10^{-5}	3.04×10^{-5}

(a) Averaged over the upper grid, for 4.47 EFPY of operation, from Reference 11.
(b) Indicates a value of less than 1.0×10^{-10}.

TABLE 8.2-5. Reference Radionuclide Inventory 3, Activated Concrete at the Reference Test Reactor[(a)]

Radionuclide	Radioactivity[(b)] Concentration at Shutdown (Ci/m^3)	Fractional Radioactivity at Decay Times of: Shutdown	10 Years	30 Years	50 Years	100 Years
^{39}Ar	1.2×10^{-3}	1.1×10^{-3}	1.1×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	8.8×10^{-4}
^{41}Ca	2.2×10^{-4}	2.0×10^{-4}	2.0×10^{-4}	2.0×10^{-4}	2.0×10^{-4}	2.0×10^{-4}
^{45}Ca	1.1×10^{-1}	1.0×10^{-1}	2.3×10^{-8}	--[(c)]	--	--
^{54}Mn	5.3×10^{-3}	4.8×10^{-3}	1.0×10^{-6}	--	--	--
^{55}Fe	9.5×10^{-1}	8.6×10^{-1}	6.6×10^{-2}	3.9×10^{-4}	2.3×10^{-6}	--
^{60}Co	2.1×10^{-2}	1.9×10^{-2}	5.2×10^{-3}	3.7×10^{-4}	2.7×10^{-5}	3.7×10^{-8}
^{59}Ni	3.7×10^{-5}	3.4×10^{-5}	3.4×10^{-5}	3.4×10^{-5}	3.4×10^{-5}	3.4×10^{-5}
^{63}Ni	4.4×10^{-3}	4.0×10^{-3}	3.8×10^{-3}	3.2×10^{-3}	2.8×10^{-3}	2.0×10^{-3}
Totals	1.1	1.0	7.7×10^{-2}	5.3×10^{-3}	4.1×10^{-3}	3.1×10^{-3}

(a) The radionuclides listed include only those whose half-life and/or initial concentration result in a significant contribution after one years' decay and/or one-hundred years' decay.
(b) Based on data from Table 7.3-5 of Reference 6.
(c) Indicates a value of less than 1.0×10^{-10}.

TABLE 8.2-6. Reference Radionuclide Inventory 4, Neutron-Activated Beryllium[(a)] in the Reference Test Reactor

Radionuclide	Radioactivity Concentration at Shutdown (Ci/m^3)	Fractional Radioactivity at Decay Times of: Shutdown	10 Years	30 Years	50 Years	100 Years
^{3}H	8.28×10^{5}	9.01×10^{-1}	5.22×10^{-1}	1.70×10^{-1}	5.51×10^{-2}	3.31×10^{-3}
^{54}Mn	8.85×10^{1}	9.63×10^{-5}	1.61×10^{-8}	--[(b)]	--	--
^{55}Fe	2.52×10^{4}	2.74×10^{-2}	2.08×10^{-3}	1.23×10^{-5}	7.22×10^{-8}	--
^{60}Co	6.55×10^{4}	7.13×10^{-2}	8.27×10^{-3}	5.96×10^{-4}	4.29×10^{-5}	5.98×10^{-8}
^{113m}Cd	1.28×10^{0}	1.39×10^{-6}	8.53×10^{-7}	3.30×10^{-7}	1.10×10^{-7}	1.02×10^{-8}
^{115m}Cd	9.39×10^{-3}	1.02×10^{-8}	--	--	--	--
Totals	9.19×10^{5}	1.00	5.32×10^{-1}	1.71×10^{-1}	5.52×10^{-2}	3.31×10^{-3}

(a) Averaged over 8 each RA blocks, for 4.47 EFPY of operation, from Reference 11.
(b) Indicates value less than 1.0×10^{-10}.

1.98 EFPD. MUR operation was generally at power levels considerably less than full power and at intermittent intervals, over about 2 years less time than the reference test reactor. However, for purposes of this study, both reactors are postulated to have had similar operating time frames.

The inventory of neutron-activated materials in the MUR is estimated from the inventory calculated for the reference test reactor and is listed in Table 8.2-7, together with the estimated total radioactivity and maximum radiation dose rates for both reactors at shutdown.

TABLE 8.2-7. Estimated Total Radioactivity and Maximum Radiation Dose Rates in the MUR at Reactor Shutdown, Based on Reference Test Reactor Data

	Total Radioactivity in Reactor Structural Materials (Ci)				Radiation Dose Rate in Components Having Greatest Activation (R/hr)		
	Stainless Steel	Beryllium	Aluminum	Total	Misc. Bolts (S.S.)	RA Blocks (Be)	Lower Grid (Al)
Test Reactor[(a)]	5.41×10^{3}[(b)]	3.23×10^{5}	4.03×10^{4}	3.69×10^{5}	3.32×10^{5}	4.47×10^{4}	3.93×10^{4}
Mock-Up Reactor[(c)]	1.09×10^{-2}	6.53×10^{-1}	8.14×10^{-1}	1.48×10^{0}	6.71×10^{-1}	9.03×10^{-2}	7.94×10^{-2}

(a) Data from Tables E.2-5, E.2-6, and E.2-7 in Appendix E (Volume 2).
(b) This total activity represents only those reactor components present in both reactor facilities times the ratio: Adjusted Total Activity, Ci/Total, Ci, shown in Table E.2-5 in Appendix E.
(c) Postulated ratio of integrated power production (0.198/98,000) = 2.02×10^{-6}.

8.2.4.2 Total Radioactivity in Neutron-Activated Components in the Reference Test Reactor and in the MUR

The total radioactivity present in the activated test reactor structural materials at the time of reactor shutdown is calculated to be about 369,000 Ci, including approximately 200,000 Ci of tritium in the beryllium reflector segments. The levels of radioactivity in selected neutron-activated components of the reference test reactor are listed in Table 8.2-8. The decay of the total radioactivity in the reference test reactor components is shown in Figure 8.2-7 as a function of time after reactor shutdown, to about 120 years later.

The total radioactivity present in the activated MUR structural materials at the time of reactor shutdown is estimated to be about 1-1/2 Ci, based on reference test reactor data (see Table 8.2-7).

8.2.4.3 Dose Rates from Selected Neutron-Activated Components in the Reference Test Reactor and in the MUR

The radiation dose rates from neutron-activated components are of concern in determining waste transportation and disposal requirements. Computed dose rates from selected components in the reference test reactor and in the MUR at the time of final reactor shutdown are presented in Table 8.2-9. Only those radionuclides in reference radionuclide inventories 1, 2, and 3 that significantly contribute to the dose rates (either at shutdown or after a long decay time) are included.

8.2.5 Surface Contamination in the Reference Test Reactor Facility

While activated corrosion products from structural materials in contact with the reactor water and fission products from leaking fuel can both contribute to radionuclide mixtures and levels of surface contamination, based on historical data no fuel failures are assumed to have occurred at the reference test reactor.[11] Therefore, fission products from leaking fuel are neglected as a general contributor to surface contamination levels. It is assumed, however, that the cutting of fuel did occur in certain hot cells in the Hot-

TABLE 8.2-8. Calculated Total Radioactivity in Selected Neutron-Activated Components of the Reference Test Reactor at Shutdown

Component	Mass (Mg)[(a)]	Radioactivity (Ci)[(a)]
• Stainless Steel[(b)]		
Thermal Shields, Total	2.2×10^{1}	1.25×10^{-2}
Reactor Pressure Vessel (wall and bottom)	1.15×10^{1}	1.2×10^{-3}
Flow Guide (upper, lower, and support)	3.46×10^{0}	1.96×10^{3}
Metering Plate	6.9×10^{-1}	3.93×10^{2}
Control Rod (upper rollers)	1.25×10^{-2}	1.78×10^{3}
Miscellaneous Bolts	1.94×10^{-3}	3.35×10^{2}
Instrumentation Thimbles	(c)	2.53×10^{4}
Shim Rod Section	(c)	2.20×10^{3}
• Aluminum and Cadmium[(d)]		
Upper Grid	1.87×10^{-1}	4.0×10^{3}
Beam Tubes	2.38×10^{-1}	6.37×10^{3}
Far South Box Plate	6.20×10^{-2}	1.47×10^{2}
Side Plate (2 each)	1.00×10^{-1}	7.43×10^{3}
Lower Grid	1.66×10^{-1}	2.26×10^{4}
VAFT Lower Section (3 each)	(c)	2.28×10^{3}
Cadmium Control Rods (6 each)	(c)	9.17×10^{1}
• Beryllium[(e)]		
North Core Box Plate	8.40×10^{-2}	8.89×10^{3}
RA, RB, RC, & RD Blocks (64 total)	5.52×10^{-1}	7.50×10^{4}
LI, II Blocks (8 each)	5.44×10^{-2}	4.00×10^{4}
LA Blocks (19 each)	1.29×10^{-1}	1.09×10^{5}
R&L Block Plugs (11R, 5L)	(c)	1.66×10^{4}
Flow Divider Plate	4.09×10^{-2}	1.76×10^{4}
Be Control Rods (5 each)	$\sim 3.3 \times 10^{-1}$	6.02×10^{4}

(a) Data from Appendix A of Reference 11.
(b) These selected data are summarized from Table E.2-5 in Appendix E.
(c) Data not available.
(d) These selected data are summarized from Table E.2-6 in Appendix E.
(e) These selected data are summarized from Table E.2-7 in Appendix E.

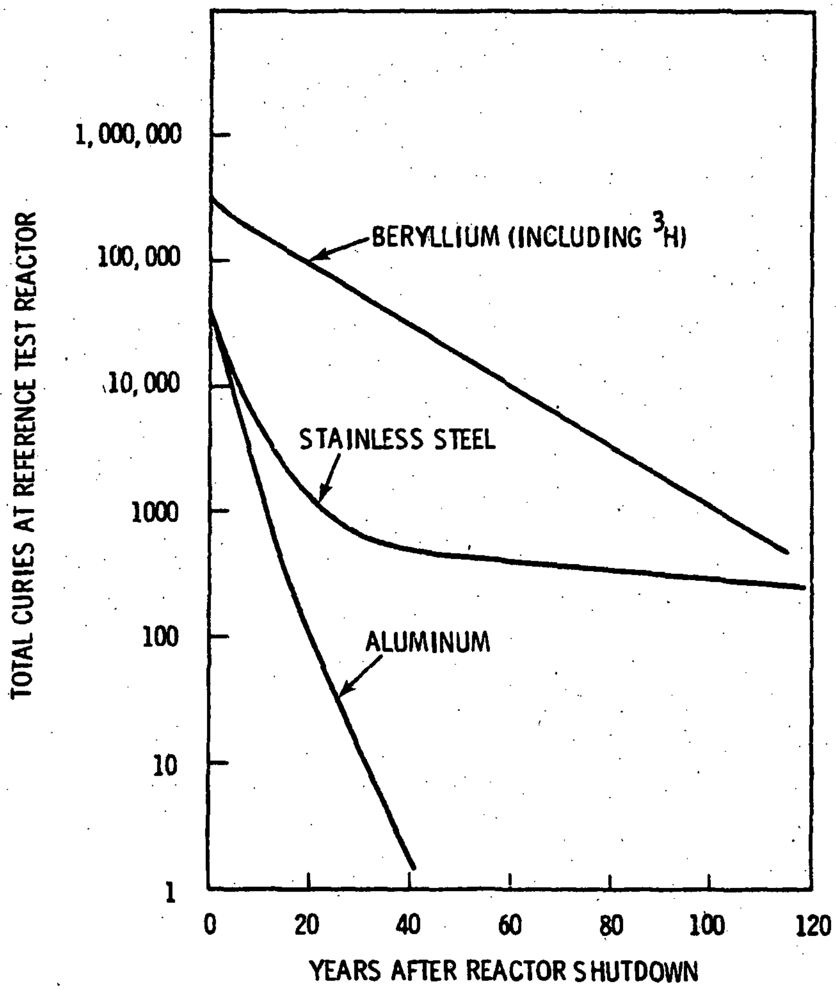


FIGURE 8.2-7. Time Dependence of Total Radioactivity in Neutron-Activated Reactor Components Following Final Reactor Shutdown

Laboratory Building. These activities were conducted under rigidly controlled conditions within local confinement envelopes and using appropriate bag-out procedures to limit surface contamination from this source to specific areas of the cell itself.

The limited amount of information on radionuclide mixtures and/or inventories present at shutdown at the reference test facility is presented in the following subsections. In those areas where actual data are unavailable, estimates are made using past experience and engineering judgement.

TABLE 8.2-9. Calculated Radiation Dose Rates from Selected Neutron-Activated Components in the Reference Test Reactor and in the MUR

Component	Calculated Radiation Dose Rate from Selected Radionuclides (R/hr) ^{60}Co	^{65}Zn
Reference Test Reactor		
• Stainless Steel[a]		
Control Rod, Upper Rollers	3.05×10^5	--
Flow Guide, Lower	7.47×10^{-1}	--
Upper	6.03×10^{-3}	--
Miscellaneous Bolts	3.32×10^5	--
• Aluminum[b]		
Upper Grid, in Core	--	1.07×10^4
in Hot Storage	--	1.30×10^1
Beam Tubes, V-2	--	2.90×10^3
HB-4	--	1.74×10^0
HB-5, 6	--	1.75×10^0
HT-1	--	8.68×10^3
HT-2	--	1.98×10^3
HB-1, 3	--	8.61×10^0
Far South Box Plate	--	5.13×10^2
Side Plate (2 each)	--	2.01×10^4
Lower Grid	--	3.93×10^4
• Beryllium[c]		
North Core Box Plate, in Core	8.98×10^3	--
in Hot Storage	1.40×10^3	--
RD Blocks (8 each)	9.91×10^2	--
RC Blocks (8 each)	3.48×10^3	--
RB Blocks (8 each)	1.51×10^4	--
RA Blocks (8 each)	4.47×10^4	--
LI, II Blocks (8 each)	2.13×10^4	--
LA Blocks (19 each)	1.55×10^4	--
Flow Divider Plate	1.47×10^1	--
Be Control Rod (5 each)	2.49×10^3	--
Mock-Up Reactor (MUR)[d]		
• Stainless Steel Miscellaneous Bolts	6.71×10^{-1}	--
• Aluminum Lower Grid	--	7.94×10^{-2}
• Beryllium RA Blocks	9.03×10^{-2}	--

(a) These selected data are summarized from Table E.2-5 in Appendix E.
(b) These selected data are summarized from Table E.2-6 in Appendix E.
(c) These selected data are summarized from Table E.2-7 in Appendix E.
(d) These selected data are summarized from Table E.2-8 in Appendix E.

8.2.5.1 Internally Contaminated Piping and Equipment

A thin layer of radioactive contamination is deposited on the internal surfaces of piping and equipment in the reference test reactor during its normal operating lifetime. The piping and equipment systems involved are described in Appendix C of Volume 2. The composition and amount of radioactivity found on internal surfaces at plant shutdown are dependent on such reactor parameters as: 1) structural material composition, 2) reactor size, design, and operating history, and 3) reactor fuel conditions. In general, the internal surface contamination is characterized by the mixture of activated corrosion products and fission products (if any) found in the reactor water.

It is estimated that after draining and flushing tasks are completed, the presence of radioactive materials elsewhere in the reference plant is minimal, mostly as trace internal and surface contamination.(11) Three exceptions are: the interior of the PCWS, the interior of certain hot cells, and the hot cell drain pipe in the Hot Pipe Tunnel. These areas are estimated to contain quantities of radioactivity ranging from a few millicuries to a few curies. These estimates are based on the actual monitoring of accessible system components performed during preparations for safe storage activities at the reference test reactor facility in early-1973 and subsequent surveys, as reported in Reference 11. The primary system contamination is assumed to be concentrated at the inlet end of the heat exchangers. Contamination in the hot cells is most prevalent on equipment located in cells 1 and 2.

Although the exact quantities of the individual constituents of the radionuclide mixtures contributing to the various surface contamination levels are unavailable, their general composition and characteristics are known and are given in Table 8.2-10.

Production of the radionuclides given in Table 8.2-10 is described in Section E.2.1.3 of Appendix E. Although significant inventories of ^{3}H are present, it is contained and confined within the metal matrix of beryllium pieces. During the operating years of the reference test reactor, operational sampling and experiments confirmed that no tritium was released even during underwater cutting

TABLE 8.2-10. Radionuclide Composition and Characteristics of Surface Contamination

Nuclide	Half-Life (years)	Emission
^{3}H	12.3	β only
^{60}Co	5.2	β and γ
^{55}Fe	2.4	X-Ray and γ
^{63}Ni	92	β only
^{59}Ni	8×10^{4}	X-Ray and γ
^{65}Zn	0.7	β and γ
^{26}Al	7.4×10^{5}	β and γ

and burning of beryllium components during replacement of bowed and fractured beryllium reactor core side plates. This lends support to the belief that tritium is well-contained within the metal matrix. Of all the radionuclides, ^{60}Co is of prime concern as a surface contaminant since this isotope heavily influences the degree of shielding and remote operations necessary to control external dose rates.

Based on actual monitoring data obtained at the reference test reactor (see Appendix D in Volume 2 for details) and making conservative upward adjustments in radiation dose rate to account for original systems' shutdown conditions, the internal surface contamination of PCWS piping and equipment is estimated. For example, using Figures E.1-1 and E.1-2 in Appendix E, a 12.5-mm stainless steel pipe in the PCWS with a contact dose rate in the 10 mr/hr range will have a ^{60}Co internal surface contamination level of about 0.3 mCi/m^2 at final reactor shutdown.

8.2.5.2 External Surface Contamination in the Reference Test Reactor

In general, the radionuclide mixture found on most externally contaminated structural surfaces in the reference test reactor, with the exception of the hot cells, is assumed to reflect the mixture of radionuclides found in the reactor water (as previously discussed in Section 8.2.5.1). Leaks occurring in normally accessible areas are assumed to be repaired and cleaned up according

to standard operating procedures. Leaks occurring in areas not normally accessible are assumed to accumulate and build up over a 12-year plant operating lifetime, which is considered conservative based on the operating histories of the eight NRC-licensed test reactors in existence. Currently (see Section 3), seven of the eight test reactors are shut down. The average operating lifetime of these seven test reactors was about 8.4 years, with the reference test reactor above average at about 12 years.

The radionuclide inventories in the hot cells are discussed in detail in Section E.2.2.3 of Appendix E. An estimate of the amounts of radioactive contaminants in the hot cells after shutdown is presented in Table 8.2-11. For each cell, about 60% of this contamination is assumed to be on the stainless steel linings of the cells and about 40% on concrete.

The estimated inventory appears reasonable and consistent with the stated bases and assumptions given in Section E.2.2.3 of Appendix E. However, these estimates are highly dependent on the operating philosophy at the plant, and the values presented in Table 8.2-11 represent what is expected to be a typical case for the reference hot cells for the assumptions used. Actual hot-cell operations could result in values different from those given.

8.2.5.3 Surface Contamination on the Reference Test Reactor Site

This subsection contains a discussion of the radionuclide mixture and contamination level present on the reference site resulting from normal test reactor operation. Releases of radionuclides resulting from accidents are not expected to significantly increase the radioactivity on the reference site and, therefore, are not considered in this analysis. Information about the level and nature of the radioactive contamination present at the time of decommissioning is needed to determine the alternative future uses of the site.

For this study, deposition of airborne radionuclides during 12 years of normal test reactor operation is considered to be insignificant because of the relatively small plant size, the absence of any fuel failures, and the extensive use of gaseous radwaste treatment systems. Naturally occurring radionuclides and those resulting from nuclear weapons testing are present

TABLE 8.2-11. Estimated Inventory of Major Radionuclides in the Hot Cells of the Hot Laboratory Building at Shutdown[a]

Fission Products	Estimated Radioactivity (Ci) Hot Cell No. 1	Hot Cell No. 2	Hot Cell No. 3	Hot Cell No. 4	Hot Cell No. 5	Hot Cell No. 6	Hot Cell No. 7	Total Inventory by Isotope, Ci
^{90}Sr, ^{90}Y[b]	3.3×10^{0}	1.7×10^{0}	8.1×10^{-2}	3.2×10^{-2}	1.2×10^{-2}	2.1×10^{-2}	4×10^{-3}	5.2
^{106}Ru, ^{106}Rh	6.6×10^{-1}	3.4×10^{-1}	1.6×10^{-2}	6.5×10^{-3}	2.4×10^{-3}	4.3×10^{-3}	8×10^{-4}	1.0
^{134}Cs	3.3×10^{-1}	1.7×10^{-1}	8×10^{-3}	3.2×10^{-3}	1.2×10^{-3}	2.1×10^{-3}	4×10^{-4}	0.5
^{137}Cs	2.6×10^{0}	1.4×10^{0}	6.5×10^{-2}	2.6×10^{-2}	9.7×10^{-3}	1.7×10^{-2}	3.2×10^{-3}	4.1
^{144}Ce, ^{144}Pr	6.6×10^{-1}	3.4×10^{-1}	1.6×10^{-2}	6.5×10^{-3}	2.4×10^{-3}	4.3×10^{-3}	8×10^{-4}	1.0
^{147}Pm	3.3×10^{-1}	1.7×10^{-1}	8×10^{-3}	3.1×10^{-3}	1.2×10^{-3}	2.1×10^{-3}	4×10^{-4}	0.5
^{151}Sm	1.3×10^{-1}	6.8×10^{-2}	3×10^{-3}	1.3×10^{-3}	5×10^{-4}	8.6×10^{-4}	2×10^{-4}	0.2
^{154}Eu	1.3×10^{-1}	6.8×10^{-2}	3×10^{-3}	1.3×10^{-3}	5×10^{-4}	8.6×10^{-4}	2×10^{-4}	0.2
Actinides								
U (all isotopes)	5.7×10^{-3}	3×10^{-3}	1.4×10^{-4}	6×10^{-5}	2.1×10^{-5}	4×10^{-5}	7×10^{-6}	<0.1
^{244}Cm	3×1^{-1}	1.6×10^{-1}	7×10^{-3}	3×10^{-3}	1.1×10^{-3}	2×10^{-3}	4×10^{-4}	0.5
Total Radioactivity	8.5×10^{0}	4.4×10^{0}	2.1×10^{-1}	8.3×10^{-2}	3.1×10^{-2}	5.5×10^{-2}	1×10^{-2}	~13.3

(a) 60% of all inventory assumed to be on stainless steel walls and 40% on concrete.
(b) Where isotopes are grouped, radioactivities are total for the groups.

on the site, but deposition of these latter radionuclides is not quantified in this study. However, low levels of radioactive contamination are anticipated to be present in three areas on the reference site as a result of deposition of waterborne radionuclides. The three areas are: 1) the contaminated drainage ditches, 2) the Emergency Retention Basin, and 3) the soil beneath the two Cold Retention Basins. Descriptions of these areas are given in Section C.4 of Appendix C in Volume 2 and are not repeated here. The results of a recent (1981) soil surface sample taken from the Emergency Retention Basin at the point of highest concentration are given in Table 8.2-12. The calculated deposited radioactivity values at various times after shutdown are shown to account for decommissioning of the aforementioned areas after specific periods of radioactive decay. A subsurface sample taken at a depth of 0.3 m directly below the surface sample indicated decreasing values for all radionuclides by factors ranging from about 5 for ^{90}Sr to 466 for ^{60}Co. The maximum surface level given in Table 8.2-12 is assumed to be the same for all three of the aforementioned areas that contain contaminated soil and is used in Appendix F to determine the maximum annual dose to the maximum-exposed individual living on the decommissioned reference site.

TABLE 8.2-12. Reference Radionuclide Inventory, Soil Contamination on the Reference Test Reactor Site[a]

Radionuclide	Deposited Radioactivity (pCi/g) at Decay Times of:				
	Shutdown	10 Years	30 Years	50 Years	100 Years
^{60}Co	1.73×10^{2}	4.7×10^{1}	3.4×10^{0}	2.4×10^{-1}	3.4×10^{-4}
^{63}Ni	1.37×10^{1}	1.28×10^{1}	1.1×10^{1}	9.7×10^{0}	6.9×10^{0}
^{90}Sr	8.23×10^{0}	6.48×10^{0}	4×10^{0}	2.5×10^{0}	7.5×10^{-1}
^{134}Cs	1.59×10^{1}	5.5×10^{-1}	6.6×10^{-4}	7.8×10^{-7}	3.9×10^{-14}
^{137}Cs	6.59×10^{1}	5.23×10^{1}	3.3×10^{1}	2.1×10^{1}	6.6×10^{0}
^{239}Pu	3×10^{-2}	3×10^{-2}	3×10^{-2}	3×10^{-2}	3×10^{-2}

(a) Based on information supplied by NASA Lewis Research Center; early-1981 sample results.

REFERENCES

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

2. J. C. Ringle, T. V. Anderson, and A. G. Johnson, Safety Analysis Report for the Oregon State University Triga Research Reactor, August 1968.

3. T. V. Anderson, et al., Oregon State University TRIGA Reactor Annual Report, Corvallis, Oregon, August 1980.

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

5. Environmental Report - Plum Brook Reactor Dismantling, NASA Lewis Research Center, February 1980.

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

7. K. J. Schneider and C. E. Jenkins, Technology, Safety and Costs of Decommissioning a Reference Nuclear Fuel Reprocessing Plant, NUREG-0278, Prepared by Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, October 1977.

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

9. U.S. Atomic Energy Commission, Final Environmental Statement Concerning Proposed Rule-Making Action: Numerical Guides for Design Objectives and Limiting Conditions for Operation to Meet the Criteria "As Low As Practicable" for Radioactive Material in Light Water-Cooled Nuclear Power Reactor Effluents, WASH-1258, Directorate of Regulatory Standards, Volume 1 of 3, Figure 6B-1, p. 6B-43 and Figure 6C-8, p. 6C-12, July 1973.

10. U.S. Atomic Energy Commission, Final Environmental Statement Related to Operation of Monticello Nuclear Generating Plant, Docket No. 50-263, pp. II-15 to II-26, November 1972.

11. Environmental Report, Plum Brook Reactor Dismantling, National Aeronautics and Space Administration, Lewis Research Center, February 1980.

12. Environmental Report, Plum Brook Mock-Up Reactor Dismantling, National Aeronautics and Space Administration, Lewis Research Center, February 1980.

13. Dismantling Plan, Plum Brook Reactor Dismantling, National Aeronautics and Space Administration, Lewis Research Center, February 1980.

14. Dismantling Plan, Plum Brook Mock-Up Reactor Dismantling, National Aeronautics and Space Administration, Lewis Research Center, February 1980.

15. NASA Plum Brook Reactor Facility Final Hazards Summary, Parts I, II, and III, Lewis Research Center, Cleveland, Ohio, December 1959.

9.0 SUGGESTED METHODOLOGY FOR DETERMINING ACCEPTABLE RESIDUAL RADIOACTIVE CONTAMINATION LEVELS FOR THE DECOMMISSIONED RESEARCH AND TEST REACTORS

This section contains a discussion of a suggested methodology for determining acceptable levels of residual radioactive contamination for decommissioned nuclear facilities. A demonstration of this methodology, using the radionuclide inventories and reference site associated with the reference research and test (R&T) reactors, is also presented. Additional information on radiation monitoring and survey requirements for determining residual radioactivity levels has also been recently developed by Oak Ridge National Laboratory.(1,2)

Detailed information about the mixture of radionuclides found at the reference R&T reactors prior to decommissioning is contained in Appendix E. Descriptions of the reference site and facilities are presented in Appendices A, B, and C. A discussion of the radiation dose models and parameters used to determine acceptable radioactive contamination levels is presented in Appendix F.

9.1 TECHNICAL APPROACH

The ultimate disposition of a decommissioned nuclear facility and its surrounding site depends on the degree and type of radioactive contamination present. Examination of existing guidelines and regulations shows a need for a general method of deriving acceptable levels of radioactive contamination to permit the unrestricted release of any decommissioned nuclear facility or site.(3) Currently, some guidance exists that defines levels of radioactive surface contamination that are acceptable to the Nuclear Regulatory Commission (NRC) for the termination of operating licenses.(4,5) Other guidance addresses specific types of nuclear facilities or accident situations involving radioactivity.(6-11)

None of these guidelines is flexible enough to accommodate the various radionuclide mixtures or site-specific features found at each unique nuclear

facility. This suggests that the methodology used to calculate the acceptable levels of residual radioactive contamination at decommissioned nuclear facilities should be based on a general concept capable of accommodating these unique radionuclide mixtures and site-specific features. One such general concept is to compare established annual dose limits with calculated annual doses to members of the public to determine acceptable radioactive contamination levels. The contamination levels derived from a maximum annual dose concept take into account the exposure of individuals to contamination remaining at a decommissioned facility or on its site following unrestricted release. The NRC has endorsed using an annual dose limit for determining unrestricted release of decommissioned property.[12,13] For the purposes of this study, acceptable residual radioactivity levels are calculated for an assumed annual dose rate of 10 mrem per year.[12]

9.1.1 Terminology and Definitions

The following terminology and definitions are used in developing a methodology for determining acceptable residual radioactive contamination levels based on annual dose:

Organs of Reference

The organs of the human body for which radiation doses are calculated. For this study, the organs of reference are the total body, lungs, bone, and thyroid. The total body is the head and trunk of the human body and includes active blood-forming organs, eye lenses, and gonads.

Exposure Pathways

The potential routes by which people may be exposed to radionuclides or radiation. Radiation exposure pathways in the environment that are considered in this study are: external exposure to contamination deposited on the ground, ingestion of food products containing radionuclides, and inhalation of airborne radionuclides. Radiation exposure pathways inside the reference research and test reactors are: external exposure from contaminated or activated room surfaces or equipment, and inhalation of airborne radionuclides. External

exposure from airborne radionuclides (air submersion) is not considered, since previous decommissioning studies have shown this exposure pathway to be insignificant compared to the others.[1,12,13]

Decay Periods

The mixtures of radionuclides in the residual inventories are constantly changing because of radioactive decay, resulting in annual doses that vary with time. This time dependence is demonstrated by calculating the doses at shutdown and at 10, 30, 50, and 100 years after shutdown of the reference R&T reactors.

Maximum-Exposed Individual

The individual who receives the maximum radiation dose to an organ of reference. The maximum-exposed individual is assumed to reside at the location of the highest airborne radionuclide concentration. Maximized exposure pathway parameters are used.

Annual Dose

The radiation dose equivalent calculated during any year following the start of continuous exposure. It is the sum of the dose received by an organ of reference during the year of interest from all exposure pathways and the dose received during that year from radionuclides deposited in the organ of reference during the previous years.

Maximum Annual Dose

The largest of the annual doses calculated to occur during the 50 years following the start of continuous exposure.

Additional terminology, radiation dose models and parameters, and derivations of the equations used to determine the annual dose are contained in Appendix F of Volume 2.

9.1.2 Definition of Use Categories

During the planning stages of decommissioning, a variety of future uses for the reference R&T reactor facilities and sites can be considered. These future uses fall into two general categories:

- Restricted Use - permits activities at the decommissioned research or test reactors within a nuclear-license restriction. Since this category requires a continuation of a nuclear license, the residual radioactive contamination levels may be similar to those found at other licensed operating nuclear facilities. Therefore, public and occupational exposure are controlled by the restrictions imposed by the nuclear license.
- Unrestricted Use - permits, without license restrictions, public use of the released portions of the decommissioned research or test reactors. For this study, the potential exposure to members of the public from residual radioactive contamination is assumed limited to an annual dose of 10 mrem to the maximum-exposed individual. In general, decommissioning a site may result in return of the land to public use.

No attempt is made to define all of the possible specific uses that may fall into these general categories. Continuing care is required to enforce the license restrictions of the restricted use category for the time period involved.

The unrestricted use category is the only one for which example acceptable residual contamination levels are calculated in this study. Acceptable contamination levels are calculated for: 1) a reference room within each facility, and 2) on the reference test reactor site. As a demonstration of the methodology, the test reactor site is assumed to be used for farming activities after decommissioning. No calculations are made for the research reactor site since it is assumed to remain free of radioactive contamination during routine operations.

9.1.3 Acceptable Radioactive Contamination Level Methodology

Determination of acceptable radioactive contamination levels for the reference R&T reactors is necessarily linked with other decommissioning considerations. The relationship of these contamination levels to both generic and site-specific studies is shown in Figure 9.1-1.

Acceptable radioactive contamination levels are calculated using a previously developed methodology,[3] together with the reference radionuclide inventories, the facility design, and the site parameters discussed in detail

- Federal Register, Vol. 46, No. 27, 1981. "Nuclear Regulatory Commission, 10 CFR Parts 30, 40, 50, 70, and 72, Decommissioning Criteria for Nuclear Facilities: Notice of Availability of Draft Environmental Impact Statement" (NRC).[12]
- Recommendations of the International Commission on Radiological Protection (ICRP), Publication 9.[16]
- Surgeon General's Guidelines (DHEW).[17]
- Appendix I of 10 CFR 50, Guides for Design Objectives for Light-Water-Cooled Nuclear Power Reactors (NRC).[18]
- Proposed Federal Guidance for the Environmental Limits of Transuranium Elements (EPA).[19]
- 40 CFR 190, Environmental Radiation Protection Standards for Normal Operations of Activities in the Uranium Fuel Cycle (EPA).[20]

Most of this guidance provides limits for operating nuclear facilities. Only the NRC Federal Register notice is specifically written to provide an annual dose limit that defines unrestricted release conditions for decommissioned property.

It is beyond the scope of this study to recommend annual radiation dose limits for public exposure to radioactive materials. Instead, acceptable residual radioactive contamination levels are calculated for a single assumed annual radiation dose limit of 10 mrem/yr. The selection of this annual dose limit is intended to be consistent with current NRC recommendations.[12] The actual levels achieved at nuclear facilities will be determined based on a cost-benefit study for each facility and site. It is also assumed in this study that any annual dose limit established for decommissioning applies to the maximum annual dose to any organ of reference, thus ensuring that applicable regulatory limits on annual radiation dose will not be exceeded.

The methodology for determining radioactive contamination levels, based on annual radiation dose, is illustrated in Figure 9.1-2 and is briefly discussed below:

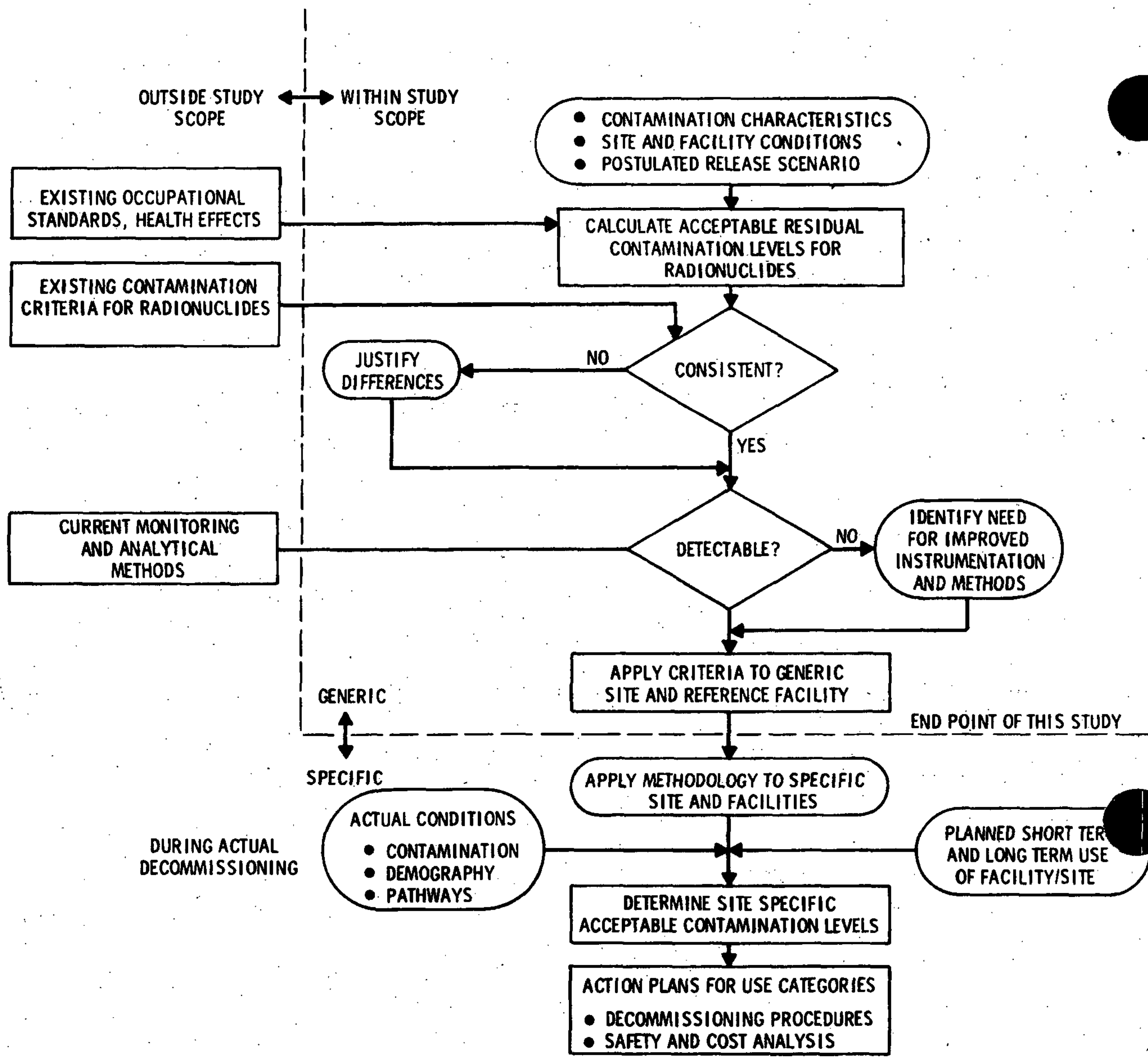


FIGURE 9.1-1. Relationship of Acceptable Radioactive Contamination Levels to Generic and Site-Specific Studies

in the appendices. The methodology for determining acceptable radioactive contamination levels is based on the assumption that an annual radiation dose limit is established for decommissioned nuclear facilities. Currently, there are no unique regulations or specific guidance on acceptable annual radiation doses to individuals working in the decommissioned facility or living on the decommissioned site. Guidance that could be interpreted as recommending annual radiation dose limits for decommissioned properties includes:

the suggested methodology both for the facility and for the site. In site-specific studies that use measured radioactivity levels, this step can be used as a decision point to determine the need for further decontamination efforts.

Calculation of Acceptable Levels Based on the Assumed Dose Limit

The acceptable radioactive contamination levels at the decommissioned reference R&T reactors are calculated and presented in the next section. These reported levels are determined by selecting the largest calculated organ dose derived from all exposure pathways. Acceptable contamination levels are reported in units of $\mu Ci/m^2$ of surface area.

9.2 EXAMPLE CALCULATIONS OF ACCEPTABLE RADIOACTIVE CONTAMINATION LEVELS FOR THE DECOMMISSIONED REFERENCE RESEARCH AND TEST REACTORS

The methodology for developing acceptable contamination levels is best demonstrated by calculating example levels for the reference R&T reactors, and for the test reactor site.

9.2.1 Acceptable Residual Radioactive Contamination Levels in the Reference Research and Test Reactor Facilities

Example acceptable residual contamination levels for the decommissioned reference R&T reactors are calculated using two radionuclide inventories discussed in Appendix E. For the reference research reactor, acceptable residual contamination levels are calculated using the inventory for neutron-activated stainless steel, given in Table E.1-5 of Appendix E. For the test reactor, acceptable residual contamination levels are calculated using the hot cell radionuclide inventory, given in Table E.2-9. The quantity of surface contamination in the reference R&T reactors is difficult to predict, since it will be specific to each reactor, and it is best determined by direct measurement at the time of reactor shutdown. To perform the calculations, it is necessary to predict the isotopic composition of the radionuclide mixture. The actual radioactivity levels are important in determining the degree of decontamination required; however, only the isotopic composition is necessary to determine the acceptable radioactive contamination levels. Therefore, for the example calculations the surface contamination levels are normalized to 1 $\mu Ci/m^2$ at reactor shutdown.

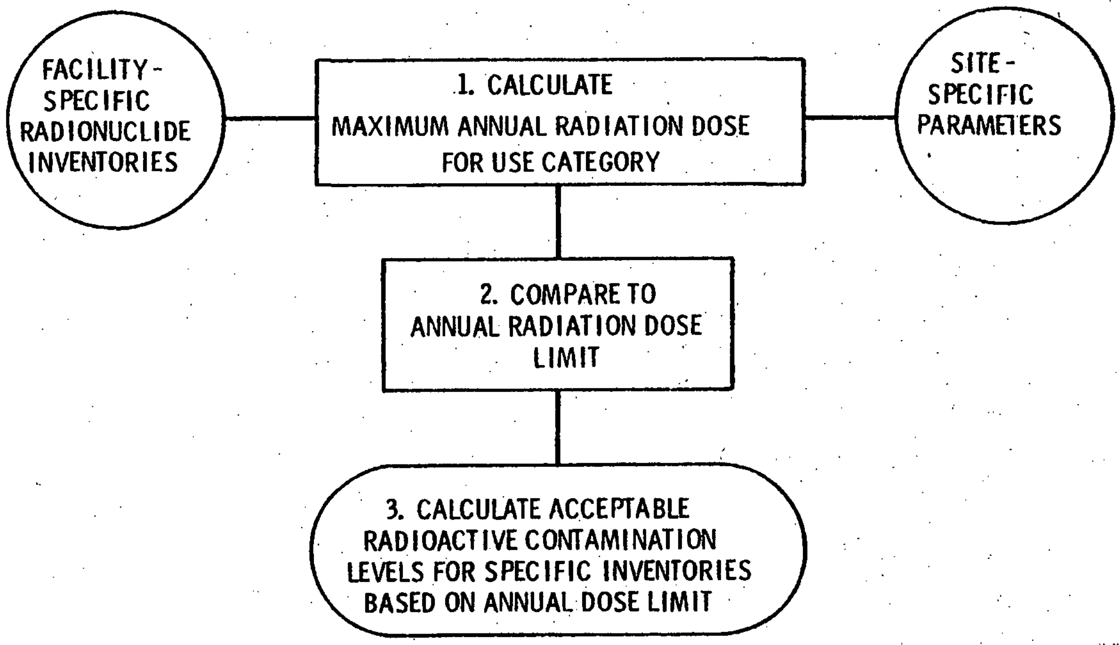


FIGURE 9.1-2. Suggested Methodology for Determining Acceptable Residual Radioactive Contamination Levels

Calculation of the Maximum Annual Radiation Dose for the Use Category Selected

For this study, the maximum annual radiation dose during 50 years of continuous exposure after decommissioning is calculated using the dose models discussed in Appendix F. Characteristic radionuclide inventories at the reference R&T reactors, used in the calculations, are presented in Appendix E. Maximum annual radiation doses are calculated for the decay periods of interest to illustrate the time dependence of the radionuclide inventories. Site-specific exposure pathway parameters, defined for the reference site in Appendix A, are used in these dose calculations. After decommissioning, unrestricted use of the facility and site is assumed.

Comparison of the Maximum Annual Dose to the Annual Dose Limit

For this study, since assumed or calculated levels of contamination are used, no direct comparison is made. Rather, the quantities of the radionuclide inventories corresponding to a dose of 10 mrem/yr are calculated to demonstrate

The residual radioactive contamination levels present during decommissioning are assumed to be appropriately monitored and suitably recorded. The decommissioning operations discussed in Section 10 and Appendix I are designed to remove surface radioactive contamination until the residual levels are acceptable for unrestricted use. These acceptable contamination levels for the reactor facilities are derived here based on radioactive surface contamination, with the assumption that all volumetric wastes generated during decommissioning are disposed of as radioactive wastes.

Acceptable radioactive contamination levels in the reference R&T reactors are calculated based on a reference room model, as discussed in Section F.3.1 of Volume 2. The room is assumed to have a floor surface area of 154 m^2 and walls 3 m high. A uniform deposition of radioactive contamination is assumed to be present on all of its surfaces (i.e., the floor, walls, and ceiling). For the maximum annual dose calculations, airborne radionuclide concentrations in the reference R&T reactor facilities are calculated using a constant resuspension factor of 5×10^{-6} m^{-1}, as discussed in Section F.3. Results of actual measurements of airborne radionuclide concentrations in decommissioned facilities could alter the allowable contamination levels calculated here.

The maximum annual doses to workers in the decommissioned R&T reactor facilities after they are released for unrestricted use are calculated using a 40-hour work week of continuing exposure for 50 years. Calculated maximum annual doses for the radioactive decay periods of interest are shown in Tables F.4-1 and F.4-2 for the research and test reactors, respectively. The doses are calculated for selected organs of reference for inhalation and external exposure pathways. Doses are listed for radionuclides that contribute more than about 1% of the dose to an organ from either exposure pathway. Ingestion of surface contamination by workers in decommissioned facilities is not considered to be a realistic pathway, and is not analyzed in this study.

Acceptable radioactive contamination levels for the most restrictive organs of reference are next calculated for a maximum annual dose of 10 mrem per year. These levels are expressed in units of microcuries per m^2 ($\mu Ci/m^2$), and are shown for the decay times of interest in Tables 9.2-1 and 9.2-2.

TABLE 9.2-1. Example Acceptable Residual Radioactive Contamination Levels Inside the Reference Research Reactor[a]

Time Exposure Begins (Years After Shutdown)[b]	Limiting Organ of Reference	Dominant Radionuclide Contributor To Dose	Acceptable Residual Contamination Levels ($\mu Ci/m^2$)[c]
0	Total Body	^{60}Co	0.066
10	Lung	^{60}Co	0.041
30	Lung	^{60}Co	0.040
50	Lung	^{60}Co	0.052
100	Lung	^{60}Co	0.074

(a) Corresponding to an annual dose of 10 mrem/yr.
(b) The time that continuous exposure begins.
(c) Based on the radionuclide inventory shown in Table E.1-5.

TABLE 9.2-2. Example Acceptable Residual Radioactive Contamination Levels Inside the Reference Test Reactor[a]

Time Exposure Begins (Years After Shutdown)[b]	Limiting Organ of Reference	Dominant Radionuclide Contributor To Dose	Acceptable Residual Contamination Levels ($\mu Ci/m^2$)[c]
0	Bone	^{90}Sr+D[d]	0.18
10	Bone	^{90}Sr+D	0.12
30	Bone	^{90}Sr+D	0.14
50	Bone	^{90}Sr+D, ^{244}Cm	0.16
100	Bone	^{90}Sr+D, ^{244}Cm	0.22

(a) Corresponding to an annual dose of 10 mrem/yr.
(b) The time that continuous exposure begins.
(c) Based on the radionuclide inventory shown in Table E.2-9.
(d) +D means plus daughter product radionuclides.

For the research reactor, external exposure is the dominant exposure pathway at all decay times, with only a small contribution from inhalation. However, it is the inhalation contribution to the total radiation dose that determines that the lungs are the most restrictive organ of reference for all

decay times after shutdown. The dose to lungs is controlled by ^{60}Co in the mixture. The change in the acceptable contamination level with time reflects the change in the composition of the residual mixture, because of radioactive decay.

For the test reactor, inhalation of resuspended surface contamination is the dominant exposure pathway at all decay times. Bone is the critical organ of reference because of the presence of ^{90}Sr and its daughter ^{90}Y in the reference radionuclide inventory. At longer decay times, ^{244}Cm also contributes to the bone dose. The acceptable contamination level changes with time, again reflecting the changing composition of the residual mixture because of radioactive decay.

The example acceptable contamination levels for the research reactor are about a factor of 2 more restrictive (less than) the levels for the test reactor. This is because of the higher-energy gammas from ^{60}Co in the research reactor radionuclides inventory, resulting in more restrictive external doses calculated using the reference room model.

9.2.2 Acceptable Residual Radioactive Contamination Levels on the Test Reactor Site

A discussion of the radioactive contamination expected to be present on the reference R&T reactor site is found in Appendix E. Since planned releases during routine operation of the reference research reactor are very small, and since no accumulation of contamination on the site occurs, no dose calculations are made. Thus, no example calculations of acceptable contamination levels on the research reactor site are made. For the test reactor, a limited area of the reactor site is assumed to be contaminated with the mixture and levels shown in Table E.2-10 of Appendix E.

Airborne concentrations of radionuclides in the environment are calculated using the time-dependent resuspension factor discussed in Section F.3.2 of Volume 2. At the time of reactor shutdown, the radionuclides are assumed to be mixed in soil to a depth of 10 mm, with no mechanical mixing or weathering effects. After decommissioning, the site is assumed to be used for farming, and plowing is assumed to mix the radioactive contamination to a depth of

0.15 m. A dry soil "surface-density" factor of 224 kg/m^2, mixed to a depth of 0.15 m, is used to determine the soil radioactivity concentration. It should be noted that the radioactive contamination levels defined for the site in Table E.2-10 are specific to measurements taken at one site. For specific sites, comprehensive measurements will be necessary at shutdown to characterize the quantity and mixture of the deposited contamination.

Maximum annual doses for the reference test reactor site are listed in Table F.4-3 at the decay times of interest for each of four organs of reference. This table contains the calculated doses for each exposure pathway, with listings of those radionuclides in the mixture that contribute 1% or more of the dose to any organ. Calculated acceptable residual contamination levels for the decommissioned test reactor site, corresponding to an annual dose of 10 mrem, are listed in Table 9.2-3.

For each decay time shown in Table 9.2-2, the most restrictive contamination level results from the annual dose to bone about 30 years after the start of continuous exposure. The bone dose is controlled by ^{90}Sr and its daughter ^{90}Y, which are accumulated in the body by ingestion of site-grown farm products. A summary of the acceptable residual radioactive contamination levels, based on the dose to bone, is listed in Table 9.2-4.

9.2.3 Acceptable Radioactive Contamination Levels on Research and Test Reactor Equipment

Two recent studies describe generic methods for estimating radiation doses to man from recycling radioactively contaminated materials reclaimed during decommissioning.[21,22] The method demonstrated in Reference 21 is for 27 radionuclides from six recycle pathways with a contamination level of 10 pCi/g. In reference 22, the dose impacts of recycling smelted alloys containing residual ^{99}Tc and low-enriched uranium are estimated. The results shown in References 21 and 22 are for generic cases and several key assumptions are made to obtain radiation dose estimates to exposed population groups. However, the methods presented in these references should be useful in determining acceptable residual contamination levels on decommissioned research and test reactor equipment.

TABLE 9.2-3. Example Residual Radioactive Contamination Levels for the Decommissioned Test Reactor Site[a]

Time Exposure Begins (Year After Shutdown)[b]	Maximum Year[c]	Organ of Reference	Dominant Radionuclide Contributor To Dose	Acceptable Radioactive Surface Contamination Levels ($\mu Ci/m^2$)	Acceptable Soil Contamination Levels: Mixed to 10 mm (pCi/g)	Acceptable Soil Contamination Levels: Mixed to 0.15 m (pCi/g)
0	1	Total Body	^{60}Co	0.44	30	1.9
	31	Bone	^{90}Sr+D[d]	0.21	14	0.93
	1	Lung	^{60}Co	0.45	30	2.0
	1	Thyroid	^{60}Co	0.45	30	2.0
10	37	Total Body	^{90}Sr+D	0.40	27	1.8
	42	Bone	^{90}Sr+D	0.11	7.4	0.49
	11	Lung	^{60}Co, ^{137}Cs	0.60	40	2.6
	11	Thyroid	^{60}Co, ^{137}Cs	0.60	40	2.6
30	59	Total Body	^{90}Sr+D	0.33	22	1.5
	62	Bone	^{90}Sr+D	0.088	5.9	0.39
	31	Lung	^{60}Co, ^{137}Cs	1.5	100	6.6
	31	Thyroid	^{60}Co, ^{137}Cs	1.5	100	6.6
50	79	Total Body	^{90}Sr+D	0.33	22	1.5
	82	Bone	^{90}Sr+D	0.091	6.1	0.40
	51	Lung	^{60}Co, ^{137}Cs	2.0	130	8.8
	51	Thyroid	^{60}Co, ^{137}Cs	2.0	130	8.8
100	129	Total Body	^{90}Sr+D	0.44	30	1.9
	131	Bone	^{90}Sr+D	0.11	7.4	0.49
	101	Lung	^{137}Cs	2.4	160	11
	101	Thyroid	^{137}Cs	2.4	160	11

(a) Corresponding to an annual dose of 10 mrem/yr to specific organs of reference.
(b) The time that continuous exposure begins.
(c) The year in which the maximum annual dose occurs following the start of continuous exposure.
(d) +D means plus daughters.

TABLE 9.2-4. Example Acceptable Residual Radioactive Contamination Levels for the Decommissioned Test Reactor Site[a]

Time Exposure Begins (Years After Shutdown)[b]	Acceptable Residual Radioactive Surface Contamination Levels ($\mu Ci/m^2$)[c]	Acceptable Soil Contamination Levels: Mixed to 10mm (pCi/g)	Acceptable Soil Contamination Levels: Mixed to 0.15m (pCi/g)
0	0.2	14	0.93
10	0.1	7.4	0.49
30	0.088	5.9	0.39
50	0.09	6.1	0.40
100	0.11	7.4	0.49

(a) Corresponding to an annual dose of 10 mrem/yr to Bone.
(b) The time that continuous exposure begins.
(c) Based on external exposure from contaminated ground and on internal exposure from inhalation and ingestion, as discussed in Appendix F.

Release of much of the equipment after decommissioning could be covered by standards developed by the ANSI Committee N13.12.[11] The complexities of decontaminating equipment for public release are great and are briefly discussed in Appendix N of Volume 2. Because decommissioning actual research or test reactors will require special administrative procedures to release equipment on a piece-by-piece basis, no further effort is made in this report to analyze equipment-release conditions.

9.3 EXISTING GUIDANCE ON RESIDUAL RADIOACTIVE CONTAMINATION

Existing guidance on acceptable radioactive contamination levels for unrestricted release of decommissioned nuclear facilities is found in Regulatory Guide 1.86,[4] the draft ANSI Standard N13.12,[11] and in a Federal Register notice by the NRC.[12] The levels reflected in References 4 and 11 are listed in Tables 9.3-1 and 9.3-2. The levels shown in Tables 9.3-1 and 9.3-2

TABLE 9.3-1. Regulatory Guide 1.86 Acceptable Surface Contamination Levels[4]

Radionuclide[a]	Average[b,c]	Maximum[b,d]	Removable[b,e]
U-nat, ^{235}U, ^{238}U and associated decay products	5 000 dpm α/100 cm^2	15 000 dpm α/100 cm^2	1 000 dpm α/100 cm^2
Transuranics, ^{226}Ra, ^{228}Ra, ^{230}Th ^{228}Th, ^{231}Pa, ^{227}Ac, ^{125}I, ^{129}I	100 dpm/100 cm^2	300 dpm/100 cm^2	20 dpm/100 cm^2
Th-nat, ^{232}Th, ^{90}Sr, ^{223}Ra, ^{224}Ra, ^{232}U, ^{126}I, ^{131}I, ^{133}I	1 000 dpm/100 cm^2	3 000 dpm/100 cm^2	200 dpm/100 cm^2
Beta-gamma emitters (nuclides with decay modes other than alpha emission or spontaneous fission) except ^{90}Sr and others noted above	5 000 dpm βγ/100 cm^2	15 000 dpm βγ/100 cm^2	1 000 dpm βγ/100 cm^2

(a) Where surface contamination by both alpha- and beta-gamma-emitting nuclides exists, the limits established for alpha- and beta-gamma-emitting nuclides apply independently.
(b) Used in this table, dpm (disintegrations per minute) means the rate of emission by radioactive material as determined by correcting the counts per minute observed by an appropriate detector for background, efficiency, and geometric factors associated with the instrumentation.
(c) Measurements of average contaminant should not be averaged over more than 1 m^2. For objects of less surface area, the average should be derived for each object.
(d) The maximum contamination level applies to an area of not more than 100 cm^2.
(e) The amount of removable radioactive material per 100 cm^2 of surface area should be determined by wiping that area with dry filter or soft absorbent paper, applying moderate pressure, and assessing the amount of radioactive material on the wipe with an appropriate instrument of known efficiency. When removable contamination on objects of less surface area is determined, the pertinent levels should be reduced proportionally and the entire surface wiped.

TABLE 9.3-2. ANSI N13.12 Surface Contamination Limits[11]

Radionuclide[a]	Activity Limit (dpm/100 cm^2) Total	Removable
Group 1:		
Nuclides for which the nonoccupational MPC_a[b] is 2×10^{-13} Ci/m^3 or less or for which the nonoccupational MPC_w[c] is 2×10^{-7} Ci/m^3 or less; includes Ac-227; Am-241, -242m, -243; Cf-249, -250, -251, -252; Cm-243, -244, -245, -246, -247, -248; I-125, I-129; Np-237; Pa-231; Pb-210; Pu-238, -239, -240, -242, -244; Ra-226, -228; Th-228, -230.	Nondetectable[d]	20
Group 2:		
Those nuclides not in Group 1 for which the nonoccupational MPC_a is 1×10^{-12} Ci/m^3 or for which the nonoccupational MPC_w is 1×10^{-6} Ci/m^3 or less; includes Es-254; Fm-256; I-126, -131, -133; Po-210; Ra-223; Sr-90; Th-232; U-232.	Nondetectable (β,γ)[e] 2 000 (α)	200
Group 3:		
Those nuclides not in Group 1 or Group 2.	5 000	1 000

(a) Values presented here are obtained from 10 CFR Part 20. The most limiting of all given MPC values (e.g., soluble vs. insoluble) are to be used. In the event of the occurrence of mixtures of radionuclides, the fraction contributed by each constituent of its own limit shall be determined and the sum of the fractions must be less than 1.
(b) MPC_a: maximum permissible concentration in air applicable to continuous exposure of members of the public as published by or derived from an authoritative source such as NCRP, ICRP or NRC (10 CFR Part 20 Appendix B Table 2, Column 1).
(c) MPC_w: maximum permissible concentration in water applicable to members of the public.
(d) The instrument utilized for this measurement shall be calculated to measure at least 100 pCi of any Group-1 contaminants uniformly spread over 100 cm^2.
(e) The instrument utilized for this measurement shall be calibrated to measure at least 1 nCi of any Group-2 beta or gamma contaminants uniformly spread over an area equivalent to the sensitive area of the detector. NOTE: Direct survey for unconditional release should be performed in areas where the background is $\leq$100 c/m. When the survey must be performed in a background exceeding 100 c/m, it may be necessary to use the indirect survey method to provide the additional sensitivity required.

are based on instrumentation capabilities for general categories of radionuclides, while the levels developed in this study using the pathways analysis approach are based on an assumed maximum annual dose of 10 mrem as recommended by the NRC.[12] Using the maximum annual dose as the general basis for determining acceptable radioactive contamination levels permits the necessary flexibility for considering the various radionuclide mixtures expected at decommissioned nuclear facilities.

9.4 SUMMARY OF EXAMPLE ACCEPTABLE CONTAMINATION LEVELS

The calculated acceptable levels of radioactivity reported in Tables 9.2-1, 9.2-2, and 9.2-4 are summarized in Table 9.4-1. In this table, the acceptable residual radioactivity levels for the reference R&T reactor facilities are characterized as surface contamination. For the test reactor site, surface contamination values are presented along with mass contamination values in units of pCi/g. The conversion from surface to mass contamination units is done assuming that the contamination is mixed in soil to a depth of 10 mm before plowing and to a depth of 0.15 m after plowing.

TABLE 9.4-1. Summary of Calculated Acceptable Residual Radioactive Contamination Levels for the Reference Research and Test Reactors

	Time Exposure Begins (Years After Shutdown)[a]	Limiting Organ	Acceptable Residual Contamination Levels Corresponding to an Annual Dose of 10 mrem/yr		
			Surface Contamination ($\mu Ci/m^2$)	Soil Contamination Mixed to 10 mm (pCi/g)	Soil Contamination Mixed to 0.15 m (pCi/g)
Research Reactor Facility[b]	0	Total Body	0.066	--	--
	100	Lung	0.074	--	--
Research Reactor Site	Not Applicable; no reactor-produced site contamination is anticipated (see Section E.1.2.3 of Appendix E).				
Test Reactor Facility[b]	0	Bone	0.18	--	--
	100	Bone	0.22	--	--
Test Reactor Site	0	Bone	0.21	14	0.93
	100	Bone	0.11	7.4	0.49

(a) The time that continuous exposure begins.
(b) In the facility, a determination of acceptable surface contamination levels, based on the mixture of radionuclides, is assumed to be used to help determine the necessary decommissioning procedures.

In summary, external exposure from ^{60}Co is the dominant exposure pathway at all decay times in the research reactor facility, with only a small contribution from inhalation. Inhalation of resuspended surface contamination is the dominant exposure pathway in the test reactor, resulting in a limiting dose to bone from ^{90}Sr and its daughter ^{90}Y. At longer decay times ^{244}Cm also contributes to the bone dose. On the test reactor site, the acceptable contamination levels are dominated by the dose to bone from ^{90}Sr through the ingestion of site-grown farm products. The acceptable contamination level on the test reactor site decreases with time, reflecting the radioactive decay of short-lived fission products in the initial radionuclide mixture.

9.5 RADIATION DETECTION CAPABILITIES

Federal regulations require that licensees conduct radiation surveys to ensure compliance with 10 CFR Part 20 limits.[23] Specifically, Paragraph 20.1(c) of 10 CFR Part 20 states that every reasonable effort should be made by the licensee to maintain radiation exposure "as low as reasonably achievable." Guidance on environmental sampling techniques to help meet these regulations is found in Regulatory Guides,[24-26] and in procedures developed by the DOE Environmental Measurements Laboratory.[27]

To ensure compliance with these regulations, personnel at operating R&T reactors routinely monitor both effluent and environmental levels of radioactivity. With the existence of annually recorded monitoring data and established sampling and laboratory measurement techniques, the ability already exists to identify radioactive species and to verify the radioactive contamination levels that correspond to the calculated acceptable contamination levels listed in Tables 9.2-1 and 9.2-2. A general discussion of environmental regulations or guidance and definition of the Lower Limit of Detection (LLD) for common laboratory methods is presented in this section. The laboratory methods discussed can be used to analyze samples from either a facility or its site.

The LLD is defined in Regulatory Guide 4.16 as being the smallest concentration of radioactive material in a sample that has a 95% probability of being detected above the system background.[28] For a particular counting system, the LLD is mathematically expressed by:

$$LLD = \frac{4.66\ S_b}{3.7 \times 10^4\ E\ V\ Y\ \exp(-\lambda\ \Delta t)} \qquad (9.1)$$

where:

LLD • the lower limit of detection, μCi/mℓ

4.66 • a factor relating the 95% confidence limit of a one-sided confidence factor for measurements where the background counting time equals the sample counting time

S_b • the standard deviation of the instrument background counting rate, counts/second

3.7×10^4 • the number of disintegrations per second per μCi

E • the detector counting efficiency, counts observed per disintegration

V • the sample volume, mℓ

Y • the fractional radiochemical yield; only applies when a radiochemical separation is performed on the sample

λ • the radioactive decay constant for the particular radionuclide, seconds^{-1}

Δt • the time elapsed between sample collection and counting.

The values of these parameters should be based on the actual characteristics of the system used, not on theoretically predicted values.

The LLD varies with the type of instrumentation used, the mixture of radionuclides in the sample, the counting time selected, the sample size, and the counting geometry. Using sodium iodide (NaI) detectors, the LLD levels for samples containing single or simple parent-daughter radionuclide pairs are listed in Table 9.5-1,[26] together with the example acceptable residual soil contamination levels for the reference test reactor site (contamination mixed in the top 10 mm of soil). Comparison of the values in the last two columns of the table shows that only ^{60}Co, ^{90}Sr, and ^{137}Cs could be readily detectable using NaI detector systems. Laboratory analysis with more sensitive equipment would be necessary to determine the relative radioactivity of the other radionuclides for use in the pathways analysis.

It should be noted that the LLDs for mixtures of radionuclides (as postulated for the reference test reactor site) would be expected to be significantly higher than those listed in Table 9.5-1 due to possible interferences between gamma rays of similar energy. Thus, quantitative measurements at these concentrations are far more difficult.

To overcome the interference problem it may be necessary to use more sophisticated detectors such as germanium-lithium (Ge[Li]) semiconductors. Typical values of the LLD for a Ge(Li) detection system are given in Table 9.5-2,

TABLE 9.5-1. Comparison of Lower Limits of Detection for NaI Systems with Calculated Example Acceptable Residual Soil Contamination Levels, for Selected Radionuclides[a]

Analysis	Lower Limit of Detection[b] Water (pCi/ℓ)	Vegetation (pCi/kg, Wet)	Soil (pCi/kg, Dry)	Example Acceptable[c] Residual Soil Contamination Level (pCi/kg, Dry)
^{3}H (HTO)	300	300[d]	--[e]	--[f]
^{54}Mn	15	150	50	--[f]
$^{58,60}Co$	15	150	50	110
^{65}Zn	30	300	100	--[f]
^{89}Sr	10	10	150	--[f]
^{90}Sr	2	2	30	560
^{95}Zr-Nb	10	150	100	--[f]
^{106}Ru-Rh	10	150	100	--[f]
^{129}I	2	10	--[e]	--[f]
^{131}I	0.4	2	--[e]	--[f]
$^{134,137}Cs$	15	150	100	800
^{140}Ba-La	15	150	100	--[f]
U	2	50	30	--[f]
Pu-Alpha	0.01	5	1	--[f]

(a) This table is based on similar values given in Regulatory Guide 4.8,[26] with adjustments and additions reflecting current experience at a commercial radioanalytical laboratory.
(b) The normal Lower Limit of Detection is defined in HASL 300, Appendix D (Rev. 8/74),[25] at the 95% confidence level. The LLD for radionuclides analyzed by gamma spectrometry varies according to the number of radionuclides encountered in environmental samples.
(c) Assumed dose limit is 10 mrem/yr, contamination mixed with top 10 mm of soil, using the mixture of radionuclides shown in Table E.2-11.
(d) After chemical extraction.
(e) Indicates that no data are available for these radionuclides in dry soil samples.
(f) Indicates that the radionuclide is not included in the test reactor site radionuclide inventory.

TABLE 9.5-2. Comparison of Lower Limits of Detection for a Typical Ge(Li) System with Calculated Example Acceptable Residual Soil Contamination Levels, for a Mixture of Fission Products

Radionuclide	Ge(Li) LLD dpm/Sample[a,b]	Example Acceptable Residual Soil Contamination Level dpm/Sample[a,c]	Radionuclide	Ge(Li) LLD dpm/Sample[a,b]	Example Acceptable Residual Soil Contamination Level dpm/Sample[a,c]
^{7}Be	68	--	^{106}Ru	68	--
^{54}Mn	4	--	^{125}Sb	21	--
^{57}Co	3	--	^{131}I	7	--
^{58}Co	4	--	^{137}Cs	7	78
^{60}Co	5	11	^{140}Ba	5	--
^{65}Zn	9	--	^{141}Ce	5	--
^{88}Y	5	--	^{144}Ce	24	--
^{95}ZR	11	--	^{147}Nd	59	--
^{103}Ru	8	--			

(a) The sample was in a 50-mm-diameter by 25-mm-deep sample-holder.
(b) For a detector efficiency of 1.2% for ^{137}Cs and a counting time of 1000 minutes.
(c) Assumed dose limit is 10 mrem/yr, contamination mixed with top 10 mm of soil.

together with example acceptable residual soil contamination levels (contamination mixed in the top 10 mm of soil).[28] The LLD values given are for samples consisting of air filters containing mixtures of fission products. The sample postulated for the acceptable residual level values has a volume of soil 50 mm in diameter and 25 mm thick. Comparison of the LLDs with the example acceptable residual levels in Table 9.5-2 shows that few radionuclides (^{60}Co, ^{137}Cs) can be successfully measured at levels corresponding to a dose of 10 mrem/yr to the maximum-exposed individual. However, if the relative composition of the mixture of radionuclides can be satisfactorily determined by careful laboratory means, and if this mixture is constant at all locations, the two radionuclides that can be measured at the example acceptable level can serve to monitor compliance with the 10 mrem/yr dose limitation.

A more detailed discussion of instrumentation and radiation survey concerns for termination survey criteria after decommissioning is given in Reference 1.

REFERENCES

1. C. F. Holoway, et al., Monitoring for Compliance with Decommissioning Termination Survey Criteria, NUREG/CR-2082, Prepared by Oak Ridge National Laboratory for the U.S. Nuclear Regulatory Commission, June 1981.

2. J. P. Witherspoon, Technology and Costs of Termination Surveys Associated With Decommissioning of Nuclear Facilities, NUREG/CR-2241, Oak Ridge National Laboratory for U.S. Nuclear Regulatory Commission, February 1982.

3. K. J. Schneider and C. E. Jenkins, Technology, Safety and Costs of Decommissioning a Reference Nuclear Fuel Reprocessing Plant, NUREG-0278, Section 6, Prepared by Pacific Northwest Laboratory for the U.S. Nuclear Regulatory Commission, October 1977.

4. U.S. NRC, Termination of Operating Licenses for Nuclear Reactors, Regulatory Guide 1.86, June 1974.

5. U.S. NRC, Guidelines for Decontamination of Facilities and Equipment Prior to Release for Unrestricted Use or Termination of Licenses for By-product, Source or Special Nuclear Material, November 1976.

6. U.S. Code of Federal Regulations, Title 49, Part 173, "Transportation," Superintendent of Documents, GPO, Washington, DC, 1976.

7. U.S. ERDA, "Prevention Control and Abatement of Air and Water Pollution," U.S. ERDA Manual, Chapter 0510, April 2, 1975.

8. J. W. Healy, A Proposed Interim Standard for Plutonium in Soils, LA-5483-MS, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, January 1974.

9. C. E. Guthrie and J. P. Nichols, Theoretical Possibilities and Consequences of Major Accidents in ^{233}U and ^{239}Pu Fuel Fabrication and Radioisotopes Processing Plants, ORNL-3441, Oak Ridge National Laboratory, Oak Ridge, Tennessee, April 1964.

10. A. J. Hazle and B. L. Crist, Colorado's Plutonium-Soil Standard, Colorado Department of Health, Occupational and Radiological Health Division Denver, Colorado, 1975.

11. ANSI Standard N13.12, Control of Radioactive Surface Contamination on Materials, Equipment and Facilities to be Released for Uncontrolled Use, Published for ANSI National Trial and Use in August 1978.

12. U.S. NRC, Federal Register, "Nuclear Regulatory Commission, 10 CFR Parts 30, 50, 70, and 72, Decommissioning Criteria for Nuclear Facilities; Notice of Availability of Draft Environmental Impact Statement," Vol. 46, No. 27., Washington, DC, 1981.

13. G. D. Calkins, Plan for Reevaluation of NRC Policy on Decommissioning of Nuclear Facilities, NUREG-0436 (Rev. 1) (Supp. 2), U.S. Nuclear Regulatory Commission, Washington, DC, 1981.

14. R. I. Smith, G. J. Konzek and W. E. Kennedy, Jr., Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station, NUREG/CR-0130, Section 8, Prepared by Pacific Northwest Laboratory for the U.S. Nuclear Regulatory Commission, June 1978.

15. C. E. Jenkins, E. S. Murphy and K. J. Schneider, Technology, Safety and Costs of Decommissioning a Reference Small Mixed Oxide Fuel Fabrication Plant, NUREG/CR-0129, Section 8, Prepared by Pacific Northwest Laboratory for the U.S. Nuclear Regulatory Commission, February 1979.

16. "Recommendations of the International Commission on Radiological Protection," ICRP Publication 9, Pergamon Press, London, 1966.

17. Surgeon General, U.S. Public Health Service, Surgeon General's Guidelines, "Use of Uranium Mill Tailings for Constructive Purposes," Hearings Before the Subcommittee on Raw Materials of the Joint Committee on Atomic Energy, October 28 and 29, 1971, pp. 52-54, 1971.

18. Code of Federal Regulations, Title 10, Part 50, Appendix I, "Licensing of Production and Utilization Facilities," Superintendent of Documents, GPO, Washington, DC, 1976.

19. U.S. Environmental Protection Agency, Proposed Guidance on Dose Limits for Persons Exposed to Transuranium Elements in the General Environment, EPA 520/4-77-016, September 1977.

20. U.S. Code of Federal Regulations, Title 40, Part 190, "Environmental Radiation Protection Standards for Nuclear Power Operations," Superintendent of Documents, GPO, Washington, DC, January 1977.

21. F. R. O'Donnell et al., Potential Radiation Dose to Man from Recycle of Metals Reclaimed from a Decommissioned Nuclear Power Plant, NUREG/CR-0134, ORNL/NUREG/TM-215, Prepared by Oak Ridge National Laboratory for the U.S. Nuclear Regulatory Commission, December 1978.

22. U.S. NRC, Draft Environmental Statement Concerning Proposed Rulemaking Exemption from Licensing Requirements for Smelted Alloys Containing Residual Technetium-99 and Low-Enriched Uranium, NUREG-0518, U.S. Nuclear Regulatory Commission, Washington, DC, October 1980.

23. U.S. Code of Federal Regulations, Title 10, Part 20, "Standards for Protection Against Radiation," Superintendent of Documents, GPO, Washington, DC, 1978.

24. Directorate of Regulatory Standards, Measurements of Radionuclides in the Environment, Sampling and Analysis of Plutonium in Soil, Regulatory Guide 4.5, U.S. Nuclear Regulatory Commission, Washington, DC, May 1974.

25. Directorate of Regulatory Standards, Measurements of Radionuclides in the Environment, Strontium-89 and Strontium-90 Analysis, Regulatory Guide 4.5, U.S. Nuclear Regulatory Commission, Washington, DC, May 1974.

26. Directorate of Regulatory Standards, Environmental Technical Specifications for Nuclear Power Plants, Regulatory Guide 4.8, U.S. Nuclear Regulatory Commission, Washington, DC, December 1975.

27. J. H. Harley, ed., HASL Procedures Manual, HASL-300, Supplement 5, Health and Safety Laboratory, HASL-300 Rev., New York, New York, August 1977.

28. J. H. Harley, ed., HASL Procedures Manual, HASL-300, Supplement 2, Health and Safety Laboratory, New York, New York, August 1974.

10.0 DECOMMISSIONING ACTIVITIES AND MANPOWER REQUIREMENTS

This section contains information concerning the activities and manpower requirements for the three different approaches to decommissioning the reference research and test (R&T) reactors: DECON, SAFSTOR, and ENTOMB. For each reference reactor, information on deferred decontamination is also included. The information presented here is a summary of the appropriate sections of Appendices H, I, J, and K in Volume 2, which respectively contain the generic decommissioning information and the details for the three decommissioning alternatives for the reference R&T reactors.

10.1 ACTIVITIES AND MANPOWER REQUIREMENTS FOR DECOMMISSIONING THE REFERENCE RESEARCH REACTOR

This subsection contains information concerning the activities and manpower requirements for decommissioning the reference research reactor via the DECON, SAFSTOR, and ENTOMB alternatives.

10.1.1 Activities and Manpower Requirements for DECON at the Reference Research Reactor

DECON is the decommissioning alternative that leads to the earliest termination of the owner's nuclear license. Planning and preparation activities, DECON activities, and the schedule and manpower requirements for DECON are presented in this subsection.

10.1.1.1 Planning and Preparation Activities

Effective planning and preparation work before final reactor shutdown is vital to successful completion of DECON activities at the reference research reactor facility. Planning and preparation for DECON is accomplished during the 12 months prior to final reactor shutdown.

Planning and preparation activities include the following:

- satisfying regulatory requirements
- gathering and analyzing data
- developing detailed work plans and procedures
- designing, procuring, and testing special equipment

- selecting and training staff
- selecting specialty contractors
- installing additional HEPA filters.

These activities are discussed in the following paragraphs.

Satisfying Regulatory Requirements. The current status of NRC regulatory requirements is presented in Section 6. Activities undertaken to satisfy these regulatory requirements are described here.

The major requirements are: 1) providing the necessary documentation for amending the facility operating license to "possession-only" status, and 2) obtaining an NRC dismantling order.

In requesting an amended license, the licensee must provide:

- a description of the current facility status
- an inventory of the onsite radioactive materials
- a description of the proposed decommissioning activities
- a description of the proposed measures to prevent criticality and to minimize radioactive releases
- any proposed changes to the technical specifications (e.g., deletion of specifications relating solely to plant operation)
- safety analyses of both the proposed activities and the proposed specification changes.

An NRC dismantling order is required for DECON. The request for such an order must include a decommissioning plan providing:

- a description of the ultimate facility status
- a description of the decommissioning activities (including radioactive material disposal and site decontamination) and the associated environmental and safety precautions
- a safety analysis of the plan and any resultant releases
- a safety analysis of the plant in its ultimate status.

In addition to the aforementioned documentation, the licensee must submit a radioactive waste handling plan, a quality assurance plan, an environmental report, and security and safeguards plans. Updated information concerning the financial qualification of the licensee may also be required (see Section 6.2 of Section 6 for further details).

Gathering and Analyzing Data. A large body of data is gathered and analyzed during the planning and preparation phase of decommissioning. These data help satisfy the regulatory requirements discussed in the previous paragraphs, particularly the inventory of radioactive materials and the various safety analyses. In addition, they provide the bases for planning the decommissioning tasks and for selecting the appropriate methods and equipment.

Included in this activity is a comprehensive survey of radiation dose rates and contamination levels in the facility. This survey, taken after final reactor shutdown, provides information for determining decontamination and temporary shielding requirements. It also provides initial data on radiation dose rates likely to be encountered during the various decommissioning tasks.

Developing Detailed Work Plans and Procedures. Detailed work plans and procedures are developed based on the information gathered during data gathering and resultant analyses and provided to the NRC with the license amendment and dismantling order requests. These detailed plans and procedures contain all the information required to actually carry out the decommissioning tasks. They address the following items:

- decommissioning methods
- schedules and sequences of events
- radioactive waste management
- contamination control
- radiological and industrial safety
- equipment requirements.

Quality assurance, security, and environmental constraints are also considered. The plans and procedures cover all aspects of the decommissioning project.

Designing, Procuring, and Testing Special Equipment. Any special equipment required to complete the decommissioning project is identified during planning and preparation. Designs and specifications are prepared for each item required. When the item is procured, it is inspected to verify that it meets specifications and complies with applicable QA and safety requirements. It is then tested to ensure that it performs as required. The testing also serves to train personnel in the use of the equipment and to provide pertinent data on its operation.

Selecting and Training Staff. At the start of planning and preparation, a decommissioning organization is created for the facility. Staff requirements are identified, and critical positions are filled with key engineering and operating personnel. The personnel are trained as required to fulfill their roles in the organization; special emphasis is given to the use of new and unique equipment and procedures. Organization of the decommissioning staff is discussed in detail later in this subsection.

Selecting Specialty Contractors. During planning and preparation, the decommissioning planning staff identifies and selects the specialty contractors required to decommission the facility. These contractors perform unique services outside of the expertise or capability of the staff. After the needs are identified, contractors are invited to bid on the required work packages. Contractual agreements are concluded prior to the start of the actual decommissioning, if possible, to ensure the uninterrupted completion of the project. Specialty contractor requirements are also discussed later in this subsection.

Installing Additional HEPA Filters. Prior to the start of the actual decommissioning tasks, HEPA filters are installed outboard of the blower in the HVAC exhaust system of the Reactor Building. These filters are installed to lessen the atmospheric release of airborne radioactivity generated during DECON, because many of the tasks are expected to generate airborne contamination that exceeds that produced during normal plant operation.

10.1.1.2 DECON Activities

The activities and requirements of DECON for the reference research reactor are discussed in this subsection, including decontamination, disassembly

and disposal, quality assurance, environmental surveillance, specialty contractors, and essential systems and services.

Decontamination. Decontamination is necessary to remove the radioactive contamination from selected systems and components. The objectives of the decontamination effort are twofold: first, to reduce the radiation levels throughout the facility in order to minimize personnel exposure during disassembly; and second, to attempt to clean as much material as possible to unrestricted levels, thereby permitting salvage of valuable material and reducing the quantities of material that must be packaged and shipped to a disposal site.

In this study, however, for several reasons, no credit is taken for the potential effectiveness of the decontamination effort in achieving reductions of the radioactive contamination to levels that permit unrestricted release of the material. First, the effectiveness of the methods has not been demonstrated to any major degree. Second, the levels of residual radioactivity that are permitted on material that is returned to the commercial stream are not defined by any regulation and third, depending on the acceptable limits of residual radioactivity, the costs of adequate radiation surveys and possible repeated cleanings to achieve releasability may be greater than the salvage value of the released material.

Decontamination methods are discussed in detail in Section G.4 of Appendix G in Volume 2. However, it is anticipated that since external radiation doses to workers will be low, most decommissioning operations, including decontamination tasks, will be efficient, hands-on activities. In general, water-jet decontamination proceeds concurrently with draining the contaminated water from tanks and pools.

Disassembly and Disposal. Disassembly of the reference research reactor is started after the reactor is defueled, systems and components are decontaminated, and temporary shielding is installed where a comprehensive radiation survey indicates the need.

The exact component removal sequence within a given system or locality is dictated by the component's accessibility and the anticipated personnel

exposures during removal. When possible, items that contribute significantly to the general level of exposure in the work area are either removed first or are temporarily shielded while the work goes on. Systems are unbolted at flanges when possible and cut into manageable sections, using an appropriate cutting device (plasma-arc torch, oxyacetylene torch, or power hacksaw). Piping is cut into lengths compatible with standard shipping boxes. Similarly, tanks and pool liners are cut into plate segments appropriately sized. In this study, all initially contaminated materials are assumed to remain contaminated to greater than unrestricted-use levels, even after decontamination, and are packaged for disposal as radioactive waste.

Packaging of radioactive materials for disposal is accomplished in accordance with DOT regulations published in 49 CFR Parts 173 through 178, and with NRC regulations published in 10 CFR Part 71 and Regulatory Guide 7.1. containers are lined with shielding material when necessary to reduce surface dose rates to acceptable levels. Some items such as the heat exchanger may have openings welded shut and be shipped using the outer shell of the exchanger as the container.

Shipping of packaged contaminated materials from the facility to a waste burial site is accomplished using a trucking company that specializes in transporting special materials. The volume of materials to be transported and the number of shipments required are estimated in Section I.1.3 of Appendix I.

The reference TRIGA reactor is postulated to be removed essentially intact after only minor remote cutting for disconnection from experimental facility components. The LL-50-100 cask[a] selected to house the complete reactor core internals intact has considerable excess length to house the cut segments of the reactor vessel as well. Therefore, the neutron-activated components can be transported in one shipment.

(a) This ATCOR Inc. cask is licensed by the Department of Transportation under Special Permit No. 6601 for large-quantity radioactive material shipments.

Small contaminated equipment is removed and packed in standard shipping boxes. Large contaminated equipment having no external smearable contamination is sealed by welding steel plates over all openings. Such equipment is then shipped to a burial ground, using the outer shell as the packaging. Contaminated equipment that is too large to be shipped as a unit is cut up either into segments that will fit into standard shipping boxes or into segments that can be sealed with welded steel plates.

Contaminated concrete is removed using a concrete spaller, which is assumed to remove a surface layer about 50 mm thick. The rubble is packaged in standard shipping boxes for disposal.

Techniques for disassembly of the reference research reactor are described generically in Appendix G. A detailed discussion of the dismantlement of the reference research reactor is given in Section I.1 of Appendix I.

Quality Assurance. An extensive quality assurance program is carried on throughout the decommissioning effort to assure that all applicable regulations are met, to assure that the work is performed according to plan, to assure that the work does not endanger public safety, and to assure the safety of the decommissioning staff.

During the 12-month period prior to shutdown, QA personnel are active in the following areas:

- reviewing decommissioning plans for quality assurance involvement
- preparing inspection/test procedures as work plans are developed
- reviewing designs of test equipment for quality input
- ordering any inspection/test equipment required to perform the quality assurance/quality control function
- receiving procured equipment and verifying acceptance
- qualifying suppliers for fabrication of radioactive shipping containers
- preparing inspection/test procedures to be imposed on contractors

- preparing inspection plans for shipment of radioactive materials, containers, trucks, etc.
- finalizing the formal quality assurance plan.

The QA efforts during the actual DECON period include the following:

- performing QA functions for procurements
- qualifying suppliers
- auditing all project activities
- monitoring worker performance for compliance with work procedures
- verifying compliance of radioactive shipments with appropriate procedures and regulations
- performing dimensional, visual, nondestructive examinations or other required inspection services to assure compliance with work plans
- maintaining auditable files on the QA audits
- preparing a final report on overall performance of the DECON program with regard to the QA function.

More details of the anticipated elements of an appropriate quality assurance program for the DECON effort are given in Section G.7 of Appendix G.

Environmental Surveillance. An abbreviated version of the environmental monitoring program carried on during plant operation is continued during the DECON period. The purpose of the program is to identify and quantify any releases of radioactivity to the surrounding areas resulting from the DECON activities. The proposed program, detailed in Section G.8 of Appendix G, is sufficient to permit evaluation of any significant releases. For emergency situations involving releases from events such as fires or malicious acts that may necessitate prompt emergency action to minimize the risk to the public, additional short-term surveillance efforts are required.

After DECON is complete, a reduced 1-year follow-up program of environmental monitoring is carried out by the same organization that performed the earlier program.

Specialty Contractors. The only specialty contractor requirement during DECON of the reference research reactor is limited in scope to a hauling contractor, for transport of packaged radioactive materials to a disposal site. If following DECON the facility is demolished and the site is restored, demolition and landscaping contractors are also required. Demolition and site restoration are discussed in detail in Section L.1 of Appendix L.

Essential Systems and Services. All or parts of certain facility systems and services must remain in place and in service until all radioactive material is either removed from the facility or secured on the site, to prevent the release of significant quantities of radionuclides (or other hazardous materials) to the environment. Some systems and services are required for cleanup and disassembly activities. Others provide personnel health and safety protection. The required systems and services are listed in Table 10.1-1, together with the justification for retaining each.

As dismantlement and decontamination are completed in areas within the facility, the essential systems and services in these areas are deactivated and, if contaminated, removed as required. Continuous service to the remaining work areas is maintained as long as necessary.

10.1.1.3 DECON Schedule

The schedule and sequence of DECON tasks is shown in Figure 10.1-1. Detailed schedules and manpower estimates for DECON of each of the buildings are presented in Section I.1 of Appendix I in Volume 2. Initial planning for DECON of the reference research reactor facility begins about 12 months before final shutdown of the reactor, as discussed previously in Section 10.1.1.1 and shown in Figure 10.1-1.

After final shutdown, the reactor is defueled, and the spent fuel is shipped to an offsite repository. A logical pattern for cleanup, decontamination, dismantlement, packaging, and shipment is followed with the tasks associated with the reference research reactor scheduled as early as possible. Tasks associated with buildings other than the Reactor Building are undertaken early in the DECON schedule, with their respective radioactive materials prepared for shipment in the reactor room staging area, which is designated for

TABLE 10.1-1. Systems and Services Required During Decommissioning

System or Service	Justification
Normal and Emergency Electric Power	Operation of electrical equipment including HVAC, lighting, and radiation monitoring
HVAC Systems	Ventilation and confinement of radioactive contamination
Demineralized Water System	Maintain purity of reactor tank water during defueling and reactor vessel/internals removal
Service Water System	Decontamination, cleanup, fire protection, and potable water
Compressed Air Systems (control and service)	Operation of pneumatic controls and tools; personnel fresh air supply
Communications Systems	Facilitate and coordinate decommissioning activities
Radwaste Systems	Treatment of radioactive liquids, solids, and gases
Fire Protection System	Health and safety
Security Systems	Public safety and plant protection considerations
Radiation Monitoring System	Personnel safety
Anti-C Protective Clothing Laundry Facilities	Health and safety

this purpose, if they cannot be packaged at their point of origin. As shown in Figure 10.1-1, DECON at the reference research reactor is completed in 8 months.

10.1.1.4 DECON Staff Requirements

In this subsection, the organization of the decommissioning staff and the types and numbers of decommissioning workers needed for DECON are discussed.

Organization of the Decommissioning Staff. The decommissioning staff for the reference research reactor is organized as shown in Figure 10.1-2. Ultimate responsibility for decommissioning activities rests with the university administration (the licensee). It is postulated that, for decommissioning of the reference research reactor, two staff committees oversee the operations and safety tasks. The operations branch, under a decommissioning superintendent, plans and performs the decommissioning activities while overseeing financial,

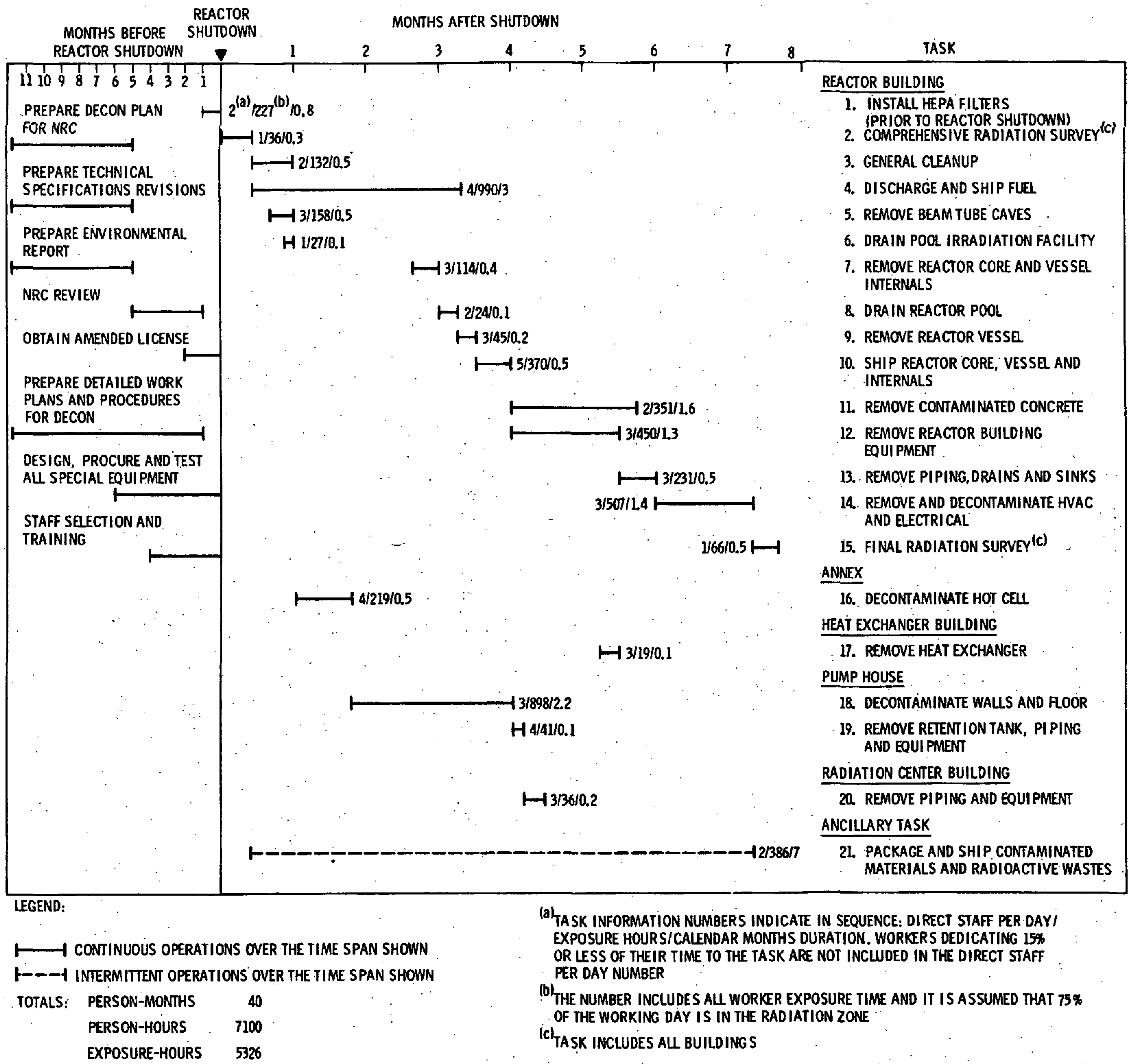


FIGURE 10.1-1. Overall Task Schedule and Sequence for DECON at the Reference Research Reactor

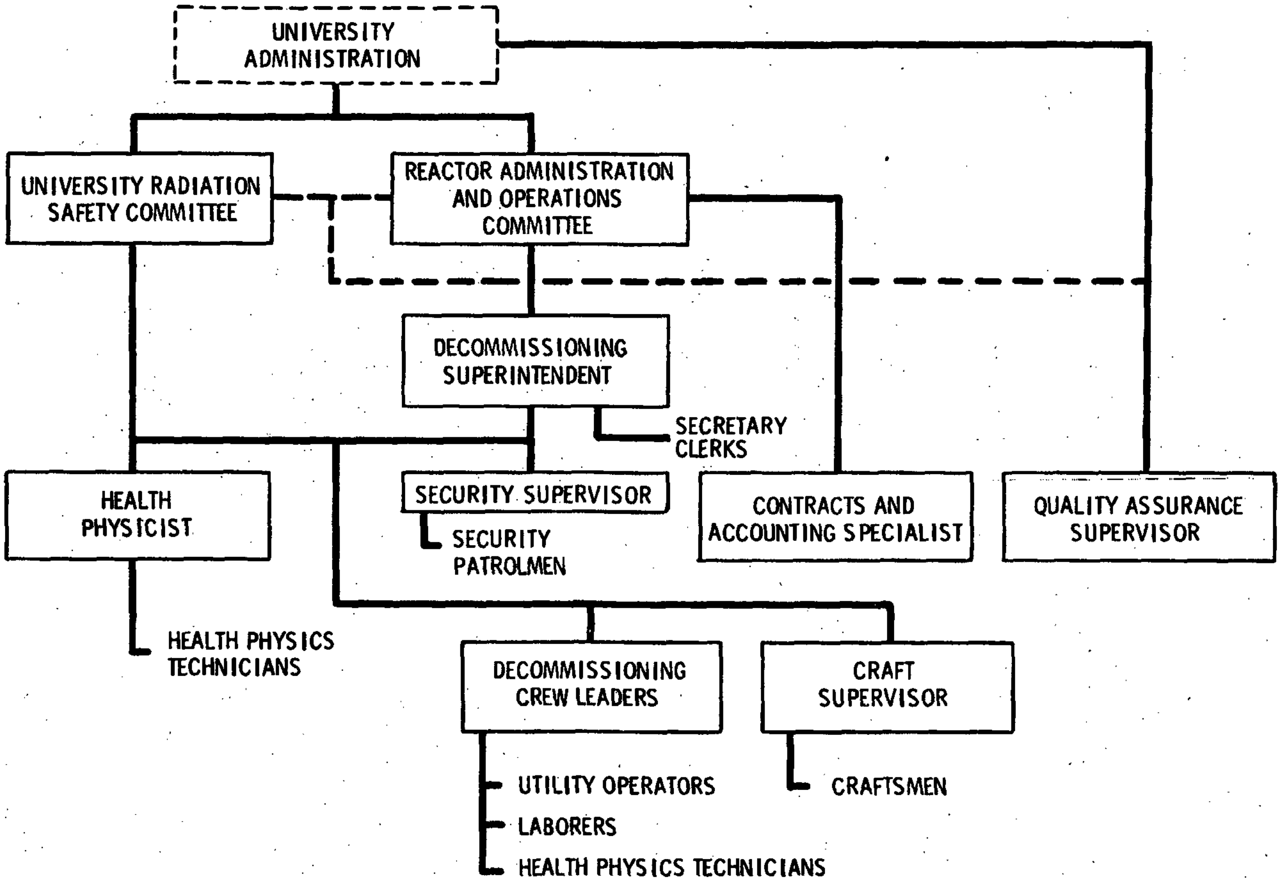


FIGURE 10.1-2. Decommissioning Staff Organization for the Reference Research Reactor

security, and safety functions. The safety branch, under a health physicist, plans and conducts radiological and industrial safety programs. As shown in Figure 10.1-2, the quality assurance supervisor interacts with both the operations and safety personnel while reporting to the staff committees, but he is directly responsible to the university administration.

DECON tasks, with few exceptions, are performed on a single 8-hour shift, five days per week. Each task presented in Figure 10.1-1 is postulated based on a crew size that provides a reasonably constant manpower loading for the bulk of the decommissioning project.

The crew on the basic working unit includes: a crew leader, a utility operator, a laborer, and the necessary craftsmen and health physics technicians. To the extent possible, decommissioning staff positions are filled

with facility operations and maintenance personnel already familiar with the reference research reactor. In this way, effective and efficient task performance is obtained. Use is made of student labor where knowledgeable personnel are available. The specific crew makeup for a given decommissioning task is tailored to fit the need. Specific crew assignments are described throughout the appendices in Volume 2.

The personnel interactions, activities, and responsibilities of key staff members are described below.

Reactor Administration and Operations Committee

This committee advises university administration on matters under its jurisdiction. Its main function is to provide overall planning and direction to the decommissioning superintendent and financial branch while interacting with the other facets of the organization.

Decommissioning Superintendent

This person plans and oversees all day-to-day decommissioning activities. Responsibilities include directing crew leaders, security supervisors, and the health physics branch.

Decommissioning Crew Leader

This individual directs a work crew in the performance of the actual decommissioning tasks.

Craft Supervisor

This person is responsible for maintenance of essential plant equipment and services as well as for assigning craft labor to particular decommissioning tasks. He instructs craftsmen in their assigned tasks and ensures the availability of tools and supplies.

Security Supervisor

This person is responsible for site security during decommissioning. This includes supervising the security personnel and, if necessary, providing liaison with offsite civil authorities. The security shift supervisor directs shift activities.

Contracts and Accounting Specialist

An experienced accountant, this individual is responsible for the financial aspects of the project. He prepares procurement documents and contracts and, with approval from the reactor administration and operations committee, disburses funds. Responsibilities include the maintenance of up-to-date financial accounts, while providing the committee with regular summary reports.

Quality Assurance Supervisor

Responsible for preparing and implementing the quality assurance plan for decommissioning, this person works with all branches of the organization to implement the plan. To ensure the independence of the quality assurance program, he reports directly to the university administration. He supervises a quality assurance unit, which maintains audit and job performance records and verifies that established safety review procedures are followed. (See Section G.7 of Appendix G for further discussion of quality assurance functions.)

University Radiation Safety Committee

This committee advises university administration on matters of radiological and industrial safety. It provides overall planning and direction to the health physicist and interacts with the decommissioning superintendent on matters of safety. Coordination is made with the reactor administration and operations committee on interrelated matters.

Health Physicist

This person recommends and enforces safety policy, both radiological and industrial. Responsibilities include maintenance of radiation exposure records, implementation of the environmental survey program, ensuring compliance with work procedures, and training and assigning health physics technicians to specific work tasks. In addition, the health physicist is responsible for the development and implementation of the in-plant radiation protection program, the survey instrumentation program including calibration, bioassay of personnel, airborne radioactivity monitoring, and ALARA planning.

DECON Staff Labor. Based on the schedule for dismantling the various systems and the estimated dose to accomplish each task, the types and number of

decommissioning workers needed to complete the radiation-zone work in the allotted time and within the assumed radiation dose limits are determined. Whole-body radiation doses to the decommissioning workers are limited in accordance with 10 CFR 20.101. The supervisors, utility operators, and health physics technicians are assumed to be long-time radiation workers whose annual exposure is limited to 5 rem/yr by the formula 5(N-18) of 10 CFR 20.101(b)(2). The craftsmen and laborers are assumed to have had little prior radiation exposure and, therefore, under 10 CFR 20.101(b)(1) and (2) may receive up to 3 rem/quarter, within the limitation of the formula 5(N-18) rems where "N" equals the individual's age in years at his last birthday. If a situation occurs where the manpower estimated for physically accomplishing a task results in a dose for a person in excess of these limits, an additional person is anticipated to be assigned to the task to keep the individual dose below set limits. In the manpower tables following, the manpower shown is adequate both to accomplish the task and to meet the occupational dose limits.

DECON tasks, with a few exceptions, are performed on a single 8-hr shift, 5 days per week. Each task in Figure 10.1-1 postulates a crew size that will provide a reasonably constant manpower loading for the bulk of the project. The overall dedicated manpower requirements for each DECON task are given in Table 10.1-2. The overall decommissioning worker requirements for the period following reactor shutdown are also shown in Table 10.1-2, and include 7000 man-hours of "hands-on" effort.

The total staff labor requirements for DECON at the reference research reactor are given in Table 10.1-3. The requirements are given in equivalent man-months for the 12 months before and the 8 months following final reactor shutdown, and include management and support staff, as well as decommissioning workers. A total effort of about 12.6 man-years is estimated for completion of DECON.

10.1.2 Activities and Manpower Requirements for SAFSTOR at the Reference Research Reactor

The SAFSTOR decommissioning alternative satisfies the requirements for protection of the public, while minimizing, in various degrees, the initial commitments of time, money, occupational radiation dose, and nuclear waste

TABLE 10.1-2. Dedicated Manpower Requirements for DECON at the Reference Research Reactor

Location/Task	Task Duration (months)	Dedicated Manpower Requirements (man-months)					
		Supervisors	Utility Operators	Laborers	Craftsmen	Health Physics Technicians	Totals
Reactor Building							
1. Install HEPA Filters[a]	0.80	0.12	--[b]	--	1.60	--	1.72
2. Comprehensive Radiation Survey[c]	0.27	--	--	--	--	0.270	0.27
3. General Cleanup	0.50	--	--	1.00	--	--	1.00
4. Discharge and Ship Fuel	3.00	3.0	2.5	0.50	--	1.50	7.50
5. Remove Beam Tube Caves	0.50	0.15	0.25	0.75	--	0.05	1.20
6. Drain Pool Irradiation Facility	0.12	0.03	--	0.12	0.05	0.01	0.21
7. Remove Reactor Core and Vessel Internals	0.36	0.16	0.02	0.39	0.25	0.04	0.86
8. Drain Reactor Pool	0.07	0.02	--	0.14	--	0.02	0.18
9. Remove Reactor Vessel	0.14	0.04	0.09	0.14	0.05	0.02	0.34
10. Ship Reactor Core, Vessel and Internals	0.50	1.00	1.20	--	--	0.60	2.80
11. Remove Contaminated Concrete	1.60	--	--	2.5-	--	0.16	2.66
12. Remove Reactor Building Equipment	1.30	0.43	0.14	2.41	0.30	0.13	3.41
13. Remove Piping Drains and Sinks[d]	0.52	0.22	--	1.00	0.48	0.05	1.75
14. Remove and Decontaminate HVAC and Electrical	1.40	--	--	2.7	1.00	0.14	3.84
15. Final Radiation Survey[c]	0.50	--	--	--	--	0.50	0.50
Annex							
16. Decontaminate Hot Cell	0.50	--	--	1.40	--	0.26	1.66
Heat Exchanger Building							
17. Remove Heat Exchanger	0.05	0.01	0.02	0.05	0.05	0.01	0.14
Pump House							
18. Decontaminate Walls and Floor	2.20	--	--	6.60	--	0.20	6.80
19. Remove Retention Tank Piping and Equipment	0.10	0.04	0.10	0.10	--	0.07	0.31
Radiation Center Building							
20. Remove Piping and Equipment From Waste Process Room	0.16	0.03	--	0.16	0.06	0.02	0.27
Ancillary Tasks							
21. Package and Ship Contaminated Materials and Radioactive Wastes[c]	7.0	--		2.73	--	0.02	2.75
TOTALS		5.25	4.32	22.64	3.84	4.07	40.17

(a) Performed before reactor shutdown.
(b) Denotes no manpower dedicated to task.
(c) Includes all buildings.
(d) Includes Heat Exchanger Building.

TABLE 10.1-3. Staff Labor Requirements for DECON at the Reference Research Reactor

Position	Staff Labor Requirements (man-months): Prior to Shutdown -12[(a)]	After Shutdown +2	+4	+6	+8	Total Staff Labor Required (man-years)
Management & Support Staff:						
Decommissioning Superintendent	4	2	2	2	2	1.00
Secretary	4	2	2	2	2	1.00
Clerk & Procurement Specialist	3	2	2	2	1	0.83
Contracts & Accounting Specialist	1.5	2	2	2	2	0.79
Security Supervisor	0	2	2	2	1.5	0.63
Security Patrolman[(b)]	0	6	6	6	4.5	1.88
Armed Guards[(b)]	0	6	4	0	0	0.83
Health Physicist & Shipment Specialist	3	2	2	2	2	0.92
Industrial Safety Specialist	1	2	2	2	1.5	0.71
Control Room Operator	0	2	1.6	0	0	0.30
Quality Assurance Specialist	1	2	2	2	1	0.67
Subtotals	17.5	30	27.6	22	17.5	9.56
Decommissioning Workers:[(c)]						
Crew Leader	0	2	3	1.0	0	0.50
Utility Operator	0	1.5	1.9	0.7	0	0.34
Laborer	0	6	7.5	7.0	3.0	1.96
Craftsman	1.6	0.1	0.3	1.1	0.8	0.33
Health Physics Technician	0	2	2	2	2	0.67
Subtotals	1.6	11.6	14.7	11.8	5.8	3.80
Totals	19.1	41.6	42.3	33.8	23.3	13.36

(a) Time relative to reactor shutdown.
(b) Based on information supplied by personnel at the reference reactor, when fuel dose is ≤100 rem/hr within 1 meter of the material's surface. Both response and access-control personnel are necessary on a 3-shift, 7-day basis. This requirement is applicable when 70%-enriched fuel is present at the site.
(c) Requirements following reactor shutdown are based on Table I.1-3.

repository space. This advantage is offset somewhat by the need to maintain the nuclear license, by the associated restrictions placed on the use of the property, and by the need for eventual decontamination of the facility. After an initial preparatory period following facility shutdown, this alternative requires continuing physical security and surveillance (safe storage) or structural integrity to ensure public protection. Planning and preparation activities, preparations for safe storage activities, schedule and manpower estimates, safe storage activities and requirements, and deferred decontamination at the end of the safe storage period for the reference research reactor facilities are discussed in the following subsections.

10.1.2.1 Planning and Preparation Activities for SAFSTOR

Successful implementation of SAFSTOR at the reference research reactor is dependent both on good planning and on completion of preparatory work before final reactor shutdown. Planning and preparation for safe storage is assumed accomplished during the 12 months prior to final reactor shutdown. Another planning and preparation period will occur just prior to deferred decontamination. Adjustments to decommissioning plans will be made and detailed work plans developed.

The planning and preparation activities for placing the reactor into safe storage are essentially the same as those described in Section 10.1.1.1 for DECON and are not discussed further here.

10.1.2.2 Safe Storage Preparations Activities

The activities and requirements to prepare the reference research reactor for safe storage include:

- decontamination, deactivation, and sealing methods
- spray painting and contaminated material transfer
- decontamination and isolation procedure
- quality assurance
- environmental surveillance
- specialty contractors
- essential systems and services.

These are discussed in the following paragraphs.

Decontamination, Deactivation, and Sealing Methods. Decontamination, deactivation, and sealing methods postulated for use in preparing the reference research reactor facility for safe storage are those in general use and are described generically in Appendix G. The objectives of the decontamination effort are to reduce the radiation levels and to immobilize radioactive contamination throughout the facility in order to minimize personnel exposure during subsequent decommissioning tasks and later safe storage activities.

All areas, except for the Reactor Building, are decontaminated to unrestricted release levels so that they can be returned to general use by the reference university. The bulk of the noncombustible, contaminated materials is stored within the Reactor Building, and all other equipment not necessary to safe storage is deactivated.

The potential spread of contamination from the Reactor Building is reduced by sealing all ports and entries from the reactor structure and from the Reactor Building. In addition, air flow leaving the areas containing radioactive material is filtered to prevent the spread of airborne contamination. Administrative controls coupled with strong physical barriers are utilized to prevent access to the Reactor Building, except for routine surveillance and maintenance activities.

Spray Painting and Contaminated Material Transfer. Spray painting and plastic wrapping are anticipated to be used for contamination control while transferring radioactive materials to the Reactor Building. Also, surfaces with radioactive contamination that cannot be removed by wiping or washing using standard decontamination solutions may be painted to fix the contamination in place (e.g., ladders and walkways in the Reactor Building).

Decontamination and Isolation Procedure. The 13-point procedure given below is postulated to be used to prepare the Reactor Building for safe storage:

1. Conduct initial radiation survey.
2. Vacuum interior surface areas.
3. Deactivate nonessential systems and equipment.

4. Clean interior surface areas and exposed surfaces of equipment and piping.
5. Clean remaining hot spots.
6. Apply protective paint (determined on a case-by-case basis).
7. Transfer contaminated equipment and materials into the Reactor Building from the other buildings as they are decontaminated.
8. Decontaminate and seal vent systems.
9. Install HEPA-filtered vents in the reactor structure and the Reactor Building.
10. Deactivate remaining nonessential systems and equipment.
11. Install intrusion alarms; provide for offsite readout for intrusion, fire, and radiation survey.
12. Conduct final radiation survey.
13. Secure the structure.

Quality Assurance. An extensive quality assurance program is carried on throughout the decommissioning effort to assure that all applicable regulations are met, to assure that the work is performed according to plan, to assure that the work does not endanger public safety, and to assure the safety of the decommissioning staff. The quality assurance program for safe storage is essentially the same as that for DECON, described in Section 10.1.1.2.

Environmental Surveillance. The required levels of environmental surveillance during the preparations for safe storage differ from those during safe storage. An abbreviated version of the environmental monitoring program carried on during plant operation is continued during the preparations for safe storage. This program is the same as that for DECON (see Section 10.1.1.2). It is postulated that personnel of the reference university staff conduct the monitoring program.

Specialty Contractors. As with DECON, the only specialty contractor required is the hauling contractor. This contractor is used for transport of the combustible radioactive materials to a shallow-land burial ground.

Essential Systems and Services. The required systems and services for preparations for safe storage differ from those required for safe storage. Essential facility systems and services such as power, heat, water, communications, and safety are maintained during the preparations for safe storage. These systems and services must remain in service until radioactive and/or contaminated materials are decontaminated, fixed in place, or removed from the facility, to prevent the release of significant quantities of radionuclides or other hazardous materials to the environment. The systems and services required for preparations for safe storage are the same as those required for DECON, which are discussed in Section 10.1.1.2.

10.1.2.3 Preparations for Safe Storage Schedule

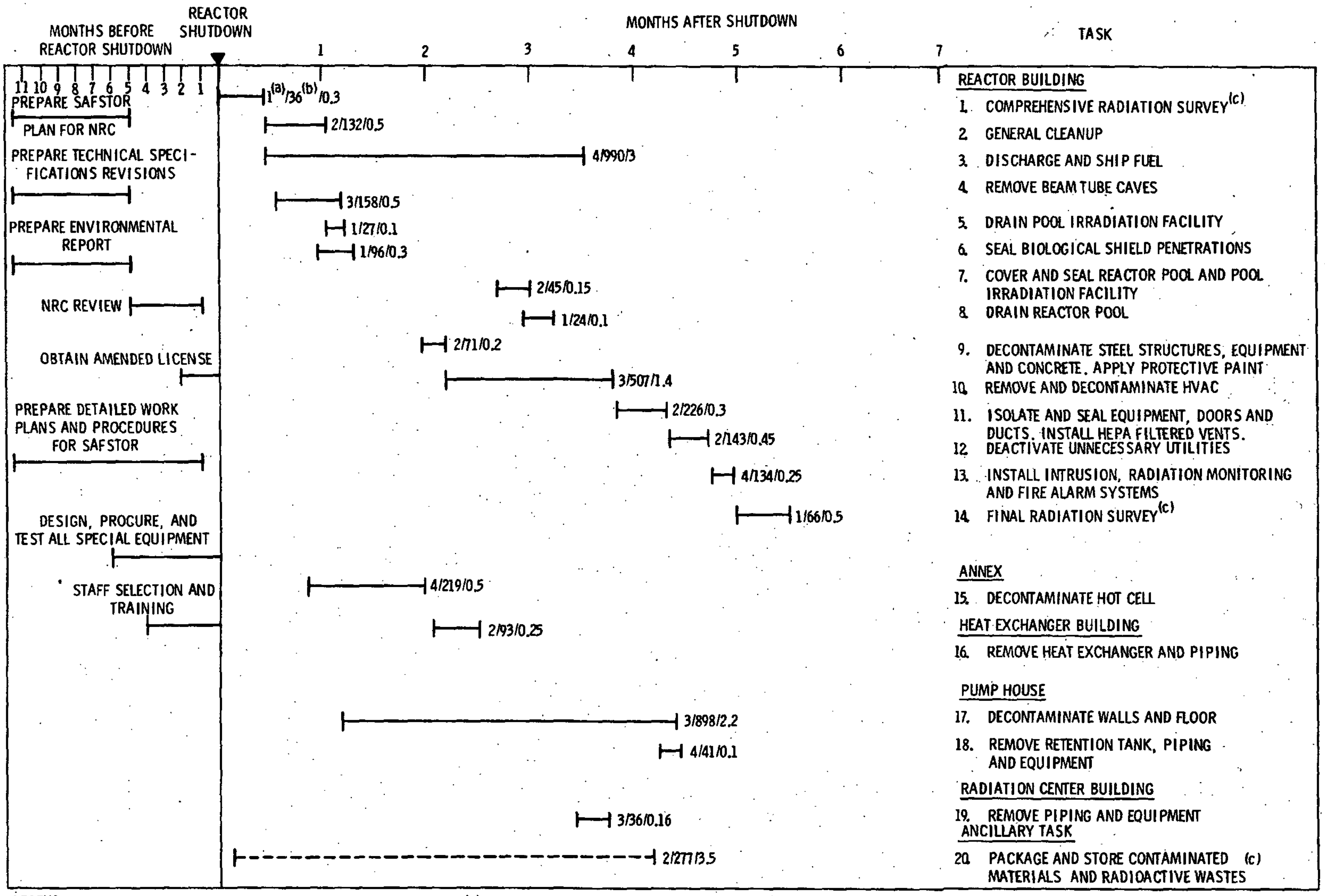
The schedule and sequence of safe storage decommissioning tasks is shown in Figure 10.1-3. Further schedule details are presented in Section J.1.2 of Appendix J. Initial planning for safe storage of the reference research reactor begins about 12 months before final shutdown.

After final shutdown, the reactor is defueled. The spent fuel is shipped either to an offsite storage location or to a reprocessing plant. Fuel shipment activities are not anticipated to interfere with other decommissioning tasks. However, pool draining activities, sealing activities, and selected cleaning activities must be scheduled only after the fuel has been removed. As shown in Figure 10.1-3, preparations for safe storage are completed in about 5 months.

10.1.2.4 Preparations for Safe Storage Staff Requirements

In this subsection, the organization of the decommissioning staff and the types and numbers of decommissioning workers needed for preparations for safe storage are discussed.

Organization of the Decommissioning Staff. The organization and functions of the preparations for safe storage decommissioning staff are the same as those for DECON, as discussed in Section 10.1.1.4.



LEGEND:

├──┤ CONTINUOUS OPERATIONS OVER TIME SPAN SHOWN

├- - -┤ INTERMITTENT OPERATIONS OVER TIME SPAN SHOWN

TOTALS: PERSON MONTHS 32.0
PERSON HOURS 5625
EXPOSURE HOURS 4850

(a) TASK INFORMATION NUMBERS INDICATE IN SEQUENCE: DIRECT STAFF PER DAY/EXPOSURE HOURS/CALENDAR MONTHS DURATION. WORKERS DEDICATING 15% OR LESS OF THEIR TIME TO THE TASK ARE NOT INCLUDED IN THE DIRECT STAFF PER DAY NUMBER.

(b) THIS NUMBER INCLUDES ALL WORKER EXPOSURE TIME AND IT IS ASSUMED THAT 75% OF THE WORKING DAY IS IN THE RADIATION ZONE.

(c) TASK INCLUDES ALL BUILDINGS.

FIGURE 10.1-3. Task Schedule and Sequence for Preparations for Safe Storage at the Reference Research Reactor

The preparations for safe storage tasks are performed on a single 8-hour shift, 5 days/week. Each task presented in Figure 10.1-3 is postulated based on a crew size that provides a reasonably constant manpower loading for the bulk of the decommissioning project.

Preparations for Safe Storage Manpower Requirements. Estimates of manpower requirements are based on the preparations for safe storage schedule and take into account both radiation dose limits and manpower limits needed to complete the individual tasks. The estimated number of decommissioning workers in each category is given for each month of preparations for safe storage in Table 10.1-4.

Staff labor requirements for the preparations for safe storage of the reference research reactor are presented in Table 10.1-5. The requirements are given in equivalent man-months for the 12 months before and the 5 months following final reactor shutdown and include management and support staff, as well as decommissioning workers. A total of about 8.8 man-years is estimated for completion of the preparations for safe storage.

10.1.2.5 Safe Storage Activities and Requirements

Activities at the reference research reactor site during the safe storage period include routine inspection, preventive and corrective maintenance on safety systems, and a regular program of radiation and environmental monitoring. Action is initiated immediately to correct any unusual or potentially unsafe conditions detected during the surveillance program. In addition to the routine tasks, a comprehensive inspection of the facility is performed annually by qualified third-party inspectors.

The safe storage period lasts until final disposition of the facility is made. The length of this period is determined by a cost-benefit analysis that balances the costs of surveillance and maintenance against the decreased decontamination costs and land use values, as well as by societal or regulatory issues.

Quality Assurance. A modest quality assurance program is anticipated to be carried on throughout the safe storage period to assure that the surveillance, security, and maintenance work does not endanger public safety or the

TABLE 10.1-4. Dedicated Manpower Requirements for Preparations for Safe Storage at the Reference Research Reactor

Location Task	Task Duration (months)	Dedicated Manpower Requirements (man-months) Supervisors	Utility Operators	Laborers	Craftsmen	Health Physics Technicians	Total Man-Months
Reactor Building							
1. Comprehensive Radiation Survey[a]	0.27	--[b]	--	--	--	0.27	0.27
2. General Cleanup	0.50	--	--	1.00	--	--	1.00
3. Discharge and Ship Fuel	3.00	3.0	2.5	0.50	--	1.50	7.50
4. Remove Beam Tube Caves	0.50	0.15	0.25	0.75	--	0.05	1.20
5. Drain Pool Irradiation Facility	0.12	0.03	--	0.12	0.05	0.01	0.21
6. Seal Biological Shield Penetrations	0.30	0.10	--	0.40	0.10	0.05	0.65
7. Cover and Seal Reactor Pool and Pool Irradiation Facility	0.015	0.02	0.03	0.18	0.08	0.02	0.33
8. Drain Reactor Pool	0.07	0.02	--	0.14	--	0.02	0.18
9. Decontaminate Steel Structures Equipment Concrete: Apply Protective Paint	0.23	0.07	--	0.45	--	0.02	0.54
10. Remove and Decontaminate HVAC	1.40	--	--	2.70	1.00	0.14	3.84
11. Isolate and Seal Equipment-Doors-Ducts. Install HEPA Filtered Vents	0.30	0.14	--	0.60	0.84	0.14	1.72
12. Deactivate Unnecessary Utilities	0.45	0.14	--	0.45	0.45	0.05	1.09
13. Install Intrusion, Radiation Monitoring and Fire Alarm System	0.25	0.25	--	0.14	0.50	0.14	1.03
14. Final Radiation Survey[a]	0.50	--	--	--	--	0.05	0.05
Annex							
15. Decontaminate Hot Cell	0.50	--	--	1.40	--	0.26	1.66
Heat Exchanger Building							
16. Remove Heat Exchanger and Piping	0.25	0.05	0.10	0.25	0.25	0.05	0.70
Pump House							
17. Decontaminate Walls and Floor	2.20	--	--	6.60	--	0.20	6.80
18. Remove Retention Tank-Piping and Equipment	0.10	0.04	0.10	0.10	--	0.07	0.31
Radiation Center Building							
19. Remove Piping and Equipment	0.16	0.03	--	0.16	0.06	0.02	0.27
Ancillary Task							
20. Package and Store Contaminated Materials and Radioactive Wastes	3.50	--	--	2.00	--	0.10	2.10
Totals		4.04	2.98	17.94	3.33	3.16	31.45

(a) Includes all buildings.
(b) Denotes no manpower dedicated to task.

TABLE 10.1-5. Staff Labor Requirements for Preparations for Safe Storage at the Reference Research Reactor

Position	Staff Labor Requirements (man-months) Prior to Shutdown	After Shutdown					Total Staff Labor Required
Management and Support Staff:	-12[a]	+1	+2	+3	+4	+5	(man-years)
Decommissioning Superintendent	2	1	1	1	1	1	0.58
Secretary	2	1	1	1	1	1	0.58
Clerk and Procurement Specialist	2	1	1	1	1	0.5	0.54
Contracts and Accounting Specialist	2	1	1	1	1	1	0.58
Security Supervisor	0	1	1	1	1	1	0.42
Security Patrolman[b]	0	3	3	3	3	2	1.2
Armed Guards[c]	0	3	3	3	1	0	0.83
Health and Physicist and Safety Specialist	2	1	1	1	1	1	0.58
Control Room Operator	0	1	1	1	0.5	0	0.29
Quality Assurance Specilist	1	1	1	1	1	0.5	0.46
Subtotals	11	14	14	14	11.5	8	6.06
Decommissioning Workers[c]							
Crew Leader		0.9	1.2	1.1	0.5	0.3	0.33
Utility Operator		0.9	0.8	1.0	0.3		0.25
Laborer		2.3	5.1	6.1	4.2	0.4	1.50
Craftsman		0.1	.2	1.0	1.3	0.7	0.28
Health and Physics Technician		1.0	1.0	1.0	1.0	1.0	0.42
Subtotals		5.2	8.3	10.2	7.3	2.4	2.78
Totals	11	19.2	22.3	24.2	18.8	10.4	8.84

(a) Time relative to reactor shutdown.
(b) Based on information supplied by personnel at the reference research reactor, when fuel dose is ≤100 rem/hr within 1 meter of the material's surface. Both response and access-control personnel are necessary on a three-shift, 7-day basis. This requirement is applicable when 70%-enriched fuel is present.
(c) Requirements following reactor shutdown are based on Table J.1-3.

safety of the safe storage staff. This program also assures that all applicable quality assurance, quality control, and records-keeping regulations and requirements are met.

Environmental Surveillance. An abbreviated version of the environmental monitoring program conducted during plant operation is carried out during safe storage. The purpose of this program is to identify and quantify releases of radioactivity to the environment. Details of this program, including the anticipated requirements, are discussed in Section G.8 of Appendix G.

Security. The protection of the public, principally against the consequences of their own actions, is an important dimension of the security program during safe storage. Conventional security detection and notification systems normally used to protect the reference university against loss or damage are augmented by audible alarms. These alarms, strategically located outside secured radiation zones, loudly warn an intruder of his potential danger. Silent sensors simultaneously alert onsite university security personnel.

Physical security to prevent inadvertent radiation exposure of safe storage personnel is provided by multiple-locked barriers. The presence of these barriers makes unauthorized entry into areas where radiation or contamination is present extremely difficult. Locks on the gates in the fence around the facility provide the first line of security. The fence is maintained in good condition throughout the safe storage period. Facility security is maintained at all times by intrusion alarms and high-security locks on exterior doors. Intrusion, fire, and radiation detection systems are remotely monitored onsite by members of the reference university security staff. Security personnel respond immediately or summon assistance as necessary, depending on the situaation indicated by the detection system alarms. Liaison with local law enforcement agencies is maintained and their assistance called for only when necessary.

A representative responsible for controlling authorized access into and movement within the facility is designated by the licensee. The representative's duties and responsibilities are discussed in a subsequent paragraph.

Essential Systems and Services Requirements. Systems and services required during safe storage are listed in Table J.1-2 in Appendix J, together with the justification for retaining each.

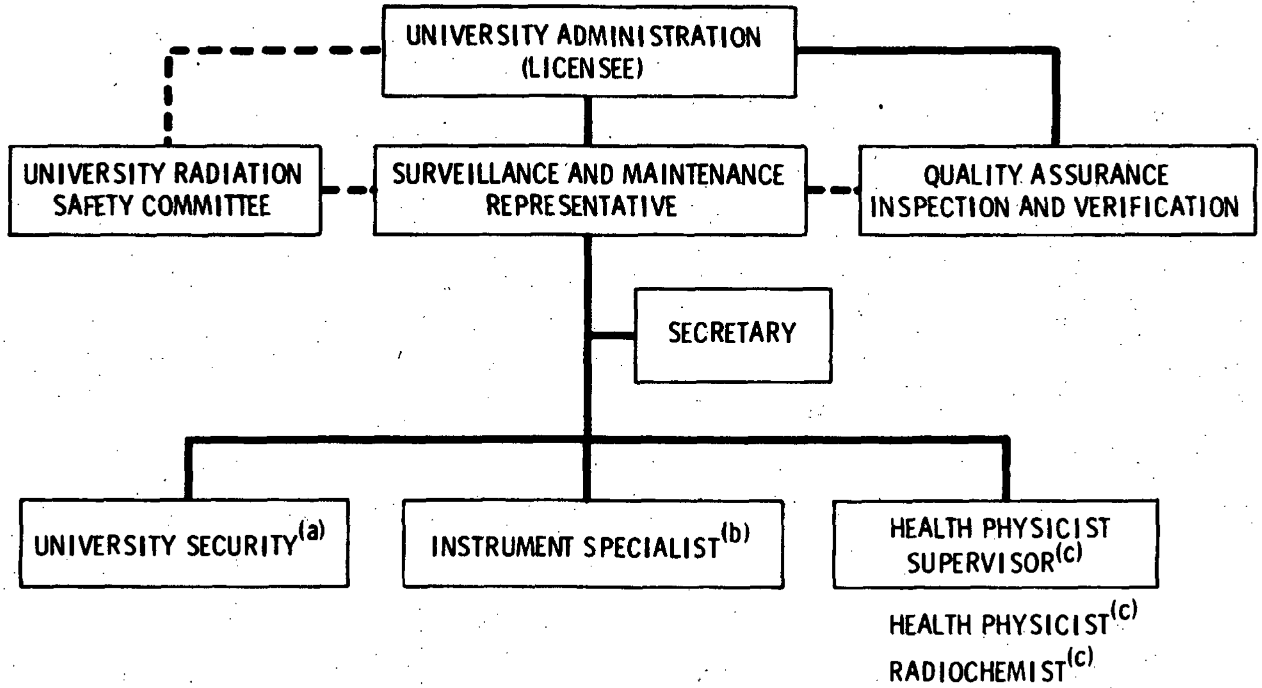
Safe Storage Staff Requirements. The staff organization shown in Figure 10-1.4, takes over the surveillance, maintenance, and security tasks for the duration of the safe storage period. The surveillance and maintenance is supervised by one part-time employee known as the surveillance and maintenance representative. In addition to controlling authorized access into and movement within the facility, he is charged with the responsibilities of appropriate actions and notifications regarding breaches of security, upkeep of plant surveillance and maintenance programs, and administrative reporting of these events as required by state and federal regulations.

10.1.2.6 Deferred Decontamination Activities and Manpower Requirements

Deferred decontamination achieves the degree of decontamination necessary for termination of the amended nuclear license for the reference research reactor after some period of safe storage. The facility and site must be shown to have residual radioactivity levels low enough to permit unrestricted use.

The same basic operations are assumed performed during deferred decontamination as are performed during DECON. The radioactive corrosion products on the inner surfaces of the piping, tanks, etc., consist mostly of ^{60}Co. It is unlikely that the residual radioactivity will decay to levels that permit unrestricted use before 50 years have elapsed. All of the systems have to be disassembled to make measurements on the interior surfaces of the systems to determine whether the material can be released or must be buried, regardless of the length of the safe storage period.

Operations such as reactor defueling and shipment of spent fuel are performed during preparations for safe storage and are not required during deferred decontamination. These activities are replaced by extensive training and familiarization of the decommissioning staff with the facility, since the staff cannot be made up of personnel from the operations staff after an extended period of safe storage. Additional effort is required to restore the services needed for decontamination throughout the facility and to remove the



(a) ASSIGNED TO SITE SECURITY TASK
(b) ASSIGNED TO EQUIPMENT MAINTENANCE TASK
(c) ASSIGNED TO ENVIRONMENTAL MONITORING TASK

FIGURE 10.1-4. Postulated Staff Organization for the Safe Storage Period

various locks, welded closures, and barricades that were installed to secure the facility during preparations for safe storage.

Significant reductions in radioactive waste volumes are expected with time as the radioactive decay processes decrease the radionuclide quantity in the stored wastes. Estimated cost savings due to this process are discussed in detail in Section J.1.6 of Appendix J.

In view of the foregoing considerations, it is reasonable to assume that a slightly smaller work force than was utilized for DECON is required for deferred decontamination, but over approximately the same period of time.

Work Schedule Estimates. Since the same basic efforts are required to decontaminate the reference research reactor regardless of when the decontamination takes place, the work schedules presented in Figure 10.1-1 for DECON

are assumed to be valid for deferred decontamination. Operations such as reactor defueling and fuel shipment are replaced by familiarization of the work force with the facility, by training, and by restoring essential services and unsecuring the facility.

Deferred Decontamination Staff Requirements. The management and support staff requirements are the same for deferred decontamination as they are for DECON. However, fewer decommissioning workers are required, since the radiation dose rates are lower when decontamination is deferred. Since the occupational radiation dose is lower because of radioactive decay, the extra workers needed to meet the occupational dose limits during DECON are not needed for deferred decontamination.

10.1.3 Activities and Manpower Requirements for ENTOMB at the Reference Research Reactor

ENTOMB, as defined by the NRC, implies that the radioactivity contained within the entombment structure will decay sufficiently during a 100-year entombment period to permit unrestricted release of the property at the end of that time. This requirement necessitates the removal and disposal elsewhere of materials containing long-lived radionuclides. Thus, the highly activated core internals are removed, but slightly activated materials are enclosed within the entombment structure. Much of the work associated with ENTOMB at the reference research reactor is the same as that postulated for DECON or SAFSTOR. Thus, the ENTOMB analysis deseribed in Section K.1 of Appendix K in Volume 2 for the reference research reactor is accomplished primarily by examining those efforts that are different from the DECON or SAFSTOR efforts, and including those efforts that are the same.

Planning and preparation, ENTOMB activities, and the schedules and manpower requirements for ENTOMB at the reference research reactor are summarized and discussed in the following subsections.

10.1.3.1 Planning and Preparation Activities

ENTOMB at the reference research reactor is a relatively complex undertaking and, consequently, the success of the project is greatly dependent on good planning and on completion of preparatory work before final reactor shutdown.

Planning and preparation for ENTOMB is assumed accomplished during the 12 months prior to final reactor shutdown.

The planning and preparation activities for ENTOMB are essentially the same as those described in Section 10.1.1.1 for DECON and are not discussed further here.

10.1.3.2 ENTOMB Activities

The major activities and requirements to accomplish entombment of the reference research reactor are:

- decontamination
- preparation of the entombment structure
- disassembly and disposition of radioactive materials
- quality assurance
- environmental surveillance
- specialty contractors
- essential systems and services.

These activities are discussed in the following paragraphs.

Decontamination. At final reactor shutdown, radioactive contamination is present on the surfaces of process systems and equipment. Decontamination is relied upon to remove the bulk of this radioactive contamination from selected systems and components. The objective of the decontamination effort during ENTOMB is to reduce the radiation levels throughout the facility in order to minimize personnel exposure during subsequent tasks.

The decontamination activities required for ENTOMB are identical to those for DECON, as discussed in Section 10.1.1.2, and are not discussed further here.

Preparation of the Entombment Structure. The postulated entombment structure for the reference research reactor is the entire concrete structure housing the TRIGA reactor shown in Figure 8.1-5 of Section 8. Both the Reactor Pool (RP) and the Pool Irradiation Facility (PIF) are utilized for storage of the contaminated materials and radioactive wastes generated during decommissioning activities. In order to accommodate all of the radioactive material

volumes anticipated from this decommissioning alternative, enlargement of the PIF is necessary. This preparatory work is described in detail in Section K.1 of Appendix K.

Disassembly and Disposition of Radioactive Materials. The disassembly and disposition of radioactive materials is carried out in the same manner as that described for DECON (see Section 10.1.1.2) with one exception: only the combustible radioactive materials resulting from ENTOMB require offsite disposal. Disassembly techniques are described generically in Appendix G.

Quality Assurance. The quality assurance program for ENTOMB is essentially the same as that for DECON, as described in Section 10.1.1.2. A more detailed review of the anticipated elements of an appropriate quality assurance program for ENTOMB is given in Section G.7 of Appendix G.

Environmental Surveillance. An abbreviated version of the environmental monitoring program carried on during facility operation is continued during the entombment period. This program is the same as that for DECON (see Section 10.1.1.2). Details of the program are discussed in Section G.8 of Appendix G.

Specialty Contractors. As with DECON, the only specialty contractor required is the hauling contractor. This contractor is used to transport combustible radioactive materials to a shallow-land burial ground.

Essential Systems and Services. All or parts of certain facility systems and services must remain in place and in service until all radioactive material is either removed from the facility or secured on the site, to prevent the release of significant quantities of radionuclides (or other hazardous materials) to the environment. Some systems and services are required for cleanup and disassembly activities, and others provide personnel health and safety protection. The systems and services essential for ENTOMB are the same as those given in Section 10.1.1.2 for DECON.

10.1.3.3 ENTOMB Schedule

Tasks necessary for entombment of the reference research reactor are nearly identical to those required for DECON and preparations for safe storage. Three tasks are unique to ENTOMB and a few tasks have subtle changes with respect to manpower needs and costs.

The task schedule and sequence for ENTOMB is given in Figure 10.1-5. Timing in the schedule reflects the need for early clearing of the pool areas within the entombment structure to allow for material storage. Draining of the reactor pool is strategically delayed to provide shielding for personnel while other necessary tasks are performed. The total time duration for accomplishing ENTOMB is 6 months, which is less than for DECON but slightly longer than for SAFSTOR.

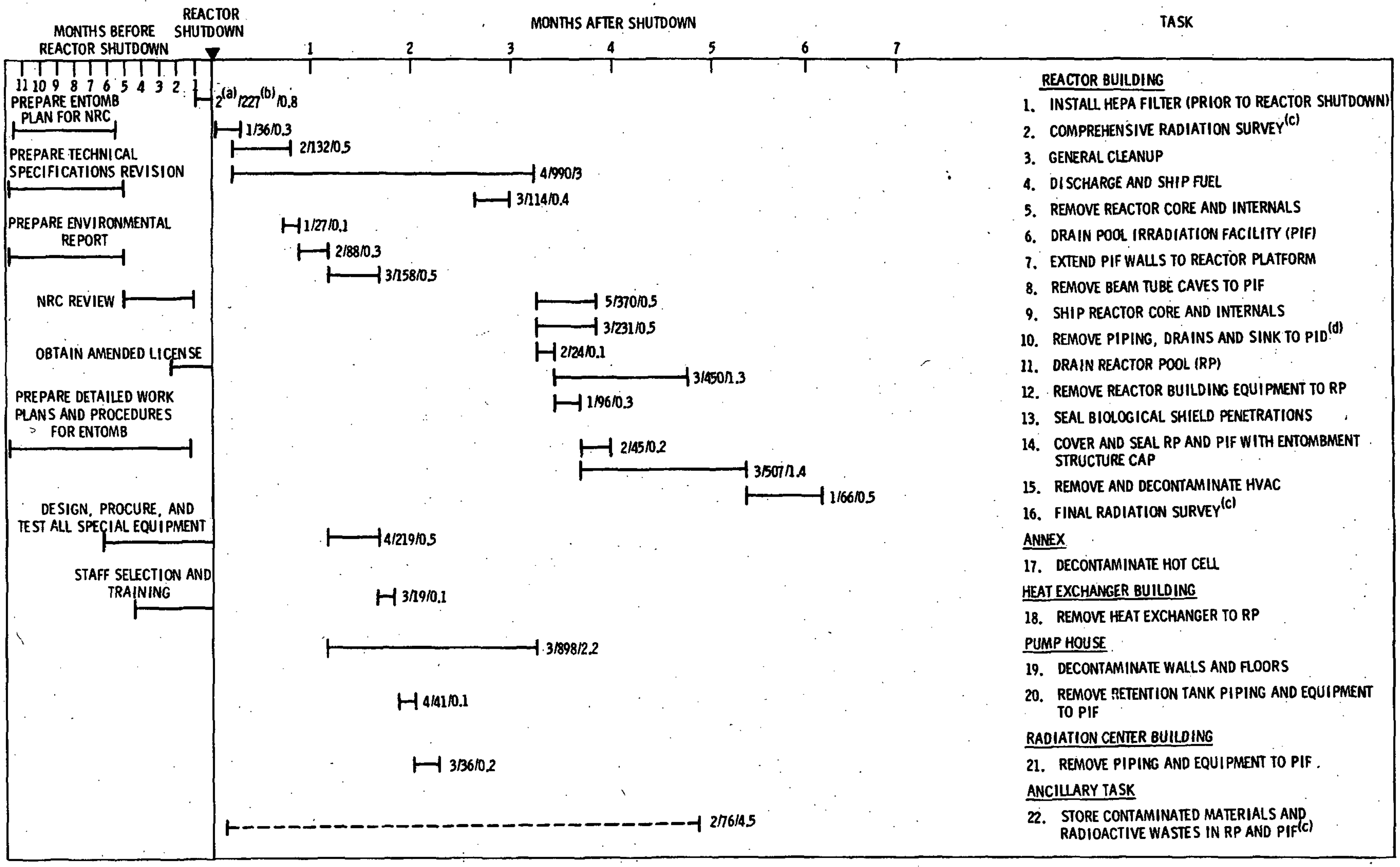
10.1.3.4 ENTOMB Staff Requirements

The organization of the ENTOMB decommissioning staff and the functions of the various staff members are the same as those for DECON, as shown in Figure 10.1-2 and discussed in Section 10.1.1.4.

The dedicated manpower requirements for ENTOMB of the reference research reactor are given in Table 10.1-6. Estimates of manpower requirements are based on the ENTOMB schedule and take into account both radiation exposure limits and actual manpower needed to complete the individual tasks. For those tasks which are identical or nearly so, the work crew makeup and shift requirements for ENTOMB and DECON are assumed to be the same. The 22 tasks defined for ENTOMB are one more than necessary for DECON; however, it can be seen from Table 10.1-6 that the direct staff needs of ENTOMB are about 7% less than those estimated for DECON (see Table I.1-1 in Appendix I for comparison). This reduction is primarily due to the relief from removal of the biological shield concrete and the reactor vessel for the ENTOMB alternative.

10.2 ACTIVITIES AND MANPOWER REQUIREMENTS FOR DECOMMISSIONING THE REFERENCE TEST REACTOR

This subsection contains information concerning the activities and manpower requirements for decommissioning the reference test reactor via the DECON, SAFSTOR, and ENTOMB alternatives.



LEGEND:

├──┤ CONTINUOUS OPERATIONS OVER TIME SPAN SHOWN

├- - -┤ INTERMITTENT OPERATION OVER TIME SPAN SHOWN

TOTAL: PERSON MONTHS 37
PERSON HOURS 6470
EXPOSURE HOURS 4850

(a) TASK INFORMATION NUMBERS INDICATE IN SEQUENCE: DIRECT STAFF PER DAY/EXPOSURE HOURS/CALENDAR MONTHS DURATION. WORKERS DEDICATING 15% OR LESS OF THEIR TIME TO THE TASK ARE NOT INCLUDED IN THE DIRECT STAFF PER DAY NUMBER.

(b) THIS NUMBER INCLUDES ALL WORKER EXPOSURE TIME AND IT IS ASSUMED THAT 75% OF THE WORKING DAY IS IN THE RADIATION ZONE.

(c) TASK INCLUDES ALL BUILDINGS.

(d) INCLUDES HEAT EXCHANGER BUILDING COMPONENTS.

FIGURE 10.1-5. Overall Task Schedule and Sequence for ENTOMB at the Reference Research Reactor

TABLE 10.1-6. Dedicated Manpower Requirements for ENTOMB at the Reference Research Reactor

Task	Task Duration (months)	Dedicated Manpower Requirements (man-months)					
		Supervisor	Utility Operator	Laborer	Craftsman	Health Physics Technician	Total
Reactor Building							
1. Install HEPA Filters[a]	0.80	0.12	--[b]	--	1.60	--	1.72
2. Comprehensive Radiation Survey[b]	0.27	--	--	--	--	0.27	0.27
3. General Cleanup	0.50	--	--	1.00	--	--	1.00
4. Discharge and Ship Fuel	3.00	3.0	2.5	0.50	--	1.50	7.50
5. Remove Reactor Core and Internals	0.36	0.16	0.02	0.39	0.25	0.05	0.87
6. Drain Pool Irradiation Facility (PIF)	0.12	0.03	--	0.12	0.05	0.01	0.21
7. Extend PIF Walls to Reactor Platform	0.25	0.09	0.05	0.51	--	0.03	0.68
8. Remove Beam Tub Caves to PIF	0.50	0.15	0.25	0.75	--	0.05	1.20
9. Ship Reactor Core and Internals	0.50	1.00	1.20	--	--	0.60	2.80
10. Remove Piping-Drains and Sink to PIF	0.52	0.22	--	1.00	0.48	0.05	1.75
11. Drain Reactor Pool (RP)	0.07	0.02	--	0.14	--	0.02	0.18
12. Remove RB Equipment to RP	1.30	0.43	0.14	2.41	0.30	0.13	3.41
13. Seal Biological Shield Penetrations	0.30	0.10	--	0.40	0.10	0.05	0.65
14. Cover and Seal RP and PIF with ENTOMBMENT Structure Cap	0.15	0.02	0.03	0.18	0.08	0.02	0.33
15. Remove and Decontaminate HVAC	1.40	--	--	2.70	1.00	0.14	3.84
16. Final Radiation Survey[c]	0.50	--	--	1.40	--	0.50	1.90
Annex							
17. Decontaminate Hot Cell	0.50	--	--	1.40	--	0.26	1.66
Heat Exchanger Building							
18. Remove Heat Exchanger to RP	0.05	0.01	0.02	0.05	0.05	0.01	0.14
Pump House							
19. Decontaminate Walls and Floors	2.20	--	--	6.60	--	0.20	6.80
20. Remove Retention Tank, Piping and Equipment to PIF	0.10	0.04	0.10	0.10	--	0.07	0.31
Radiation Center Building							
21. Remove Piping and Equipment to PIF	0.16	0.03	--	0.16	0.06	0.02	0.27
Ancillary Task[c]							
22. Store Contaminated Materials and Radiactive Waste in RP and PIF	--	--	--	1.00	0.01	0.10	1.11
Totals		5.42	4.31	20.82	3.98	4.07	38.60

(a) Performed before reactor shutdown.
(b) Denotes no manpower.
(c) Includes all buildings.

10.2.1 Activities and Manpower Requirements for DECON at the Reference Test Reactor

DECON is the decommissioning alternative that leads to the earliest termination of the owner's nuclear license. Planning and preparation activities, DECON activities, and the schedule and manpower requirements for DECON are presented in this subsection.

10.2.1.1 Planning and Preparation Activities

Effective planning and preparation work before final reactor shutdown is vital to successful completion of DECON activities at the reference test reactor facility. Planning and preparation for DECON is accomplished during the 2 years prior to final reactor shutdown. Planning and preparation activities include the following:

- satisfying regulatory requirements
- gathering and analyzing data
- developing detailed work plans and procedures
- designing, procuring, and testing special equipment
- selecting and training staff
- selecting specialty contractors.

These activities are identical to those already discussed for the reference research reactor and are not repeated here (see Section 10.1.1.1 for details).

10.2.1.2 DECON Activities

The activities and requirements of DECON for the reference test reactor are discussed in this subsection, including decontamination, disassembly and disposal, quality assurance, environmental surveillance, specialty contractors, and essential systems and services.

Decontamination. At final reactor shutdown,[a] significant radioactive contamination is present on the surfaces of process systems and equipment, and decontamination is necessary to remove the bulk of this contamination. The

(a) The term "reactor shutdown" in this case refers to both the reference test reactor and its associated mock-up reactor (i.e., the MUR).

objectives of the decontamination effort are twofold: first, to reduce the radiation levels throughout the facility in order to minimize personnel exposure during disassembly; and second, to attempt to clean as much material as possible to unrestricted levels, thereby permitting salvage of valuable material and reducing the quantities of material that must be packaged and shipped to a disposal site.

In this study, however, for several reasons, no credit is taken for the potential effectiveness of the decontamination effort in achieving reductions of radioactive contamination to levels that permit unrestricted release of the material. First, the effectiveness of the methods has not been demonstrated to any major degree. Second, the levels of residual radioactivity that are permitted on material that is returned to the commercial stream are not defined by any regulation, and third, depending on the acceptable limits of residual radioactivity, the costs of adequate radiation surveys and possible repeated cleanings to achieve releasability may be greater than the salvage value of the released material.

Decontamination methods are discussed in detail in Section G.4 of Appendix G. In general, water-jet decontamination proceeds concurrently with draining the contaminated water from tanks and pools (e.g., the quadrants and canals).

Disassembly and Disposal. Disassembly of the reference test reactor and the MUR is started after the reactors are defueled, systems and components are decontaminated, and temporary shielding is installed where a comprehensive radiation survey indicates the need.

The disassembly methods proposed for DECON of the reference test reactor and the MUR employ techniques that have been used successfully and are described generically in Appendix G. Generic descriptions for the dismantlement of equipment located in each building and area at the reference test reactor facility are described in detail in Section I.2.1.1 in Appendix I.

The exact component removal sequence within a given system or locality is dictated by the component's accessibility and the anticipated personnel exposures during removal. When possible, items that contribute significantly to

the general level of exposure in the work area are either removed first or are temporarily shielded while the work goes on. Systems are unbolted at flanges when possible and cut into manageable sections, using an appropriate cutting device (plasma-arc torch, oxyacetylene torch, or power hack saw). Piping is cut into lengths compatible with standard shipping boxes. Similarly, tanks are cut into plate segments appropriately sized. In this study, all initially contaminated materials are assumed to remain contaminated to greater than unrestricted use levels, even after decontamination, and are packaged for disposal as radioactive waste.

Packaging of radioactive materials for disposal is accomplished in accordance with DOT regulations published in 49 CFR Parts 173 through 178, and with NRC regulations published in 10 CFR Part 71 and Regulatory Guide 7.1. Containers are lined with shielding material when necessary to reduce surface dose rates to acceptable levels. Some items such as heat exchangers and selected tanks may have openings welded shut and be shipped using the outer shells of the units as the containers.

The reference test reactor vessel internals are cut underwater and removed from the reactor vessel with the vessel partially filled with water. Components welded in place in the reactor vessel are cut loose using an underwater plasma-arc torch. These components are cut into pieces that fit into DOT-approved shipping containers for transport to the disposal site. The neutron-activated components are placed in B3 shielded shipping containers and the contaminated materials are packaged in standard shipping boxes (1.2 m x 1.2 m x 2.4 m) or in specially made boxes.

After all in-tank components are removed, the inner reactor tank surfaces are decontaminated before cutting and removal operations begin. It is assumed that tank removal is accomplished with a cutting torch. A conceptual generalized procedure for tank removal is given in Section I.2 of Appendix I.

The MUR core structure and all other equipment in Canal H are removed, including the MUR cleanup system at the -4.6 m elevation. The entire MUR core box with beryllium, beam tube mock-ups, flow guide, rod box, and support frame is packaged in one wooden box, 1.83 m by 1.83 m by 1.83 m, for shipment to a licensed disposal site.

Contaminated concrete is removed using a concrete spaller, which is assumed to remove a surface layer about 50 mm thick. The rubble is packaged in standard shipping boxes for disposal.

The two buildings with the largest involvement requiring disassembly and disposal of radioactive materials are the Reactor Building/Containment Vessel (RB/CV) and the Hot Laboratory Building (HLB). Some of the radioactive materials in these buildings is well defined and its disposition is straightforward. Such material can either be decontaminated or shipped in accordance with applicable regulations for burial. Other radioactive materials are not so well defined, and during an actual decontamination and dismantling process it is postulated that differing quantities of materials might have to be removed than are postulated in this study. This is particularly true in the case of contaminated soil in the areas of site ditches and the Emergency Retention Basin.

The remaining structures and areas to be decontaminated and dismantled are:

- the Primary Pump House
- the Office and Laboratory Building
- the Emergency Retention Basin and Site Ditches
- the Cold Retention Area
- the Hot Retention Area
- the Fan House
- the Waste Handling Building
- the Hot Pipe Tunnel and Stack.

Disassembly and disposal techniques for the radioactive materials contained within these structures and areas is similar to that described for the RB/CV and the HLB and is discussed in detail of Section I.2.1 in Appendix I.

Shipping of packaged contaminated materials from the reference test reactor facility to a waste burial site is accomplished using a trucking company that specializes in transporting special materials. The volume of materials to be transported and the number of shipments required are estimated in Section I.2.3 of Appendix I.

Quality Assurance. An extensive quality assurance program is carried on throughout the decommissioning effort to assure that all applicable regulations are met, to assure that work is performed according to plan, to assure that work does not endanger public safety, and to assure the safety of the decommissioning staff.

During the 2-year period prior to shutdown, QA personnel are active in the following areas:

- reviewing decommissioning plans for quality assurance involvement
- preparing inspection/test procedures as work plans are developed
- reviewing designs of test equipment for quality input
- ordering any inspection/test equipment required to perform the quality assurance/quality control function
- receiving procured equipment and verifying acceptance
- qualifying suppliers for fabrication of radioactive shipping containers
- preparing inspection/test procedures to be imposed on contractors
- preparing inspection plans for shipment of radioactive materials, containers, trucks, etc.
- finalizing the formal quality assurance plan.

The QA efforts during the actual DECON period include the following:

- performing QA functions for procurements
- qualifying suppliers
- auditing all project activities
- monitoring worker performance for compliance with work procedures
- verifying compliance of radioactive shipments with appropriate procedures and regulations
- performing dimensional, visual, nondestructive examinations or other required inspection services to assure compliance with work plans

- maintaining auditable files on the QA audits
- preparing a final report on overall performance of the DECON program with regard to the QA function.

More details of the anticipated elements of an appropriate quality assurance program for the DECON effort are given in Section G.7 of Appendix G.

Environmental Surveillance. An abbreviated version of the environmental monitoring program carried on during plant operation is continued during the DECON period. The purpose of the program is to identify and quantify any releases of radioactivity to the surrounding areas resulting from the DECON activities. The proposed program, detailed in Section G.8 of Appendix G, is sufficient to permit evaluation of any significant releases. For emergency situations involving releases from events such as fires or malicious acts that may necessitate prompt emergency action to minimize the risk to the public, additional short-term surveillance efforts are required.

After DECON is complete, a reduced 1-year follow-up program of environmental monitoring is carried out by the same organization that performed the earlier program.

Specialty Contractors. During decommissioning, specialty contractors are employed to provide services beyond the capability of the licensee's decommissioning staff. Use of these contractors increases the overall cost-effectiveness of the project by improving the efficiency of specialty operations and reducing the need for specialized staff training. In addition, specialized experience gained from similar projects is directly applied to the decommissioning by these contractors, thus reducing the mistakes and wasted effort inherent in learn-as-you-go situations.

The specialty contractors used during DECON of the reference test reactor are:

- environmental monitoring specialists, for implementing the environmental surveillance program discussed previously
- explosive specialists, for breaking up selected concrete areas within the RB/CV

- hauling contractors, for transport of packaged radioactive materials to a disposal site
- temporary radwaste handling and solidification support, for radwaste handling and final cleanup after the installed radwaste handling systems are decontaminated.

If following DECON the facility is demolished and the site is restored, demolition and landscaping contractors are also required. Demolition and site restoration of the reference test reactor facility are discussed in detail in Section L.2 of Appendix L.

Essential Systems and Services. All or parts of certain facility systems and services must remain in place and in service until all radioactive material is either removed from the facility or secured on the site, to prevent the release of significant quantities of radionuclides (or other hazardous materials) to the environment. Some systems and services are required for cleanup and disassembly activities. Other systems provide personnel health and safety protection. The required systems and services for the reference test reactor are identical to those listed in Table 10.1-1 for the reference research reactor and are not repeated here.

As decontamination and dismantlement is completed in areas within the facility, the essential systems and services in these areas are deactivated and, if contaminated, removed as required. Continuous service to the remaining work areas is maintained as long as necessary.

10.2.1.3 DECON Schedule

The overall task schedule and sequence of DECON tasks is shown in Figure 10.2-1. Detailed schedules and manpower estimates for DECON of each of the buildings and areas are presented in Section I.2 of Appendix I. Initial planning for DECON at the reference test reactor facility begins about 2 years before final shutdown of the reactor, as discussed previously in Section 10.2.1.1 and shown in Figure 10.2-1.

After final shutdown, the reference test reactor and the MUR are defueled. For the purposes of this study, it is postulated that the spent fuel is shipped to a government reprocessing plant. This disposition is based on historical

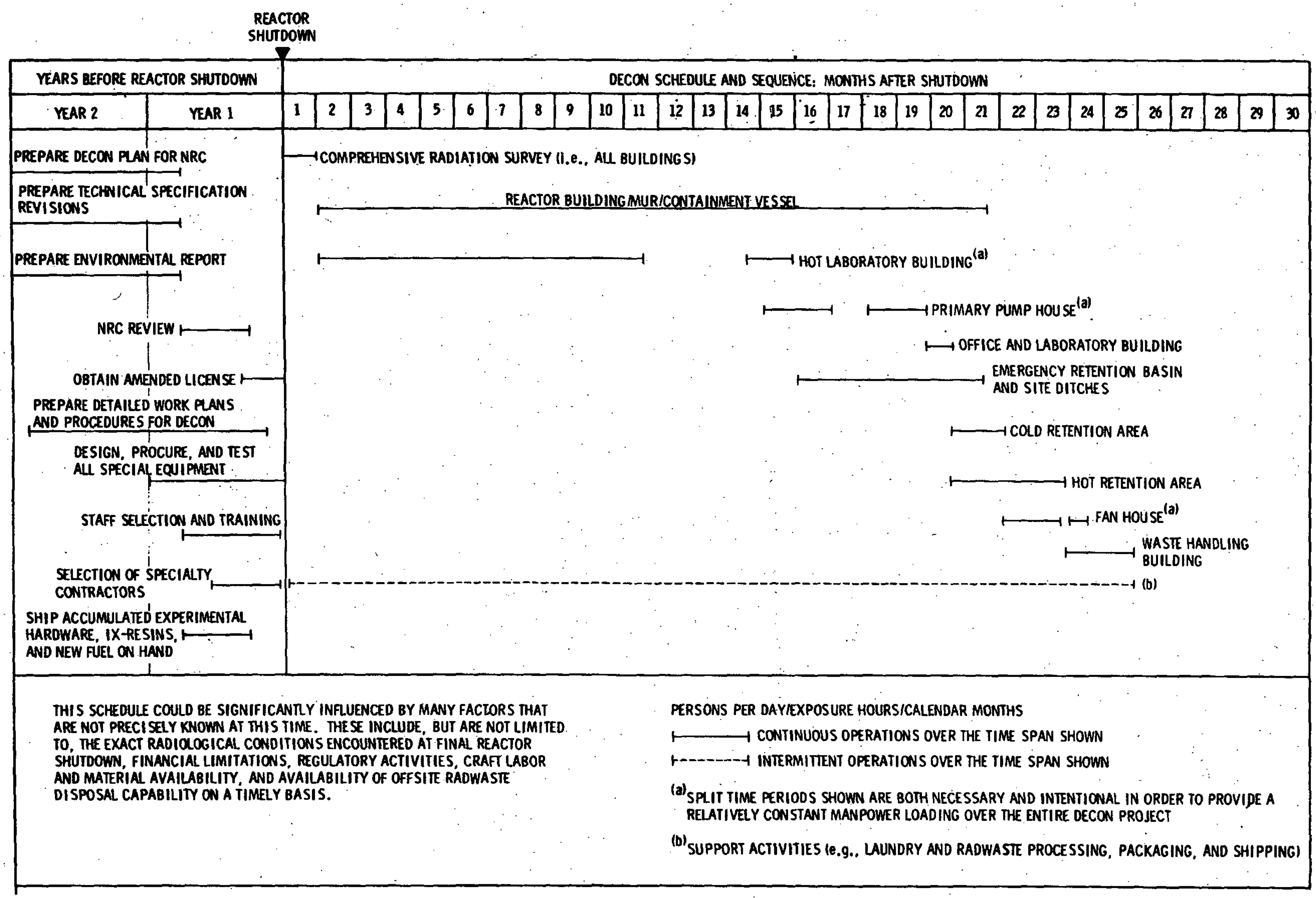


FIGURE 10.2-1. Overall Task Schedule and Sequence for DECON at the Reference Test Reactor

data supplied by NASA. Following fuel removal, the sequence in which the various systems must be drained and/or flushed and dismantled is determined. Dismantlement begins in the RB/CV. The MUR is postulated to be removed first, before the reference test reactor, to provide a potential "lessons learned" dismantling basis. Starting with the hot cells, decontamination and dismantlement activities in the HLB are conducted concurrently with those in the RB/CV.

After decommissioning of the RB/CV/MUR and HLB, the remaining structures and areas are decontaminated and dismantled. These are:

- the Primary Pump House
- the Office and Laboratory Building
- the Emergency Retention Basin and Site Ditches
- the Cold Retention Area
- the Hot Retention Area
- the Fan House
- the Waste Handling Building
- the Utility Tunnels and Stack.

The liquid and solid radwaste systems located in the Fan House and the Waste Handling Building are needed to process most of the contaminated liquids contained in the systems at final reactor shutdown and generated during DECON. In addition, continuous waste air-handling service to the remaining work areas is maintained as long as necessary. As shown in Figure 10.2-1, DECON of the reference test reactor facility is completed in 25 months.

10.2.1.4 DECON Staff Requirements

In this subsection, the organization of the decommissioning staff and the types and numbers of decommissioning workers needed for DECON are discussed.

Organization of the Decommissioning Staff. The decommissioning staff for the reference test reactor is organized as shown in Figure 10.2-2, and has five branches under a decommissioning superintendent. The project engineering branch, under a decommissioning engineer, develops detailed procedures of the decommissioning activities and performs the actual decommissioning activities. The support services branch provides craftsmen who assist the decommissioning crew leaders and perform plant maintenance as required. Support services also

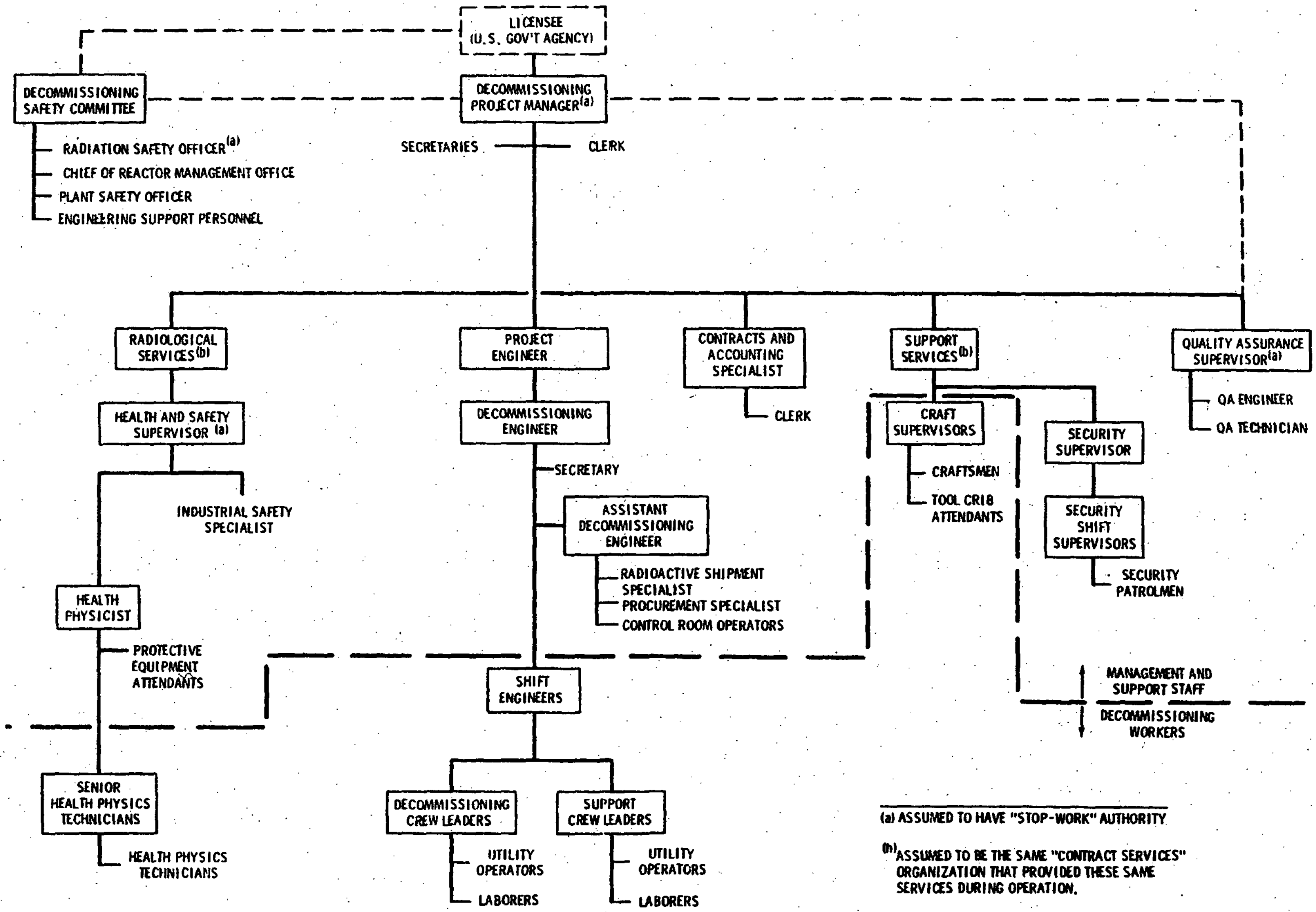


FIGURE 10.2-2. Decommissioning Staff Organization for the Reference Test Reactor

provides security patrolmen for plant security. The radiological services branch plans and conducts both radiological and industrial safety programs. The quality assurance branch maintains audit and job performance records and verifies that established safety review procedures are followed. The financial branch is responsible for the financial aspects of the project.

DECON tasks, with a few exceptions, are performed on two 8-hour shifts, five days per week. Shipments of spent fuel, neutron-activated reactor vessel internals, and reactor vessel segments are conducted three shifts per day, 7 days per week, as requried. Nearly optimum decommissioning worker requirements are met by using a relatively constant manpower loading almost to the very end of the DECON project (see Table I.2-5 in Appendix I for details).

The basic working unit is the shift, which is supervised by a shift engineer. The crew on each shift includes: a crew leader (typically a reactor operator), utility operators, and laborers, plus craftsmen (e.g., welders, pipefitters, electricians, and air-balance technicians) and health physics technicians assigned as needed. Craftsmen and health physics technicians on the support crews report directly to the crew leaders because, on the third shift and on weekends, crew leaders are the only supervisory personnel on plant. Craftsmen and health physics technicians assigned to the regular decommissioning crews report to the crafts supervisor and to the senior health physics technician on the day and swing shifts, respectively. The specific crew makeup for a given decommissioning task will be tailored to fit the need. Specific crew assignments are described throughout the appendices

Detailed knowledge of and familiarity with the reference test reactor increases the effectiveness of the decommissioning staff. Consequently, staff positions are filled with facility operations and maintenance personnel to the maximum extent possible. Specialty contractors and consultants are hired as needed to assist in areas outside the staff's expertise or capability.

In general, hot-cell operations at the reference test reactor are conducted by specialists. These same specialists should be retained for both the planning and preparation phase and the operational phase of decommissioning

the hot cells. Their special operative talents should prove invaluable and cost-effective in the actual hot-cell decontamination and dismantling activities.

Key decommissioning staff members perform the functions described below.

Decommissioning Superintendent

Directly responsible to management, the superintendent coordinates and oversees all decommissioning activities. He directs the decommissioning engineer and the health and safety supervisor, as well as support services (security, craftsmen), quality assurance, and contracts and accounting, to ensure the safety and cost-effectiveness of the decommissioning project. He provides necessary liaison with regulatory agencies and management.

Decommissioning Engineer

This individual plans, coordinates, and supervises the actual decommissioning tasks. He provides the engineering services and detailed procedures required to carry out the decommissioning plan in a safe and cost-effective manner. He prepares all routine and special reports as well as a chronological history of the project.

Assistant Decommissioning Engineer

This person supervises the decommissioning support personnel and assists the decommissioning engineer in developing detailed work procedures. He writes specifications for special equipment and tools that must be procured or fabricated. He also prepares reports requested by the decommissioning engineer.

Shift Engineer

Responsible for carrying out the actual decommissioning work during a shift, this person supervises the crew leader and craft supervisor. He reports to the decommissioning engineer. As he supervises the day-to-day performance of the shift, he recommends changes in procedures and schedules to improve the safety and/or cost-effectiveness of the project.

Crew Leader

Reporting to the shift engineer, this individual directs the work crews in the performance of the actual decommissioning tasks.

Craft Supervisor

This person is responsible for maintenance of essential plant equipment and services as well as for assigning craft labor to particular decommissioning tasks. He instructs craftsmen in their assigned tasks and ensures the availability of required tools and supplies.

Security Supervisor

This person is responsible for site security during decommissioning. He supervises the security personnel and, if necessary, provides liaison with offsite civil authorities. The security shift supervisor directs shift activities.

Contracts and Accounting Specialist

An experienced accountant, this individual is responsible for the financial aspects of the project. He prepares procurement documents and contracts and, with approval from the decommissioning superintendent and the decommissioning engineer, disburses funds. He maintains up-to-date financial accounts and provides the decommissioning superintendent with regular summary reports.

Health and Safety Supervisor

This person (typically a senior health physicist) recommends and enforces safety policy, both radiological and industrial. He advises the decommissioning superintendent on all safety matters. He maintains the occupational radiation exposure records, and also develops and implements the environmental survey (via a specialty contractor) and the emergency preparedness programs. He supervises and is assisted by the industrial safety specialist and the health physicist.

Health Physicist

This individual is responsible for ensuring compliance with radiation work procedures. He directs the activities of the health physics technicians who monitor all decommissioning activities, measure and record on-the-job radiation dose information, and operate the plant laboratory facilities, including sampling and analysis. The senior health physics technician assigns and trains others on the shift. In addition, the health physicist is responsible for the

development and implementation of the in-plant radiation protection program, the survey instrumentation program including calibration, bioassy of personnel, airborne radioactivity monitoring, and ALARA planning.

Quality Assurance Supervisor

This person is responsible for preparing the quality assurance plan for decommissioning and works with the decommissioning engineer to implement it. To ensure the independence of the quality assurance program, he reports directly to corporate headquarters. He supervises a quality assurance unit, which maintains audit and job performance records and verifies that established safety review procedures are followed. (See Section G.7 of Appendix G for further discussion of quality assurance functions.)

DECON Staff Labor. Based on the schedule for decontaminating and dismantling the various systems and the estimated dose to accomplish each task, the types and number of decommissioning workers needed to complete the radiation-zone work in the allotted time and within the assumed radiation dose limits are determined. Whole-body radiation doses to the decommissioning workers are limited in accordance with 10 CFR 20.101. The supervisors, utility operators, and health physics technicians are assumed to be long-time radiation workers whose annual exposure is limited to 5 rem per year by the formula 5(N-18) of 10 CFR 20.101(b)(2). The craftsmen and laborers are assumed to have had little prior radiation exposure and, therefore, under 10 CFR 20.101(b)(1) and (2) may receive up to 3 rem per quarter, within the limitation of the formula 5(N-18) rems where "N" equals the individual's age in years at his last birthday. If a situation occurs where the staff labor estimated for physically accomplishing a task results in a dose for a person in excess of these limits, an additional person is anticipated to be assigned to the task to keep the individual dose below set limits. In the manpower tables following, the manpower shown is adequate both to accomplish the task and to meet the occupational dose limits.

The total staff labor requirements for DECON at the reference test reactor are given in Table 10.2-1. These requirements are given in equivalent man-years for the 2 years before and the 2.08 years following final reactor shutdown, and include management and support staff as well as the decommissioning

TABLE 10.2-1. Staff Labor Requirements for DECON at the Reference Test Reactor

Position	Time Relative to Final Shutdown (year) -2	-1	1	2	3	Total Staff Labor Required (man-years)
	Annual Staff Labor Requirement (man-years)[(a)]					
Management and Support Staff						
Decommissioning Superintendent	0.3	1.0	1.0	1.0	0.5[(b)]	3.8
Secretary	1.0	2.0	3.0	3.0	1.0[(b)]	10.0
Clerk	0	1.0	2.0	2.0	0.5	5.5
Decommissioning Engineer	1.0	1.0	1.0	1.0	0.5[(b)]	4.5
Assistant Decommissioning Engineer	1.0	1.0	1.0	1.0	0.1	4.1
Radioactive Shipment Specialist	0	1.0	1.0	1.0	0.1	3.1
Procurement Specialist	0.3	1.0	1.0	1.0	0.1	3.4
Tool Crib Attendant	0	0	2.0	2.0	0.2	4.2
Control Room Operator[(c)]	0	0	5.0	5.0	0	10.0
Security Supervisor	0	0	1.0	1.0	0.1	2.1
Security Shift Supervisor[(d)]	0	0	5.0	5.0	0.2	10.2
Security Patrolman[(d)]	0	0	16.0	12.0	0.4	28.4
Contracts and Accounting Specialist	0.3	1.0	1.0	1.0	0.5[(b)]	3.8
Clerk	0	1.0	1.0	1.0	0.5[(b)]	3.5
Health and Safety Supervisor	1.0	1.0	1.0	1.0	0.5[(b)]	4.5
Health Physicist	0	0.5	1.0	1.0	0.2	2.7
Protective Equipment Attendant	0	0	2.0	2.0	0.2	4.2
Industrial Safety Specialist	0.3	1.0	1.0	1.0	0.2	3.5
Quality Assurance Supervisor	0.3	1.0	1.0	1.0	0.5[(b)]	3.8
Quality Assurance Engineer	0.5	1.0	1.0	1.0	0.2	3.7
Quality Assurance Technician	0	0.5	2.0	2.0	0.4	4.9
Consultants (Safety Review Committee)	0.5	0.5	0.5	0.5	0	2.0
Subtotals, Management and Support Staff	6.5	15.5	50.5	46.5	6.9	125.9
Decommissioning Workers[(e)]						
Shift Engineer	1.0	2.0	2.0	2.0	0.2	7.2
Crew Leader	0	1.0	5.0	5.0	0.5	11.5
Utility Operator	0	3.0	11.0	11.0	0.6	25.6
Laborer	0	0	7.0	7.0	0.4	14.4
Craft Supervisor	0	0.5	2.0	2.0	0.2	4.7
Craftsman	0	5.0	10.0	10.0	1.0	26.0
Senior Health Physics Technician	0	1.0	2.0	2.0	0.2	5.2
Health Physics Technician	0	1.5	5.0	5.0	0.2	11.7
Subtotals, Decommissioning Workers	1.0	14.0	44.0	44.0	3.3	106.3
Totals	7.5	29.5	94.5	90.5	10.2	232.2

(a) Rounded to the next higher 0.1 man-year.
(b) Includes an additional 4 months following active decommissioning in order to complete the documentation and other unspecified license and contract termination requirements.
(c) Based on one operator per shift in the test reactor control room, three shifts per day, seven days per week.
(d) Based on 10 CFR 73; includes both response and access-control personnel on a three-shift, seven-day week basis.
(e) Requirements during the 2 years following reactor shutdown are based on a relatively constant manpower loading using the staff breakdown given in Table I.2-5 in Appendix I.

workers. About 232 man-years of effort are estimated for DECON of the reference test reactor, including approximately 126 man-years for the management and support staff and about 106 man-years for the decommissioning workers.

10.2.2 Activities and Manpower Requirements for SAFSTOR at the Reference Test Reactor

The SAFSTOR decommissioning alternative satisfies the requirements for protection of the public, while minimizing, in various degrees, the initial commitments of time, money, occupational radiation dose, and nuclear waste repository space. This advantage is offset somewhat by the need to maintain the nuclear license, by the associated restrictions placed on the use of the property, and by the need for eventual decontamination of the facility. After an initial preparatory period following facility shutdown, this alternative requires continuing physical security and surveillance (safe storage) of structural integrity to ensure public protection. Planning and preparation activities, preparations for safe storage activities, schedule and manpower estimates, safe storage activities and requirements, and deferred decontamination at the end of the safe storage period for the reference test reactor facility are discussed in the following subsections.

10.2.2.1 Planning and Preparation Activities for SAFSTOR

Successful implementation of SAFSTOR for the reference test reactor facility is dependent both on good planning and on completion of preparatory work before final reactor shutdown. Planning and preparation for safe storage is assumed accomplished during the 1-1/2 years prior to final reactor shutdown. Another planning and preparation period will occur just prior to deferred decontamination. Adjustments to decommissioning plans will be made and detailed work plans developed.

The planning and preparation activities for placing the reactor into safe storage are essentially the same as those described in Section 10.2.1.1 for DECON and are not discussed further here.

10.2.2.2 Safe Storage Preparations Activities

The activities and requirements to prepare the reference test reactor for safe storage include:

- preparatory activities
- decontamination, deactivation, and sealing methods
- spray painting
- relocation of contaminated equipment and materials
- decontamination and isolation procedure
- reduction of plant exclusion area
- quality assurance
- environmental surveillance
- specialty contractors
- essential systems and services.

These are discussed in the following paragraphs.

Preparatory Activities. Following completion of planning and preparation (see Section H.1 of Appendix H) and cessation of facility operations, a comprehensive radiation survey of the reference test reactor facility is completed. These surveys are required to finalize plans for draining and flushing contaminated process systems and for installing temporary shielding for personnel protection during subsequent decommissioning operations. Next, a general cleanup is accomplished and a total inventory of equipment is taken to determine usefulness of specific equipment to the decommissioning project. Equipment not so designated is identified for later disposal, reuse elsewhere, or onsite storage.

Following the final inventory cleanout, fuel shipments commence, and final decontamination operations are initiated. The conditions outlined below are met before commencing these operations.

1. Responsible management and safety personnel approve the following plans and procedures:
   - radiation work, industrial safety, and emergency procedures
   - equipment handling, dissassembly, cleaning, and packaging and shipping procedures
   - equipment and facility decontamination plans and procedures.
2. Disposition is predetermined for all equipment. The equipment can be decontaminated for reuse, sold as scrap, or buried in the local

landfill dump; partially decontaminated for use at another restricted plant, left in place, or shipped to a licensed burial ground for contaminated materials.

3. All ventilation equipment, personnel protection systems, emergency power systems, fire protection systems, and radiation monitoring equipment in the building and onsite are in service and fully functional.

4. All personnel and contractors are adequately trained to perform their jobs.

5. Appropriate occupational safety equipment and continuous air sampling equipment are available for equipment disassembly, transfers, and cleanup.

6. Temporary portable cleaning chambers for decontaminating equipment are available (e.g., greenhouse with tank for water and steam rinsing of equipment, washing tanks, degreasers, etc.).

7. Packaging materials and shipping containers are available.

8. All equipment for dismantlement (where required) and decontamination operations is available.

9. A comprehensive radiation survey is completed, with all results mapped and used as a basis for each building, room, and area's work plan.

10. The system and procedures for the functions of special nuclear material accountability measurements and measurement control are established.

11. All unneeded process material supplies (e.g., bottled gases, acids and caustics) are disconnected from the plant and disposed of.

The primary cooling water system is drained and flushed after the fuel is removed from the test reactor core. In addition, after the fuel is removed from the MUR and all fuel and experimental hardware are removed from Canal H, Canal H can then be drained, cleaned, dried, and further decontamination work completed on the MUR.

Following defueling of both reactors, the irradiated fuel is shipped to a government reprocessing plant so that technical specifications associated with having the fuel onsite can be eliminated and guard forces can be reduced. The MTR-type fuel is prepared for shipment by cutting the aluminum box ends off each spent fuel assembly before loading a critically safe complement of fuel plates into the spent fuel cask. The aluminum box end pieces are packaged as radioactive waste for shipment to a burial ground.

Disassembly, disposal, and further decontamination begins in the Reactor Building/Containment Vessel, proceeds through the Hot Laboratory Building, and concludes with the Waste Handling Building. The auxiliary structures described in Section C.2.12 of Appendix C, with the exception of the exhaust stack, are assumed to be uncontaminated.

Decontamination, Deactivation, and Sealing Methods. Decontamination, deactivation, and sealing methods proposed for the reference test reactor and the MUR employ techniques that have been used successfully and are described generically in Appendix G. In general, areas of the facility that must be accessible during safe storage are decontaminated to unrestricted use levels. Noncombustible, contaminated materials, which are not removed for the facility, may be placed in the drained and cleaned quadrants and canals. These areas are isolated from the remainder of the facility by structurally substantial physical barriers. In any case, the primary concern is to ensure that no recontamination of clean areas occurs and that air leaving a given area flows through a filter system or, in the case of liquid effluents, through the existing contaminated waste systems.

The particular method used to decontaminate, deactivate, and seal each system or piece of equipment is identified during the planning phase. In general, all systems not necessary to prvent the spread of contamination are deactivated. Equipment deactivation, isolation of contaminated areas, and sealing techniques are described generically in Sections G.2 and G.3, respectively, of Appendix G. Generic decontamination methods used in the preparations for safe storage are described in Section G.4.

It is assumed that two of the preparatory methods that can be used for temporary contamination control before transferring equipment and materials

are: 1) wrapping these items in plastic; and 2) spray painting. Spray painting and transfer techniques are described in subsequent paragraphs.

Spray Painting. After the readily removable contamination is removed by the physical cleaning methods described in Section G.4, the rooms or areas and their associated equipment may be spray painted before isolation or removal procedures begin. The contaminated surfaces may be coated both inside and outside to prevent the entrainment of radioactivity in the air during the active decommissioning tasks or during subsequent surveillance and maintenance activities.

In general, if the contamination on a surface cannot be removed by wiping or washing using standard decontamination solutions, it may be painted to fix the contamination in place. An example is a concrete surface that has been penetrated by contaminated liquids. While the surface might be cleaned initially, the subsurface contamination can migrate to the surface and be dispersed by air movement and/or foot traffic. On protected, interior surfaces with essentially no traffic or adverse environment, such paint coatings can be expected to last almost indefinitely. Part of the surveillance program is to monitor painted areas for deterioration of the coatings and to recoat them as necessary.

Relocation of Contaminated Equipment and Materials. Unsalvageable, contaminated equipment and other miscellaneous noncombustible items may be relocated to other secured, onsite retrievable storage areas (see Section J.2.1.1 in Appendix J for details). It is anticipated that before transferring small equipment items, the items are carefully wrapped in plastic and/or spray painted to immobilize any contamination. Freshly exposed surfaces may be immediately painted to prevent dispersal of contamination. The disconnected items are carefully bagged and transferred into a retrievable storage area. The equipment and ductwork remaining in the work area is physically decontaminated as described in Section G.4 of Appendix G and, in addition, may be spray painted as previously described.

Decontamination and Isolation Procedure. The 13-point procedure given below is postulated to be used to prepare the contaminated areas throughout the reference test reactor facility for safe storage:

1. Conduct initial radiation survey.
2. Vacuum interior surface areas.
3. Deactivate nonessential systems and equipment.
4. Clean interior surface areas and exposed surfaces of equipment and piping.
5. Clean remaining hot spots.
6. Apply protective paint (determined on a case-by-case basis).
7. Transfer, as feasible, contaminated equipment and materials.
8. Decontaminate and seal vent systems.
9. Install HEPA-filtered vents.
10. Deactivate remaining nonessential systems and equipment.
11. Install intrusion alarms; provide for offsite readout for intrusion, fire, and radiation survey.
12. Conduct final radiation survey.
13. Secure the structure.

Quality Assurance. An extensive quality assurance program is carried on throughout the decommissioning effort to assure that all applicable regulations are met, to assure that the work is performed according to plan, to assure that the work does not endanger public safety, and to assure the safety of the decommissioning staff. The quality assurance program for safe storage is essentially the same as that for DECON, which is described in Section 10.2.1.2.

Environmental Surveillance. The required levels of environmental surveillance during the preparations for safe storage differ from those during safe storage. An abbreviated version of the environmental monitoring program carried on during plant operation is continued during the preparations for safe storage. This program is the same as that for DECON (see Section 10.2.1.2).

Specialty contractors. The use of specialty contractors while preparing the reference test reactor for safe storage is similar to that discussed for DECON (see Section 10.2.1.2) with only minor modifications and allowances made to account for the shorter time frame.

A specialty contractor, who will be responsible for security during the safe storage period, begins work during the preparations period, including making a site-security survey, reducing the size of the security area, and procuring and installing the necessary remote-readout security equipment.

Essential Systems and Services. The required systems and services for preparations for safe storage differ from those required for safe storage. Essential facility systems and services such as power, heat, water, communications, and safety are maintained during the preparations for safe storage. These systems and services must remain in service until radioactive and/or contaminated materials are decontaminated, fixed in place, or removed from the facility, to prevent the release of significant quantities of radionuclides or other hazardous materials to the environment. The systems and services required for preparations for safe storage are the same as those required for DECON, which are discussed in Section 10.2.1.2.

10.2.2.3 Preparations for Safe Storage Schedule

The schedule and sequence of safe storage decommissioning tasks is shown in Figure 10.2-3. Further schedule details are presented in Section J.2.2 of Appendix J. Initial planning for safe storage of the reference test reactor begins about 18 months before final shutdown.

After final shutdown, fuel is removed from the reference test reactor and the MUR. The irradiated fuel is shipped to a government reprocessing plant. Initial efforts are directed at draining contaminated systems and the quadrants and canals. Decommissioning activities begin in the RB/CV, proceed through the HLB, and conclude with the Waste Handling Building. As shown in Figure 10.2-3, preparations for safe storage are completed in about 6-3/4-months.

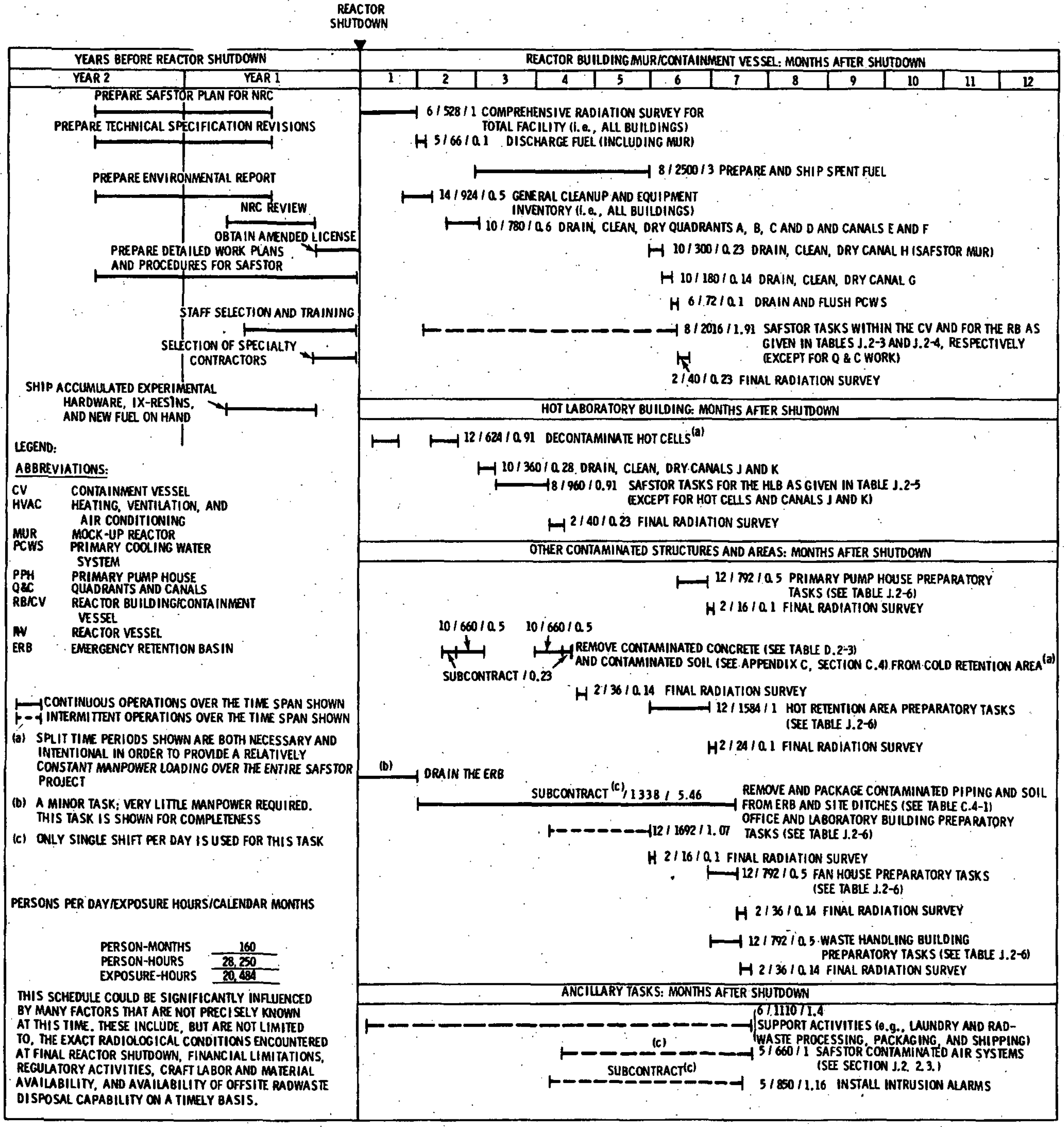


FIGURE 10.2-3. Task Schedule and Sequence of the Preparations for Safe Storage at the Reference Test Reactor

10.2.2.4 Preparations for Safe Storage Staff Requirements

In this subsection, the organization of the decommissioning staff and the types and numbers of decommissioning workers needed for preparations for safe storage are discussed.

Organization of the Decommissioning Staff. The organization and functions of the preparations for safe storage decommissioning staff are the same as those for DECON, as discussed in Section 10.2.1.4.

The preparatory tasks, with few exceptions, are performed on two 8-hour shifts, five days per week. Shipment of spent fuel is conducted three shifts per day, 7 days per week, as required. Nearly optimum decommissioning worker requirements are met by using a relatively constant manpower loading almost to the very end of the decommissioning project. (See Table J.2-3 in Appendix J for details.)

Preparations for Safe Storage Manpower Requirements. Estimates of manpower requirements are based on the preparations for safe storage schedule and take into account both radiation dose limits and manpower limits needed to complete the individual tasks. The total staff labor requirements for preparations for safe storage of the reference test reactor are given in Table 10.2-2 in equivalent man-years for the 1.5 years before and the 0.56 years following final reactor shutdown, and include management and support staff as well as decommissioning workers. About 76 man-years of effort are estimated for preparing the reference test reactor for safe storage, including approximately 44 man-years for the management and support staff and about 32 man-years for the decommissioning workers.

10.2.2.5 Safe Storage Activities and Requirements

Activities at the reference test reactor site during the safe storage period include routine inspection, preventive and corrective maintenance on safety systems, and a regular program of radiation and environmental monitoring. Action is initiated immediately to correct any unusual or potentially unsafe condition detected during the surveillance program. In addition to the routine tasks, a comprehensive inspection of the facility is performed annually by qualified third-party inspectors.

TABLE 10.2-2. Staff Labor Requirements for Preparations for Safe Storage at the Reference Test Reactor

Position	Time Relative to Final Shutdown (year) -2	-1	1	Total Staff Labor Required (man-years)
	Annual Staff Labor Requirement (man-years)[a]			
Management and Support Staff				
Decommissioning Superintendent	0.5	1.0	0.73[b]	2.23
Secretary	0.5	1.0	0.73[b]	2.23
Clerk	0	1.0	0.57	1.57
Decommissioning Engineer	0.5	1.0	0.73[b]	2.23
Assistant Decommissioning Engineer	0.5	1.0	0.57	2.06
Radioactive Shipment Specialist	0	1.0	0.57	1.57
Procurement Specialist	0.2	1.0	0.57	1.77
Tool Crib Attendant	0	0	0.57	0.57
Control Room Operator[c]	0	0	0.57	0.57
Security Supervisor	0	0	0.57	0.57
Security Shift Supervisor[d]	0	0	2.85	2.85
Security Patrolman[d]	0	0	9.12	9.12
Contracts and Accounting Specialist	0.2	1.0	0.73[b]	1.93
Clerk	0	1.0	0.73[b]	1.73
Health and Safety Supervisor	0.5	1.0	0.73[b]	2.23
Health Physicist	0	0.5	0.57	1.07
Protective Equipment Attendant	0	0	1.14	1.14
Industrial Safety Specialist	0.2	1.0	0.57	1.77
Quality Assurance Supervisor	0.2	1.0	0.73[b]	1.93
Quality Assurance Engineer	0.3	1.0	0.57	1.87
Quality Assurance Technician	0	0.5	1.14	1.64
Consultants (Safety Review Committee)	0.3	0.5	0.5	1.3
Subtotals, Management and Support Staff	3.9	14.5	25.56	43.96
Decommissioning Workers[e]				
Shift Engineer	0.5	2.0	1.14	3.64
Crew Leader	0	1.0	2.85	3.85
Utility Operator	0	2.0	3.42	5.42
Laborer	0	0	2.85	2.85
Craft Supervisor	0	0.5	1.14	1.64
Craftsman	0	2.5	5.7	8.2
Senior Health Physics Technician	0	1.0	1.14	2.14
Health Physics Technician	0	1.5	2.85	4.35
Subtotals, Decommissioning Workers	0.5	10.5	21.09	32.09
Totals	4.4	25.0	46.65	76.05

(a) Rounded to next higher 0.01 man-year.
(b) Includes an additional 2 months following active decommissioning in order to complete the documentation and other unspecified license and/or contract termination requirements.
(c) Based on one operator per shift in the test reactor control room, three shifts per day, 7 days per week.
(d) Based on 10 CFR Part 73; includes both response and access-control personnel on a three shift, 7-day-week basis.
(e) Requirements during the 6-3/4 months following reactor shutdown are based on a relatively constant manpower loading utilizing the staff breakdown given in Table J.2-3 in Appendix J.

It is postulated that an outside consultant, a registered architect, is hired for developing a long-range planned maintenance program, based on a visual inspection and a review of construction drawings. This planned maintenance program for the reference test reactor is described and discussed in Section J.2.3.3 of Appendix J.

The safe storage period lasts until final disposition of the facility is made. The length of this period is determined by a cost-benefit analysis that balances the costs of surveillance and maintenance against the decreased decontamination costs and land use values, as well as by societal or regulatory issues.

Quality Assurance. A modest quality assurance program is anticipated to be carried on throughout the safe storage period to assure that the surveillance, security, and maintenance work does not endanger public safety or the safety of the safe storage staff. This program also assures that all applicable quality assurance, quality control, and records-keeping regulations and requirements are met.

Environmental Surveillance. An abbreviated version of the environmental monitoring program conducted during plant operation is carried out during safe storage. The purpose of this program is to identify and quantify releases of radioactivity to the environment. Details of this program, including the anticipated requirements, are discussed in Section G.8 of Appendix G.

Security. The protection of the public, principally against the consequences of their own actions, is an important dimension of the security program during safe storage. Conventional security detection and notification systems normally used to protect the facility against loss or damage are augmented by audible alarms. These alarms, strategically located outside secured radiation zones, loudly warn an intruder of his potential danger. Silent sensors simultaneously alert offsite security personnel.

Physical security to prevent inadvertent radiation exposure of safe storage personnel is provided by multiple-locked barriers. The presence of these barriers makes unauthorized entry into areas where radiation or contamination is present extremely difficult. Locks on the gates in the fence around the

facility provide the first line of security. The fence is maintained in good condition throughout the safe storage period. Facility security is maintained at all times by intrusion alarms and high-security locks on exterior doors. Intrusion, fire, and radiation detection systems are remotely monitored by an offsite commercial security agency. Security agency personnel respond immediately or summon assistance as necessary, depending on the situation indicated by the detection system alarms.

Routine patrol checks by onsite guards are not considered to be cost-effective. By contracting for the services of a reputable private security agency, the facility owner is assured of adequate surveillance and prompt response to alarms without overloading the local law enforcement unit. Liaison with local law enforcement agencies is maintained and their assistance is called for only when necessary.

A representative, who is responsible for controlling authorized access into and movement within the facility, is designated by the licensee. The representative's duties and responsibilities are discussed in a subsequent paragraph.

Essential Systems and Services Requirements. Systems and services required during safe storage are listed in Table J.2-2 in Appendix J, together with the justification for retaining each.

Safe Storage Staff Requirements. The staff organization shown in Figure 10.2-4 takes over the surveillance, maintenance, and security tasks for the duration of the safe storage period. The surveillance and maintenance is supervised by one part-time employee known as the surveillance and maintenance representative. In addition to controlling authorized access into and movement within the facility, he is charged with the responsibilities of appropriate actions and notifications regarding breaches of security, upkeep of plant surveillance and maintenance programs, and administrative reporting of these events as required by state and federal regulations.

10.2.2.6 Deferred Decontamination Activities and Manpower Requirements

Deferred decontamination achieves the degree of decontamination necessary for termination of the amended nuclear license for the reference test reactor

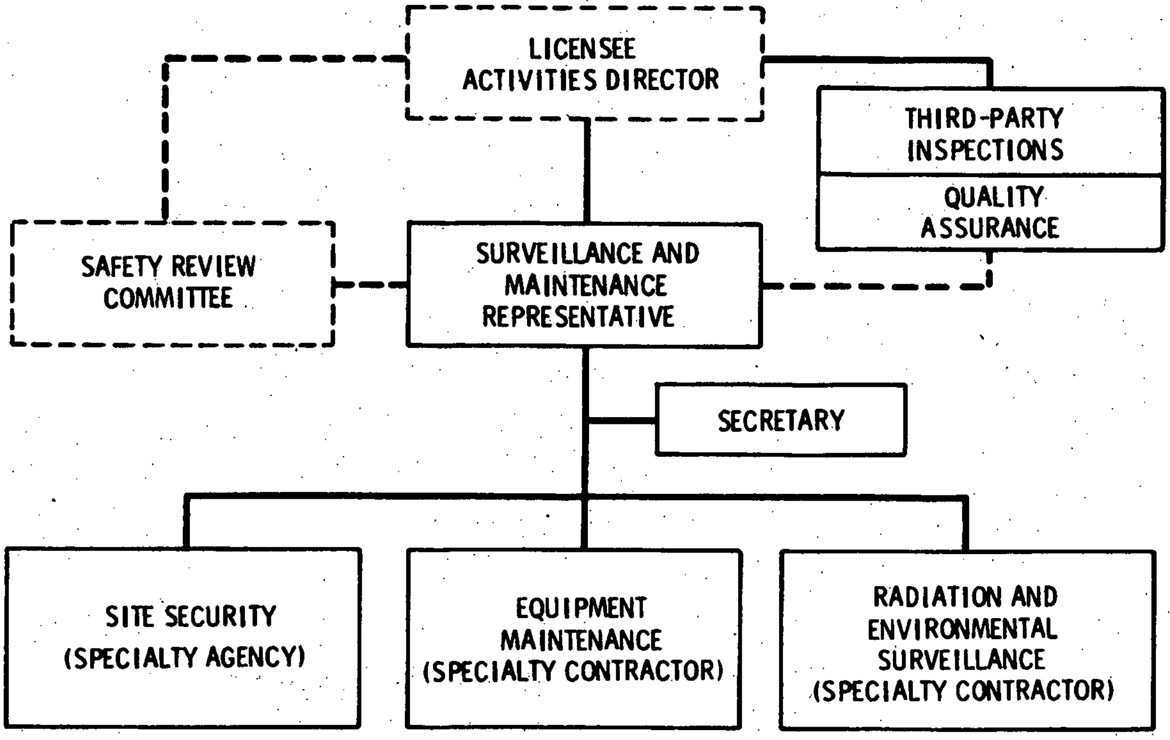


FIGURE 10.2-4. Postulated Staff Organization for the Safe Storage Period

after some period of safe storage. The facility and site must be shown to have residual radioactivity levels low enough to permit unrestricted use.

The same basic operations are assumed performed during deferred decontamination as are performed during DECON. The radioactive corrosion products on the inner surfaces of the piping, tanks, etc., consist mostly of ^{60}Co. It is unlikely that the residual radioactivity will decay to levels that permit unrestricted use before 50 years have elapsed. All of the systems have to be disassembled to make measurements on the interior surfaces of the systems to determine whether the material can be released or must be buried, regardless of the length of the safe storage period.

A number of DECON tasks are accomplished during the preparations for safe storage (i.e., discharging and shipping the fuel; draining of contaminated liquid systems; the removal, packaging, and shipping of contaminated soil from the ERB and buried concrete piping from the site ditches; and removal of radioactive wastes, such as filters, resins, and slurries). During deferred decontamination, the time not expended on these tasks is offset by the time spent

on familiarization of the work force with the facility, removal of locks and barriers installed to secure the facility, and restoration of essential services that were unneeded during the safe storage period. Therefore, it is assumed that the basic work force and time required for deferred decontamination are the same as for DECON.

Work Schedule Estimates. Since the same basic efforts are required to decontaminate the reference test reactor regardless of when the decontamination takes place, the work schedules presented in Figure 10.2-1 for DECON are also assumed to be valid for deferred decontamination. Operations such as reactor defueling and fuel shipment are replaced by familiarization and orientation of the work force with the facility, by training, and by restoring essential services and unsecuring the facility.

Deferred Decontamination Staff Requirements. The management and support staff requirements are the same for deferred decontamination as they are for DECON. However, fewer decommissioning workers are required for deferred decontamination than for DECON, since the radiation dose rates are lower when decontamination is deferred. Since the occupational radiation dose is lower because of radioactive decay, the extra workers needed to meet the occupational dose limits during DECON are not needed for deferred decontamination.

10.2.3 Activities and Manpower Requirements for ENTOMB at the Reference Test Reactor

ENTOMB, as defined by the NRC, implies that the radioactivity contained within the entombment structure will decay sufficiently during a 100-year entombment period to permit unrestricted release of the property at the end of that time. This requirement necessitates the removal and disposal elsewhere of materials containing long-lived radionuclides. Thus, the highly activated core internals are removed, but slightly activated materials are enclosed within the entombment structure. Much of the work associated with ENTOMB of the reference test reactor is the same as that postulated for DECON or SAFSTOR. Thus, the ENTOMB analysis described in Section K.2 of Appendix K for the reference test reactor is accomplished primarily by examining those efforts that are different from the DECON or SAFSTOR efforts, and including those efforts that are the same.

Planning and preparations, ENTOMB activities, and the schedules and manpower requirements for ENTOMB at the reference test reactor are summarized and discussed in the following subsections.

10.2.3.1 Planning and Preparation Activities

ENTOMB is a relatively complex undertaking at the reference test reactor and, consequently, the success of the project is greatly dependent on good planning and on completion of preparatory work before final reactor shutdown. Planning and preparation for ENTOMB is assumed accomplished during the 2 years prior to final reactor shutdown.

The planning and preparation activities for ENTOMB are essentially the same as those described in Section 10.2.1.1 for DECON and are not discussed further here.

10.2.3.2 ENTOMB Activities

The major activities and requirements to accomplish entombment of the reference test reactor are:

- decontamination
- preparation of the entombment structure
- disassembly and disposition of radioactive materials
- quality assurance
- environmental surveillance
- specialty contractors
- essential systems and services.

These activities are discussed in the following paragraphs.

Decontamination. At final reactor shutdown, radioactive contamination is present on the surfaces of process systems and equipment. Decontamination is relied upon to remove the bulk of this radioactive contamination from selected systems and components. The objective of the decontamination effort during ENTOMB is to reduce the radiation levels throughout the facility in order to minimize personnel exposure during subsequent tasks.

The decontamination activities required for ENTOMB are identical to those for DECON, as discussed in Section 10.2.1.2, and are not discussed further here.

Preparation of the Entombment Structure. The entombment structure postulated for the reference test reactor encompasses the below-grade portion of the reactor containment vessel (CV). Radioactive materials and equipment are removed from their locations external to the CV and are placed within the quadrants surrounding the reactor pressure vessel and biological shield. The contaminated drains from within the CV are cut, plugged, and capped at the CV wall. After the radioactive materials and equipment are placed within the CV, the concrete floors and other surfaces at the 0 elevation are partially removed to permit installation of forming and structural support for the entombment structure cap. This cap is nominally 0.6 m in thickness, is bonded to the concrete structures forming the quadrants and the CV liner, and is designed to support floor loadings typical of a high-bay warehouse, manufacturing, or maintenance facility.

The above-grade portion of the CV is decontaminated and released for unrestricted use, as is the remainder of the facility external to the CV.

Disassembly and Disposition of Radioactive Materials. To meet the criterion for unrestricted release of the entombment structure after 100 years, it is necessary to remove the neutron-activated materials from the reference test reactor and from the mock-up reactor, as it is done in DECON. The contaminated equipment and material from outside the CV and the contaminated concrete from surfaces external to the CV are placed within the quadrants, thus eliminating the packaging, shipment, and burial costs for those materials. The wet solid radioactive wastes are also placed within the quadrants. The dry solid radioactive wastes are disposed of as in DECON. These wastes are largely combustible material. While the likelihood of a fire occurring in this material within the sealed entombment structure is rather remote, it seems prudent to exclude combustibles.

Disassembly techniques are described generically in Appendix G. A detailed discussion of entombment of the reference test reactor is presented in Section K.2 of Appendix K.

Quality Assurance. An extensive quality assurance program is carried on throughout the decommissioning effort, to ensure that all applicable regulations are met, that the work is performed according to plan, and that the work

does not endanger the safety of the public or of the decommissioning staff. The quality assurance program for ENTOMB is essentially the same as that for DECON, as described in Section 10.2.1.2. A more detailed review of the anticipated elements of an appropriate quality assurance program for ENTOMB is given in Section G.7 of Appendix G.

Environmental Surveillance. An abbreviated version of the environmental monitoring program carried on during facility operation is continued during the entombment period. This program is the same as that for DECON (see Section 10.2.1.2). Details of the program are discussed in Section G.8 of Appendix G.

Specialty Contractors. In addition to the specialty contractor requirements for DECON (see Section 10.2.1.2), installation of the entombment cap will require a contractor to install the forms and structural support members and concrete. Also, it is postulated that a demolition contractor removes all structures external to the CV following decontamination, thus leaving the CV intact with the below-grade portion entombed and the above-grade portion decontaminated and released for unrestricted use.

Essential Systems and Services. All or parts of certain facility systems and services must remain in place and in service until all radioactive material is either removed from the facility or secured on the site, to prevent the release of significant quantities of radionuclides (or other hazardous materials) to the environment. Some systems and services are required for cleanup and disassembly activities, and others provide personnel health and safety protection. The systems and services essential for ENTOMB are the same as those given in Section 10.2.1.2 for DECON.

10.2.3.3 ENTOMB Schedule

Most of the tasks required to entomb the reference test reactor are identical to the tasks required for DECON. Three new tasks are added, seven DECON tasks are deleted, and several tasks are reduced in scope, from the schedule shown in Figure I.2-1 in Appendix I, to create the schedule for entombing the reactor CV, as shown in Figure 10.2-5. The points in time for performing some of the tasks are shifted relative to the DECON schedule to allow for the placement of the material being entombed.

TASK	REACTOR BUILDING/MUR/CONTAINMENT VESSEL: MONTHS AFTER SHUTDOWN (Persons per day/Exposure hours/Calendar months)
1. COMPREHENSIVE RADIATION SURVEY FOR TOTAL FACILITY (i.e., ALL BUILDINGS)	6/528/1
2. DISCHARGE FUEL (INCLUDING MUR)	5/66/0.1
3. PREPARE AND SHIP SPENT FUEL	8/2500/3
4. GENERAL CLEANUP AND EQUIPMENT INVENTORY (i.e., ALL BUILDINGS)	14/924/0.5
5. DRAIN, CLEAN, DRY QUADRANTS A, B, C AND D AND CANALS E AND F	10/780/0.6
6. PLACE RADIOACTIVE MATERIAL IN CV	5/9000/17 (intermittent)
7. DRAIN, CLEAN, DRY CANAL H	10/180/0.14
8. REMOVE, PACKAGE, AND SHIP MUR AND ASSOCIATED HARDWARE	10/576/0.45
9. DRAIN, CLEAN, DRY CANAL G	10/180/0.14
10. REMOVE LOOSE EQUIPMENT IN Q&Cs AND DRY ANNULUS	10/936/0.55
11. DRAIN AND FLUSH PCWS	6/72/0.1
12. ISOLATE RV AND ADD DEIONIZED WATER FOR SHIELDING	6/72/0.1
13. REMOVE RV INTERNALS AND SHIP ACTIVATED RV INTERNALS	16/10366/3.75
14. CUT AND CAP CV PENETRATIONS	16/3840/1.5
15. REMOVE FIXED EQUIPMENT OUTSIDE CV	101/1728/1.3
16. REMOVE PCWS PIPING TO PPH	10/2820/2.14
17. REMOVE RB CONTAMINATED CONCRETE	10/1300/1
18. REMOVE MISCELLANEOUS CONTAMINATED DRAINS	15/2520/1.62
19. REMOVE CONTAMINATED HVAC FROM RB/CV	8/960/0.91
20. INSTALL ENTOMBMENT CAP	SUBCONTRACT/7000/4
21. FINAL RADIATION SURVEY	2/50/0.5

PERSONS PER DAY/EXPOSURE HOURS/CALENDAR MONTHS

━━━ CONTINUOUS OPERATIONS OVER THE TIME SPAN SHOWN

━ ━ ━ INTERMITTENT OPERATIONS OVER THE TIME SPAN SHOWN

TOTALS		
	PERSON-MONTHS	324
	PERSON-HOURS	56,094
	EXPOSURE-HOURS	46,398

ABBREVIATIONS:

CV	CONTAINMENT VESSEL
HVAC	HEATING, VENTILATION, AND AIR CONDITIONING
MUR	MOCK-UP REACTOR
PCWS	PRIMARY COOLING WATER SYSTEM
PPH	PRIMARY PUMP HOUSE
Q&C	QUADRANTS AND CANALS
RB/CV	REACTOR BUILDING / CONTAINMENT VESSEL
RV	REACTOR VESSEL

FIGURE 10.2-5. Task Schedule and Sequence and Decommissioning Worker Requirements for ENTOMB Activities in the Reactor/Containment Building

The task schedules for the Hot Laboratory Building and the other contaminated structures are identical in content but are also shifted in time relative to the DECON schedules. The overall schedule for the ENTOMB project is shown in Figure 10.2-6. While the time distribution of tasks for ENTOMB is different from DECON, the total duration of ENTOMB activities is essentially the same as for DECON, about 25 months following reactor shutdown.

10.2.3.4 ENTOMB Staff Requirements

The shift schedule and the makeup of the work crews are assumed to be the same for ENTOMB as are given for DECON in Section 10.2.1.4. The elimination of seven cleanup and removal tasks in the CV reduces the total direct staff labor need for ENTOMB by about 12% relative to DECON. However, it is estimated that the additional effort associated with the three new tasks plus placing the contaminated materials within the CV will increase the total ENTOMB direct staff labor by a like amount, resulting in no significant change in staff labor needs.

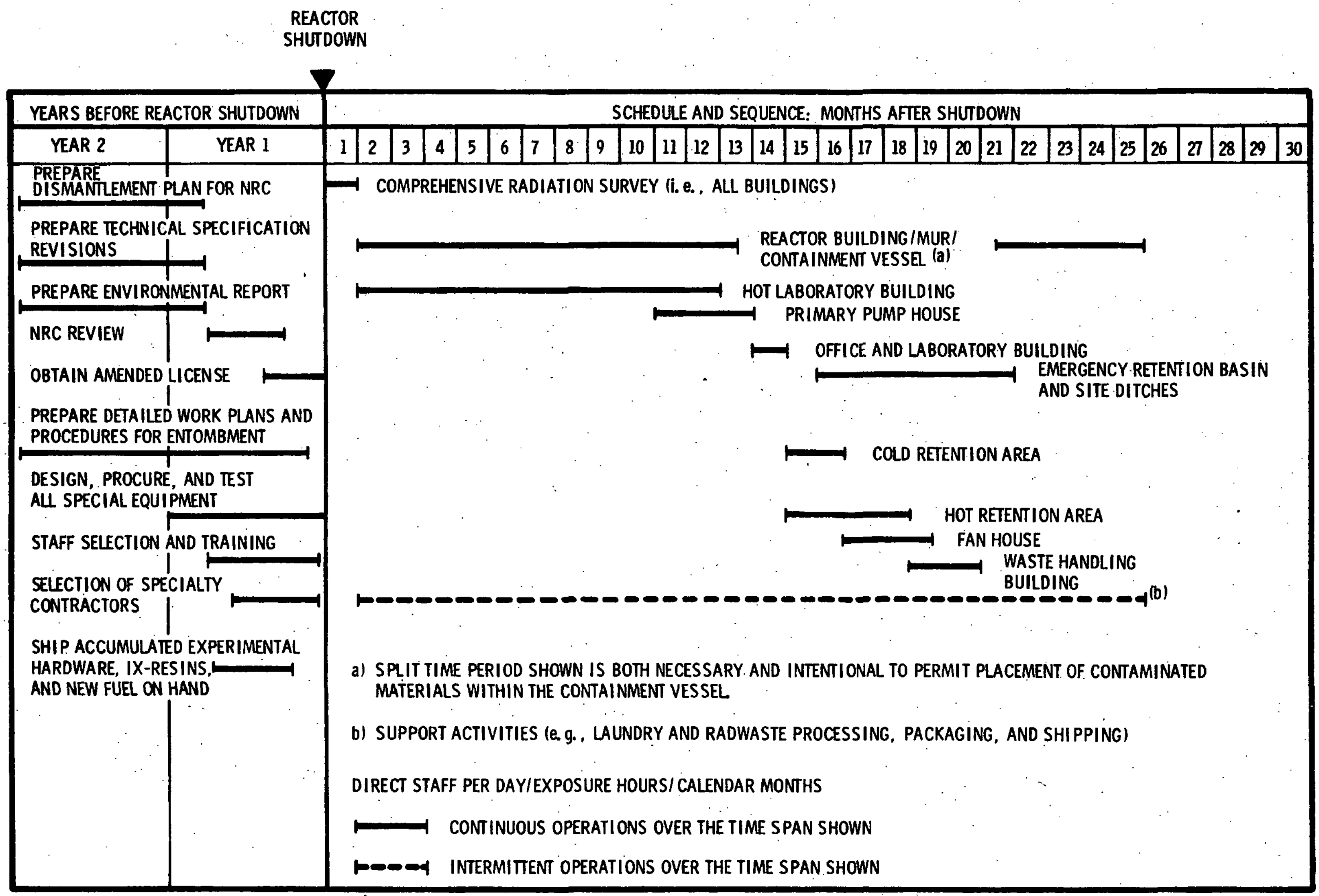


FIGURE 10.2-6. Overall ENTOMB Project Schedule for the Reference Test Reactor

11.0 DECOMMISSIONING COSTS

The estimated costs of decommissioning the reference research and test (R&T) reactors via the DECON, SAFSTOR, and ENTOMB alternatives are developed in detail utilizing a unit-component approach in Appendices I, J, and K in Volume 2, respectively, and are summarized in this section.

The principal assumptions made in the generation of cost estimates for the decommissioning of the reference reactors are:

- The decommissioning staff is drawn from the technical and operations staffs of the plant to the maximum extent possible. Thus, all support services and the part-time assistance of many plant staff members can be utilized during the planning and preparation period, with only nominal costs to the decommissioning program.
- The amended nuclear license is in place by final reactor shutdown, permitting decommissioning activities to begin promptly.
- Costs are based on 1981 prices and wage rates.

11.1 COST OF DECOMMISSIONING THE REFERENCE RESEARCH REACTOR

The costs of decommissioning the reference research reactor via the DECON, SAFSTOR, and ENTOMB alternatives are summarized in subsequent subsections.

11.1.1 Cost of DECON

The estimated cost of DECON for the reference research reactor, including a 25% contingency, is $0.846 million, as summarized in Table 11.1-1. Details of the development of these costs are discussed in Section I.1.3 of Appendix I.

Other possible DECON requirements (i.e., spent fuel shipment and facility demolition and site restoration) are estimated to cost about $0.322 million, including a 25% contingency.

TABLE 11.1-1. Summary of Estimated Costs of DECON for the Reference Research Reactor

Cost Category		Estimated Costs ($)[a,b]	Percent of Total[c]
Disposal of Radioactive Materials			
Neutron-Activated Materials	16 610		
Contaminated Materials	60 060		
Radioactive Wastes	9 620		
Total Disposal Costs		86 290	12.8
Staff Labor		530 570	78.4
Energy		13 790	2.0
Special Tool and Equipment		21 150	3.1
Miscellaneous Supplies		6 210	0.9
Nuclear Insurance		4 620	0.7
License Fees		13 950	2.1
Subtotal		676 580	100.0
Contingency (25%)		169 150	
Total, DECON Costs		845 730	
Other Possible Costs			
Spent Fuel Shipment		60 980[d]	
Facility Demolition & Site Restoration		196 750[e]	
Subtotal		257 730	
Contingency (25%)		64 430	
Total, Other Possible Costs		322 160	

(a) 1981 costs used.
(b) The number of figures shown is for computational accuracy and does not imply precision to the nearest $10.
(c) Individually rounded to the nearest 0.1%.
(d) Includes cost of containers, overpacks, and 800 km transportation only.
(e) Based on Table L.3-1 in Appendix L.

Disposal of Radioactive Materials

Three types of radioactive materials in the reference research reactor that require disposal are: 1) neutron-activated materials, 2) contaminated

materials, and 3) radioactive wastes. The total cost for disposal of these materials is about $86,000, which is approximately 13% of the total DECON cost. The disposal cost includes the container, transportation, and burial costs but not the direct labor costs for removing and packaging the materials.

Details of the disposal of the neutron-activated materials are given in Table I.1-6 in Appendix I. The packaged materials require an estimated four legal truck shipments and occupy 160 m^3 of space in a shallow-land burial facility. The estimated total cost for disposal of the neutron-activated materials in a shallow-land burial facility is about $16,600.

Contaminated materials in the reference research reactor are assumed to include much of the piping and equipment located in the Reactor Building. In addition, specified concrete surfaces (see Appendix D in Volume 2 for details) are assumed to be contaminated, thus requiring surface removal to a depth of about 0.05 m. Breakdowns of the disposal costs for contaminated materials are given in Table I.1-7 in Appendix I. These materials require an estimated 133 m^3 of space (including the disposable containers, as required) at a shallow-land burial site. The estimated total disposal cost for contaminated materials from the reference research reactor is about $60,000.

Radioactive wastes generated during DECON at the reference research reactor are categorized as either wet solid wastes or dry solid wastes. Wet solid wastes result from the processing of contaminated water volumes. Wet solid wastes are assumed to be mixed with a cement solidifying agent and encapsulated in a standard steel drum (0.21 m^3) prior to being shipped to a shallow-land burial facility. Dry solid wastes include discarded contaminated materials such as plastic sheeting, rags, and anticontamination clothing. They are expected to occur as a result of most of the tasks specified in Section I.1 of Appendix I and are estimated on a taskwise basis. Dry solid wastes are compacted as much as possible to reduce their volume. The total cost for disposal of wet and dry solid radioactive wastes from DECON is estimated to be $9,600.

Staff Labor

The cost of staff labor during DECON is shown in detail in Table I.1-8 in Appendix I. More than 78% of the DECON cost is associated with the staff labor requirements. A total staff labor cost of about $0.53 million is estimated for DECON of the reference research reactor. Specialty contractor labor is not included in this total.

The dedicated manpower costs for the DECON tasks are given in Table I.1-9. These costs are attributed to manpower that is specifically assigned to the tasks and do not include either nondedicated personnel or management and support staff (see Figure H.2-1 in Appendix H).

Energy

The cost of energy used during DECON is presented in Table I.1-10 in Appendix I. The usage of electricity is estimated based on detailed analysis of the requirements for the essential systems and services and the DECON tasks and schedule, presented in Table 10.1-1 and Figure 10.1-1 in Section 10, respectively.

A total of 551 MWh of electricity is estimated to be used during DECON at a cost of $13,790, which represents about 2% of the total DECON cost.

Special Tools and Equipment

The estimated costs of the special tools and equipment that are required for DECON at the reference research reactor are presented in Section I.1.3.4 of Appendix I. The estimated total cost for special tools and equipment is $21,150, which is approximately 3% of the total DECON cost.

Miscellaneous Supplies

A variety of supplies are used during DECON. These include expendable glass-fiber and HEPA filters, anticontamination clothing, cleaning and contamination control supplies, expendable hand tools, cutting and welding supplies, decontamination chemicals, and filter/demineralizer resins. The estimated costs of these items are given in Section I.1.3.4 of Appendix I. The estimated total cost of miscellaneous supplies during DECON at the reference research reactor is $6,210 and represents about 1% of the total DECON cost.

Nuclear Insurance

The cost of nuclear liability insurance during DECON is estimated from the current annual operating premium of $7,700 at the reference research reactor. The estimated total cost of nuclear insurance is $4,620, which represents about 0.7% of the total DECON cost.

Licensing Fees

The fees charged for licensing services performed by the NRC are delineated in 10 CFR Part 170.[1] The cost of licensing fees during DECON of the reference research reactor are given in Table I.1-12 in Appendix I. The estimated total cost for licensing services is about $14,000, which is approximately 2% of the total DECON cost.

Other Possible Costs

Three additional costs could figure into the total DECON cost, depending on how they are classified. In this study, these costs are presented separately, since they cannot be clearly identified as belonging to DECON. The tasks that result in these additional costs are:

- shipment of spent reactor fuel to an offsite repository
- demolition of the structures and restoration of the site
- alternative disposal of the highly activated materials in a deep geologic disposal facility.

It is assumed in this study that the fuel assemblies are shipped by truck to a repository located 800 km from the reference research reactor. The estimated total cost for shipping the spent fuel to the repository is $60,980, not including handling costs at the reactor or handling and storage costs at the repository.

The cost of demolishing the decontaminated and uncontaminated structures of the reference research reactor are summarized in Table L.3-1 in Appendix L (Volume 2). The estimated total cost of $196,750 (without contingency) includes labor, supplies, overheads, and profit, but not extraordinary insurance premium, bonding, or state sales tax. Details of cost estimates for this task are given in Section L.3.1 of Appendix L.

The estimated disposal cost for the neutron-activated materials given in Table 11.1-1 is based on the assumption that all of these materials are placed in a shallow-land disposal site. If the amount of radioactivity in these neutron-activated materials is sufficiently great for them to be classified as intermediate-level wastes, they would have to be placed in a deep geologic disposal facility. The incremental cost for disposing of these materials in a deep geologic disposal facility is not precisely known at this time since such a facility does not currently exist in the United States; however, it can logically be assumed that a significantly higher cost could be anticipated than for shallow-land burial of these materials.

11.1.2 Cost of SAFSTOR

The estimated costs of activities required to place and maintain the reference research reactor facility in safe storage are presented in this section, together with costs of possible deferred decontamination.

11.1.2.1 Cost of Preparations for Safe Storage

The estimated cost of preparations for safe storage, including a 25% contingency, is $0.492 million, as summarized in Table 11.1-2. Details of the development of these costs are given in Section J of Appendix J (Volume 2).

A possible cost associated with preparations for safe storage--spent fuel shipment--is estimated to cost about $61,000, not including a 25% contingency.

Disposal and Storage Radioactive Materials. Only dry solid wastes require disposal during preparations for safe storage. The total cost for disposal of these materials is about $5,530 and is approximately 1% of the preparations cost. The disposal cost includes the container, transportation, and burial costs, but does not include the direct labor costs for removing and packaging these materials.

Provisions for onsite storage of noncombustible radioactive materials and contaminated wastes are estimated to cost about $11,200, which is about 3% of the preparations cost. The storage cost includes the container cost, but does not include the direct labor costs for removing and packaging these materials.

TABLE 11.1-2. Summary of Estimated Costs of Placing the Reference Research Reactor in Safe Storage

Cost Category	Estimated Costs ($)[a,b]	Percent of Total[c]
Disposal of Radioactive Materials[c]	5 530	1.4
Storage of Radioactive Materials and Contaminated Wastes	11 200	2.8
Staff Labor	335 210	85.1
Energy	8 080	2.1
Special Tools and Equipment	2 340	0.6
Miscellaneous Supplies	15 000	3.8
Nuclear Insurance	2 890	0.7
License Fees	13 950	3.5
Subtotal	394 200	100.0
Contingency (25%)	98 550	
Total, Preparations for Safe Storage	492 750	
Other Possible Costs		
Spent Fuel Shipment	60 980[d]	
Contingency (25%)	15 245	
Total, Other Possible Costs	76 225	

(a) 1981 costs used.
(b) The number of figures shown is for computational accuracy and does not imply precision to the nearest $10.
(c) Only includes dry solid wastes.
(d) Includes cost of containers, overpacks and 800-km transportation, only.

Staff Labor. The costs of staff labor during preparations for safe storage are shown in detail in Table J.1-8 in Appendix J. More than 85% of the cost for prepararations for safe storage is associated with staff labor. A total staff labor cost of about $335,200 is estimated for preparing the reference research reactor for safe storage.

Energy. The cost of energy used during preparations for safe storage is presented in Table J.1-9 in Appendix J, together with the estimated usage of electricity. The usage of electricity is estimated based on a detailed analysis of the requirements for the essential systems and services (the same as for DECON, see Table 10.1-1) and on the tasks and schedule for preparations for safe storage, presented in Figure 10.1-3 in Section 10.

A total of about 323 MWh of electricity, costing about $8,100, is estimated to be used and represents about 2% of the total cost of preparations for safe storage.

Special Tools and Equipment. The estimated costs of the special tools and equipment that are required for preparing the reference research reactor for safe storage are discussed in Section J.1.4.5 in Appendix J. The estimated total cost of special tools and equipment is approximately $2,300, which represents less than 1% of the total cost for preparations for safe storage.

Miscellaneous Supplies. A variety of supplies are used during preparations for safe storage. These include expendable glass-fiber and HEPA filters, anti-contamination clothing, cleaning and contamination control supplies, expendable hand tools, cutting and welding supplies, decontamination chemicals, and demineralizer resins. The estimated costs for these items are discussed in Section J.1.4.5 in Appendix J. The estimated total cost for miscellaneous supplies is $15,000 and represents about 4% of the total cost of preparations for safe storage.

Nuclear Insurance. The cost of nuclear liability insurance during preparations for safe storage is estimated from the annual operating premium of $7,700. The estimated total cost for nuclear insurance is $2,890, which represents <1% of the total cost of preparations for safe storage.

Licensing Fees. The fees charged for licensing services performed by the NRC are delineated in 10 CFR Part 170.[1] The costs of licensing fees during preparations for safe storage of the reference research reactor are shown in Table J.1-10 in Appendix J. The estimated total cost of licensing services is $13,950, which is approximately 4% of the total cost of preparations for safe storage.

Other Possible Costs. Other possible costs are discussed in detail in Section 11.1.1; however, only the costs associated with spent fuel shipment are applicable to the total cost analysis during preparations for safe storage. The costs of spent fuel shipment are the same as those for DECON. The estimated spent fuel shipment cost of $60,980 (without contingency) does not include either handling costs at the reactor or handling and storage costs at the repository.

11.1.2.2 Annual Cost During Safe Storage

The estimated annual cost of safe storage for the reference research reactor is developed in Section J.1.5 of Appendix J and is summarized in Table 11.1-3. The total annual cost is estimated to be $33,100 and would continue until the facility is decontaminated.

Staff labor accounts for about 72% of the total, with allowances for all other costs contributing the remaining 28% of the annual cost.

11.1.2.3 Cost of Deferred Decontamination

The estimated cost of deferred decontamination of the reference research reactor at various times after shutdown is given in Table 11.1-4. Details of these cost estimates are given in Section J.1.6 of Appendix J. It is assumed that the size of management and support staff is the same for deferred decontamination as it is for DECON. However, fewer decommissioning workers are required for deferred decontamination than are required for DECON, since the radiation dose rates are lower when decontamination is deferred.

The total cost of SAFSTOR for the reference research reactor, including deferred decontamination after 10, 30, 50, and 100 years, is given in Table 11.1-5. The total SAFSTOR cost is the sum of the costs of preparations for safe storage, safe storage, and deferred decontamination. In constant dollars, the cost of SAFSTOR for the reference research reactor is considerably more expensive than the $0.844 million cost for DECON.

TABLE 11.1-3. Estimated Annual Safe Storage Costs for the Reference Research Reactor

Labor	Estimated Annual Cost ($)
Surveillance and Maintenance	2 480
Secretarial	1 940
Repair	2 570
Security	3 050
Environmental and Radiological Monitoring	7 960
Inspection and Quality Assurance Verification	940
Total Labor Cost	18 940
Other Costs	
Reactor Building Roof Repair[a,b]	720
Reactor Building Roof Replacement[a,c]	1 420
Pest Control	400
Equipment and Supplies	500
Parts for Monitoring Intrusion and Fire System Including Video Monitoring and Remote Readout	1 000
Emergency Maintenance	500
Energy	1 080
License Fee	650
Nuclear Liability Insurance	770
Total, Other Costs	7 540
Subtotal	26 480
Contingency (25%)	6 620
Total, Annual Safe Storage Costs	33 100

(a) Amortized on an annual basis.
(b) Estimated cost of $3,600 every 5 years.
(c) Estimated cost of $28,400 every 20 years.

TABLE 11.1-4. Estimated Costs of Deferred Decontamination for the Reference Research Reactor

Cost Category	Costs ($ thousands) Decontamination Deferred 10 Years	30 Years	50 Years	100 Years
Disposal of Radioactive Materials				
Neutron-Activated Materials	15.93	14.32	8.79	8.79
Contaminated Materials	59.87	37.05	10.64	10.64
Radioactive Wastes	9.41	5.90	1.20	1.20
Staff Labor	530.14	526.61	516.73	516.73
Energy	13.79	13.79	13.50	13.50
Special Tools and Equipment	21.15	4.45	4.28	4.28
Miscellaneous Supplies	6.21	5.15	5.15	5.15
Nuclear Insurance	0.64	0.64	0.64	0.64
License Fees	12.00	12.00	12.00	12.00
Subtotal	669.14	619.91	572.93	572.93
Contingency (25%)	167.29	154.98	143.23	143.23
Totals	836.43	774.89	716.16	716.16

TABLE 11.1-5. Estimated SAFSTOR Costs for the Reference Research Reactor

Decontamination Deferred (years)	Decommissioning Costs ($ millions)[a,b] Preparations for Safe Storage	Safe Storage[c]	Deferred Decontamination	Total
10	0.493	0.314	0.836	1.643
30	0.493	0.974	0.775	2.242
50	0.493	1.634	0.716	2.843
100	0.493	3.284	0.716	4.493

(a) Values include a 25% contingency.
(b) Values are in constant 1981 dollars.
(c) The safe storage period extends from the time of completion of the preparations for safe storage, about 0.5 years, until the start of deferred decontamination.

11.1.3 Cost of ENTOMB

The estimated cost of ENTOMB for the reference research reactor, developed in detail in Section K.1.2 of Appendix K (Volume 2), is summarized in Table 11.1-6. The costs are grouped in categories consistent with those used for DECON and SAFSTOR. ENTOMB, with activated reactor vessel internals removed, is estimated to cost about $0.56 million. Annual continuing care costs are estimated to be $6,120. Other possible costs are estimated to be about $101,400. The total costs include a 25% contingency allowance.

TABLE 11.1-6. Summary of Estimated Costs of ENTOMB for the Reference Research Reactor

Cost Category	Estimated Costs ($)[a,b]	Percent of Total
Disposal of Neutron-Activated Materials	16 610	3.8
Disposal of Radioactive Wastes[c]	6 800	1.5
Staff Labor	378 890	85.2
Energy	9 290	2.1
Special Tools and Equipment	2 340	0.5
Miscellaneous Supplies	5 210	1.2
Specialty Contractor[d]	8 620	1.9
Nuclear Insurance	2 790	0.7
License Fees	13 950	3.1
Subtotal	444 500	100.0
Contingency (25%)	111 130	
Total, Costs of Entombment[e]	555 630	
Other Possible Costs		
Spent Fuel Shipment	60 980	
Facility Demolition & Site Restoration	20 100[d]	
Subtotal	81 080	
Contingency (25%)	20 270	
Total, Other Possible Costs	101 350	

(a) 1981 costs used.
(b) The number of figures shown for computational accuracy and does not imply precision to the nearest $10.
(c) Only includes dry solid wastes.
(d) Does not include demolition of the Reactor Building and the reactor structure.
(e) The "total" ENTOMB costs would also include the annual surveillance and maintenance service costs of $6,120 times "x" number of years that these services were provided.

Disposal of Radioactive Materials

Estimated costs include disposal of neutron-activated materials and radioactive (dry) wastes. All other radioactive materials are placed into the reactor pool and the enlarged PIF cavity (i.e., within the confines of the postulated entombment structure). The estimated total cost of disposal of radioactive materials is $23,410 (about 3.8% of the total ENTOMB costs).

Staff Labor

Staff labor costs include both the management and support staff and the decommissioning workers and cover the planning and preparation period as well as the years of active decommissioning. However, specialty contractor labor is not included in this category. Staff labor is estimated to cost about $0.379 million, which is approximately 85% of the total cost.

Energy

The cost of energy used during decommissioning of the reference research reactor via the ENTOMB alternative is estimated to be $9,290. This amounts to 2.1% of the total ENTOMB cost.

Special Tools and Equipment

The estimated cost of special tools and equipment that are required to decommission the reference research reactor via the ENTOMB alternative is $2,340; this represents less than 1% of the total ENTOMB costs.

Miscellaneous Supplies

Items such as disposable protective clothing, decontamination chemicals, decontamination agents, rags, mops, plastic bags and sheeting, glass-fiber and HEPA filters, ion exchange resins, and expendable tools are grouped together as miscellaneous supplies. The total cost of miscellaneous supplies is estimated to be $5,210, which is about 1.2% of the total ENTOMB cost.

Specialty Contractors

Installation of the entombment structure by a specialty contractor is discussed in detail in Section K.1.2.2 of Appendix K. The estimated total cost for the entombment structure is $8,620, representing 1.9% of the total ENTOMB cost.

Nuclear Insurance and Licensing Fees

Nuclear insurance and licensing fees, estimated to cost $2,790 and $13,950, respectively, make up the balance of the ENTOMB costs, representing less than 1% and about 3%, respectively, of the total.

Continuing Care

Continuing care, involving surveillance and maintenance of the entombment structure, is estimated to cost about $6,100 annually. Thus, a continuing care period of 100 years adds about $610,000 to the cost of decommissioning the reference research reactor via the ENTOMB alternative. It should be recognized that there is no fixed number of years for nuclear reactor facilities to be entombed; it depends on the facility-specific radionuclides and how long they take to decay to unrestricted use levels. For the purposes of this study, all ENTOMB time periods given are for illustration only. In addition, deferred decontamination of the entombment structure may be required before the amended nuclear license can be terminated, thus adding significantly to the overall decommissioning cost.

Other Possible Costs

The other possible costs shown at the bottom of Table 11.1-6 are calculated in the same way as those for DECON, which are discussed in Section 11.1.1. The cost of spent fuel shipment is the same as for DECON. However, the cost of facility demolition and site restoration after decommissioning by ENTOMB is considerably less than that after DECON, because the Reactor Building and the reactor structure are not demolished.

11.2 COST OF DECOMMISSIONING THE REFERENCE TEST REACTOR

The cost of decommissioning the reference test reactor via the DECON, SAFSTOR, and ENTOMB alternatives is summarized in subsequent subsections.

11.2.1 Cost of DECON

The estimated cost of DECON for the reference test reactor, including the 25% contingency, is $15.6 million, as summarized in Table 11.2-1. Details of the development of these costs are discussed in Section I.2.3 of Appendix I.

TABLE 11.2-1. Summary of Estimated Costs of DECON for the Reference Test Reactor

Cost Category		Estimated Costs ($ millions)[a,b]	Percent of Total
Disposal of Radioactive Materials			
Neutron-Activated Materials			
Reference Test Reactor	0.131		
Mock-Up Reactor (MUR)	0.004		
Contaminated Materials	2.338		
Radioactive Wastes	0.099		
Total Disposal Costs		2.572	20.7
Staff Labor		8.63	69.3
Energy		0.076	0.6
Special Tools and Equipment		0.361	2.9
Miscellaneous Supplies		0.203	1.6
Specialty Contractors[c]		0.616	4.9
Nuclear Insurance		--[d]	--
License Fees		--[e]	--
Subtotal		12.458	100.0
Contingency (25%)		3.115	
Total, DECON Costs		15.573	
Other Possible Costs			
Spent Fuel Shipment		0.204[f]	
Facility Demolition and Site Restoration		2.289[g]	
Subtotal		2.493	
Contingency (25%)		0.623	
Total, Other Possible Costs		3.116	

(a) 1981 costs.
(b) The number of figures shown is for computational accuracy and does not imply precision to the nearest $1,000.
(c) Includes selected demolition, explosives, temporary radwaste, and environmental monitoring services.
(d) Indemnity fees are currently $100/yr for each license (i.e., the test reactor license and the MUR license) at the reference test facility and are not included in this study since they represent only a small fraction of 1% of the total decommissioning cost.
(e) Because the reference test reactor is assumed to be federally owned these fees are not applicable; however, where applicable for other nuclear R&T reactor facilities, the schedule of fees for license amendments and other approvals required by the license or NRC regulations is given in 10 CFR 170.
(f) Does not include costs for handling at the reactor or handling and storage at the repository.
(g) This total cost is only for those demolition tasks remaining after license termination (see Section I.2.3.9 in Appendix I and Appendix L for details).

Other possible DECON requirements (i.e., spent fuel shipment and facility demolition and site restoration) are estimated to cost about $3.12 million, including a 25% contingency.

Disposal of Radioactive Materials

The three types of radioactive materials in the reference test reactor (including the MUR) that require disposal are: 1) neutron-activated materials, 2) contaminated materials, and 3) radioactive wastes. The estimated total cost of disposal for these materials is about $0.26 million and is approximately 21% of the total DECON cost. The disposal cost includes the container, transportation, and burial costs but not the direct labor costs for removing and packaging the materials.

Details of the disposal of the neutron-activated materials from the reference test reactor and from the MUR are given in Tables I.2-9 and I.2-10 in Appendix I, respectively. The packaged materials from both reactors require an estimated 16 legal-weight truck shipments and occupy 62 m^3 of space in a shallow-land burial facility. The estimated total cost of disposal for all of the neutron-activated materials from both reactors in a shallow-land burial facility is $135,000.

Contaminated materials in the reference test reactor (including the MUR) are assumed to include much of the piping and equipment located in the Reactor Building. In addition, specified concrete surfaces (see Appendix D of Volume 2 for details) are assumed to be contaminated, thus requiring surface removal to a depth of about 0.05 m. Breakdowns of the disposal costs for contaminated materials are given in Table I.2-11 in Appendix I. These materials require an estimated 4,762 m^3 of space (including the disposable containers, as required) at a shallow-land burial site. The estimated total cost of disposal for contaminated materials from the reference test reactor (including the MUR) is about $2.4 million.

Radioactive wastes generated during DECON of the reference test reactor are categorized as either wet solid wastes or dry solid wastes. Wet solid wastes result from the processing of contaminated water volumes. Wet solid

wastes are assumed to be mixed with a cement solidifying agent and encapsulated in a standard steel drum (0.21 m^3) prior to being shipping to a shallow-land burial facility. Dry solid wastes include discarded, contaminated materials such as plastic sheeting, rags, and anticontamination clothing. They are expected to occur as a result of most of the tasks specified in Section I.2.2 of Appendix I and are estimated on a taskwise basis. Dry solid wastes are compacted as much as possible to reduce their volume. The estimated total cost for disposal of wet and dry solid radioactive wastes from DECON is $0.099 million.

Staff Labor

The costs of staff labor during DECON is shown in detail in Table I.2-14 in Appendix I. More than 69% of the DECON cost is associated with the staff labor requirements. A total staff labor cost of about $8.63 million is estimated for DECON of the reference test reactor. Specialty contractor labor is not included in this total.

Energy

The cost of energy used during DECON is presented in Table I.2-15 in Appendix I. The anticipated monthly usage of electricity and natural gas is based on data (1978) supplied in Reference 2, adjusted for inflation to mid-1981, and applied to the time frame estimated for DECON tasks (i.e., about 25 months). The estimated total cost of energy is about $76,250 and represents less than 1% of the total DECON cost.

Special Tools and Equipment

The estimated costs of special tools and equipment that are required for DECON of the reference test reactor are presented in Table I.2-16 in Appendix I. The estimated total cost for special tools and equipment is $0.361 million, which is approximately 3% of the total DECON cost.

Miscellaneous Supplies

Various supplies are used during DECON. These include expendable glass-fiber and HEPA filters, anticontamination clothing, cleaning and contamination control supplies (chemical agents, sweeping compounds, rags, mops, and plastic bags and

sheeting), expendable handtools, cutting and welding supplies (saw blades, torch gas, and welding rods), and decontamination chemicals, as well as office supplies. The estimated individual costs for these items are given in Table I.2-17 in Appendix I. The estimated total cost for miscellaneous supplies during DECON of the reference test reactor is about $0.2 million and represents less than 3% of the total DECON cost.

Nuclear Insurance

Indemnity fees are currently $100/yr for each license (i.e., the test reactor license and the MUR license) at the reference test facility and are not included in this study since they represent only a small fraction of 1% of the total decommissioning cost.

Licensing Fees

The fees charged for licensing services performed by the NRC are delineated in 10 CFR 170.[1] The costs of licensing fees during DECON of the federally owned reference test reactor are not included in this study since the federal government does not charge itself for these inspections.

Other Possible Costs

Three additional costs could figure into the total DECON cost, depending on how they are classified. In this study, these costs are presented separately, since they cannot be clearly identified as belonging to DECON. The tasks that result in these additional costs are:

- shipment of the spent reactor fuel to an offsite reprocessing plant
- demolition of the structures and restoration of the site
- alternative disposal of the highly activated materials in a deep geologic disposal facility.

It is assumed in this study that the fuel assemblies are shipped by truck to a federal reprocessing plant located 2,400 km from the reference test reactor. The estimated total cost for shipping the spent fuel to the reprocessing plant is $0.204 million. This does not include either handling costs at the reactor or handling and storage costs at the reprocessing plant.

The cost of demolishing the decontaminated and uncontaminated structures of the reference test reactor is summarized in Table L.3-3 in Appendix L (Volume 2). The total cost of $2.289 million (without contingency) includes labor, supplies, overheads, and profit, but not extraordinary insurance premium, bonding, or state sales tax. Details of cost estimates for this task are given in Section L.3.2 of Appendix L.

The estimated cost of disposal for the neutron-activated materials given in Table 11.2-1 is based on the assumption that all of these materials are placed in a shallow-land disposal site. If the amount of radioactivity in these neutron-activated materials is sufficiently great for them to be classified as intermediate-level wastes, they would have to be placed in a deep-geologic disposal facility. The incremental cost for disposing of these materials in a deep geologic disposal facility is not precisely known at this time since such a facility does not currently exist in the United States; however, it can logically be assumed that a significantly higher cost could be anticipated than for shallow-land burial of these materials. Therefore, an analysis is needed to determine the alternative costs for disposing of the neutron-activated materials from the reference test reactor and from the MUR in a deep geologic disposal facility.

11.2.2 Cost of SAFSTOR

The estimated costs of activities required to place and maintain the reference test reactor facility in safe storage are presented in this section, together with the cost of possible deferred decontamination.

11.2.2.1 Cost of Preparations for Safe Storage

The estimated cost of preparations for safe storage, including a 25% contingency, is $6.7 million, as summarized in Table 11.2-2. Details of the development of these costs are given in Section J.2.5 of Appendix J (Volume 2).

A possible cost associated with preparations for safe storage--spent fuel shipment--is estimated to cost about $0.204 million, not including a 25% contingency.

TABLE 11.2-2. Summary of Estimated Costs of Placing the Reference Test Reactor in Safe Storage

Cost Category	Estimated Costs ($ millions)[a,b]	Percent of Total
Disposal of Radioactive Materials	1.384	25.9
Staff Labor	3.096	57.9
Energy	0.021	0.4
Special Tools and Equipment	0.196	3.7
Miscellaneous Supplies	0.065	1.2
Special Contractors[c]	0.585	10.9
Nuclear Insurance	--[d]	--
License Fees	--[e]	--
Subtotal	5.347	100.0
Contingency (25%)	1.337	
Total, Preparations for Safe Storage	6.684	
Other Possible Costs		
Spent Fuel Shipment	0.204	
Contingency (25%)	0.051	
Total, Other Possible Costs	0.255	

(a) 1981 costs.
(b) The number of figures shown is for computational accuracy and does not imply precision to the nearest $1,000.
(c) Includes selected demolition, security preparations, and environmental monitoring services.
(d) Indemnity fees are currently $100/yr for each license (i.e., the test reactor license and the MUR license) at the reference test facility and are not included in this study since they represent only a small fraction of 1% of the total decommissioning cost.
(e) Because the reference test reactor is assumed to be federally-owned, these fees are not applicable; however, where applicable for other nuclear R&T reactor facilities, the schedule of fees for license amendments and other approvals required by the license or NRC regulations is given in 10 CFR 170.

Disposal of Radioactive Materials. Wet solid wastes, dry solid wastes, and contaminated concrete pipe and soil in the reference test reactor facility

require disposal during preparations for safe storage. Table J.2-12 in Appendix J contains a breakdown of the disposal costs for the dry solid wastes. The wet solid wastes and the contaminated soil and buried concrete pipe are disposed of as in DECON. The total cost of disposal for all of these materials is about $1.4 million and is approximately 26% of the total cost of preparations for safe storage. The disposal cost includes the container, transportation, and burial costs, but does not include the direct labor costs for removing and packaging these materials. Labor costs are discussed in a later paragraph. The cost of offsite disposal for those materials shipped to a low-level waste burial ground is summarized in Table J.2-13 in Appendix J.

Staff Labor. The cost of staff labor during preparations for safe storage is shown in Table J.2-14 in Appendix J. Approximately 58% of the total preparations cost is due to staff labor. A total staff labor cost of about $3.1 million is estimated for preparing the reference test reactor facility for safe storage. Specialty contractor labor is not included in this total.

Energy. The cost of energy used during the preparations for safe storage is presented in Table J.2-15 in appendix J. The use of electricity and natural gas as shown in the table is based on data (1978) supplied in Reference 2. The costs are adjusted for inflation to mid-1981, and applied to the time frame estimated for SAFSTOR tasks (i.e., about 6-3/4 months). The total cost of energy is about $21,350 and represents less than 0.5% of the total cost of preparations for safe storage.

Special Tools and Equipment. The estimated costs of special tools and equipment that are required for preparing the reference test reactor for safe storage are discussed in Section J.2.5.1 in Appendix J. The estimated total cost for special tools and equipment is approximately $0.2 million and is approximately 4% of the total cost for preparations.

Miscellaneous Supplies. A variety of supplies are used during the preparations for safe storage. These include expendable glass-fiber and HEPA filters, anticontamination clothing, cleaning and contamination control supplies (chemical agents, sweeping compounds, rags, mops, and plastic bags and sheeting), expendable handtools, cutting and welding supplies (saw blades, torch gas, and

welding rods), and decontamination chemicals, as well as office supplies. The estimated costs of these items are given in Table J.2-17 in Appendix J. The total estimated cost of miscellaneous supplies during preparations for safe storage of the reference test reactor is $0.065 million and represents less than 1.5% of the total preparations cost.

Nuclear Insurance. Indemnity fees are currently $100/yr for each license (i.e., the test reactor license and the MUR license) at the reference test facility and are not included in this study since they represent only a small fraction of 1% of the total decommissioning cost.

Licensing Fees. The fees charged for licensing services performed by the NRC are delineated in 10 CFR 170.[1] The costs of licensing fees during DECON of the federally owned reference test reactor are not included in this study since the federal government does not charge itself for these inspections.

Another Possible Cost. One possible additional cost is the shipment of spent reactor fuel to a federal reprocessing plant as described previously for DECON (see Section I.2.3.9 of Appendix I). The estimated total cost for this task is about $255,000, including a 25% contingency.

11.2.2.2 Annual Cost During Safe Storage

The estimated annual cost of safe storage for the reference test reactor is developed in Section J.2.5.2 of Appendix J and is summarized in Table 11.2-3. The total annual cost is estimated to be about $120,100 and would continue until the facility is decontaminated.

11.2.2.3 Cost of Deferred Decontamination

The estimated costs of deferred decontamination for the reference test reactor facility at various times after shutdown are given in Table 11.2-4. Details of these cost estimates are given in Section J.2.5.3 of Appendix J. It is assumed that the management and support staff is the same size for deferred decontamination as it is for DECON. However, fewer decommissioning workers are required for deferred decontamination than are required for DECON, since the radiation dose rates are lower when decontamination is deferred.

TABLE 11.2-3. Estimated Annual Costs of Surveillance, Maintenance, and Security During Safe Storage of the Reference Test Reactor[a]

SAFSTOR Item	Estimated Annual Cost ($)[b]
Minor Maintenance Repair:	5 600
Custodial (twice per year)	
Grounds and Yard	
Utilities	
Trapping Varmints	
Major Repair[c]	32 000
Offsite Laboratory Work and Equipment Repairs	5 000
Reference Reactor Facility Services:	42 000
Lab Samples (outfall, air, water, health physics)	
Surveillance/Monitoring	
EPA Samples and Reporting Requirements	
Security	11 500[d]
Subtotal	96 100
Contingency (25%)	24 025
Total, Annual Continuing Care Costs	120 125

(a) These services are assumed to be provided by specialty contractors.
(b) The number of figures shown is for computational accuracy and does not imply precision to the nearest dollar.
(c) Accruing for use; frequency varies depending on the type of repair.
(d) See Table J.2-9 in Appendix J for initial costs.

The estimated costs of SAFSTOR for the reference test reactor, after 10, 30, 50, and 100 years, are given in Table 11.2-5. The total SAFSTOR cost is the sum of the costs of preparations for safe storage, safe storage, and deferred decontamination. In constant dollars, the cost of SAFSTOR for the reference test reactor is considerably more expensive than the $15.6 million cost for DECON.

TABLE 11.2-4. Estimated Costs of Deferred Decontamination for the Reference Test Reactor

Cost Category	Costs ($ millions)			
		Decontamination Deferred		
	DECON[a]	10 to 30 Years	50 Years	100 Years
Disposal of Radioactive Materials				
Neutron-Activated Materials	0.135	0.135	0.135	0.135
Contaminated Materials	2.338	0.974	0.009	0.009
Radioactive Wastes	0.099	0.064	0.052	0.036
Staff Labor	8.63	6.076	6.076	6.076
Energy	0.076	0.055	0.055	0.055
Special Tools and Equipment	0.361	0.260	0.260	0.260
Miscellaneous Supplies	0.203	0.140	0.140	0.140
Specialty Contractors	0.616	0.107	0.107	0.107
Nuclear Insurance[b]	--	--	--	--
License Fees[c]	0	0	0	0
Subtotal	12.458	7.811	6.834	6.818
Contingency (25%)	3.115	1.953	1.709	1.705
Totals	15.573	9.764	8.543	8.523

(a) From Table 11.2-1.
(b) Indemnity fees are currently $100/yr for each license (i.e., the test reactor license and the MUR license) at the reference test facility and are not included in this study since they represent only a small fraction of 1% of the total decom-
(c) missioning cost.
(c) Because the reference test reactor is assumed to be federally owned, these fees are not applicable; however, where applicable for other nuclear R&T reactor facilities, the schedule of fees for license amendments and other approvals required by the license or NRC regulations is given in 10 CFR 170.

TABLE 11.2-5. Estimated SAFSTOR Costs for the Reference Test Reactor

Decontamination Deferred (years)	Decommissioning Costs ($ millions)[a,b]			
	Preparations for Safe Storage	Safe Storage[c]	Deferred Decontamination	Total
10	6.7	1.1	9.8	17.6
30	6.7	3.5	9.8	20.0
50	6.7	6.0	8.5	21.2
100	6.7	12.0	8.5	27.2

(a) Values include a 25% contingency.
(b) Values are in constant 1981 dollars.
(c) The safe storage period extends from the time of completion of the preparations for safe storage, about 0.6 years, until the start of deferred decontamination.

11.2.3 Cost of ENTOMB

The estimated cost of ENTOMB for the reference test reactor, developed in detail in Section K.2.2 of Appendix K (Volume 2), is summarized in Table 11.2-6. The costs are grouped in categories consistent with those used for DECON and SAFSTOR costs. ENTOMB, with activated reactor vessel internals removed, is estimated to cost about $14.6 million.

The cost of continuing care during ENTOMB is estimated to be about $41,000 per year. This cost could vary depending on the need for a security system and on the level of environmental surveillance required.

No detailed cost estimates are developed for deferred decontamination of the entombed test reactor since the intent is to leave the structure intact until the radioactivity has decayed to release levels.

Disposal of Radioactive Materials

To meet the criteria for unrestricted release of the entombment structure after 100 years, it is necessary to remove the neutron-activated materials from the reference test reactor and from the MUR, as is done in DECON. The contaminated equipment and material from outside the CV and the contaminated concrete from surfaces external to the CV are placed within the quadrants, thus eliminating the packaging, shipment, and burial costs for those materials. The wet solid radioactive wastes are also placed within the quadrants. The dry solid radioactive wastes are disposed of as in DECON. These wastes are largely combustible material. While the likelihood of a fire occurring in this material within the sealed entombment structure is rather remote, it seems prudent to exclude combustibles. The total cost of disposal for radioactive materials is about $1.6 million (about 13.5% of the total entombment costs).

Staff Labor

Staff labor costs include both the management and support staff and the decommissioning workers and cover the planning and preparation period as well as the years of active decommissioning. Specialty contractor labor is not included in this category. Staff labor is estimated to cost about $8.63 million, which is approximately 74% of the total cost.

TABLE 11.2-6. Summary of Estimated Costs of ENTOMB for the Reference Test Reactor

Cost Category		Estimated Costs ($ millions)[a,b]	Percent of Total
Disposal of Radioactive Materials			
Neutron-Activated Materials			
Reference Test Reactor	0.131		
Mock-Up Reactor (MUR)	0.004		
Contaminated Materials	1.352		
Radioactive Wastes	0.087		
Total Disposal Costs		1.574	13.5
Staff Labor		8.63	73.7
Energy		0.076	0.6
Special Tools and Equipment		0.361	3.1
Miscellaneous Supplies		0.202	1.7
Specialty Contractors[c]		0.862	7.4
Nuclear Insurance		--[d]	--
License Fees		--[e]	--
Subtotal		11.706	100.0
Contingency (25%)		2.927	
Total, Costs of Entombment[f]		14.633	
Other Possible Costs			
Spent Fuel Shipment		0.204	
Facility Demolition and Site Restoration		1.783	
Subtotal		1.987	
Contingency (25%)		4.497	
Total, Other Possible Costs		2.484	

(a) 1981 dollars.
(b) The number of figures shown is for computational accuracy and does not imply precision to the nearest $1,000.
(c) Includes selected demolition, security preparations, environmental monitoring services, and entombment cap installation.
(d) Indemnity fees are currently $100/yr for each license (i.e., the test reactor license and the MUR license) at the reference test facility and are not included in this study since they represent only a small fraction of 1% of the total decommissioning cost.
(e) Because the reference test reactor is assumed to be federally owned, these fees are not applicable; however, where applicable for other nuclear R&T reactor facilities, the schedule of fees for license amendments and other approvals required by the license or NRC regulations is given in 10 CFR 170.
(f) The "total" ENTOMB costs would also include the annual surveillance and maintenance service costs of about $41,000 (maximum) times "x" number of years that these services are provided.

Energy

The cost of energy during decommissioning of the reference test reactor via the ENTOMB alternative is estimated to be about \$0.076 million. This amounts to less than 1% of the total cost of entombment.

Special Tools and Equipment

The estimated cost of special tools and equipment that are required to entomb the reference test reactor is about \$0.361 million; this represents about 3% of the total ENTOMB costs.

Miscellaneous Supplies

Items such as disposable protective clothing, decontamination chemicals, decontamination agents, rags, mops, plastic bags and sheeting, glass-fiber and HEPA filters, ion exchange resins, and expendable tools are grouped together as miscellaneous supplies. The total cost of miscellaneous supplies is estimated to be about \$0.202 million, which is about 2% of the total ENTOMB cost.

Specialty Contractors

Installation of the entombment cap will require a contractor to install forms, structural support members, and concrete. It is estimated that approximately 445 m^3 of concrete are required to form a cap 0.6 m thick at the elevation level within the CV at a cost of about \$427/m^3, for a total cost of about \$190,000. This cost is in addition to the contractor cost identified previously for DECON, thus raising the total cost of specialty contractors for ENTOMB of the reference test reactor to about \$0.862 million (about 7.4% of the total cost).

Nuclear Insurance and Licensing Fees

Indemnity fees are currently \$100/yr for each license (i.e., the test reactor license and the MUR license) at the reference test facility and are not included in this study since they represent only a small fraction of 1% of the total decommissioning cost.

The fees charged for licensing services performed by the NRC are delineated in 10 CFR 170.(1) The costs of licensing fees for ENTOMB are not included in this study since the reference test reactor is federally owned, and the federal government does not charge itself for these inspections.

Continuing Care

Continuing care, involving surveillance and maintenance of the entombment structure, is estimated to cost about $41,000 annually. Thus, a continuing care period of 100 years adds about $4.1 million to the cost of decommissioning the reference test reactor via the ENTOMB alternative. It should be recognized that there is no fixed number of years for nuclear reactor facilities to be entombed; it depends on the facility-specific radionuclides and how long they take to decay to unrestricted use levels. For the purposes of this study, all ENTOMB time periods given are for illustration only. In addition, deferred decontamination of the entombment structure may be required before the amended nuclear license can be terminated, adding significantly to the overall decommissioning cost.

Other Possible Costs

The other possible costs shown at the bottom of Table 11.2-6 are calculated in the same way as those for DECON, which are discussed in Section 11.2.1. The cost of spent fuel shipment is the same as for DECON. However, it is postulated that all structures external to the CV are removed following decontamination, leaving the CV intact with the below-grade portion entombed and the above-grade portion decontaminated and released for unrestricted use. As a result, the demolition cost for the Reactor Building and CV given in Table L.3-3 of Appendix L is expected to be reduced by approximately two-thirds, for a net cost of about $260,000. Thus, the total cost for demolition of the decontaminated structures external to the CV and for onsite restoration work is estimated to be about $1.78 million, without contingency.

REFERENCES

1. U.S. Code of Federal Regulations, Title 10, Part 170, "Fees for Facilities and Materials Licenses and Other Regulatory Services Under the Atomic Energy Act of 1954, As Amended," Superintendent of Documents, GPO, Washington, D.C. 20555, 1979.

2. "OPTIONS" Teledyne Isotopes Study for Further Decommissioning the PBRF, July 1978.

12.0 DECOMMISSIONING SAFETY

Occupational, public, and transportation safety impacts from decommissioning the reference research and test (R&T) reactors are summarized in this section. Decommissioning safety impacts include: 1) radiation doses and industrial accidents involving decommissioning workers during the performance of decommissioning tasks, 2) radiation doses to the public from routine or accidental atmospheric releases of radioactivity during decommissioning, and 3) radiation doses to transportation workers and the public during shipment of radioactive materials from the site. A conservative approach, using parameters that tend to maximize the consequences, is used to evaluate the safety impacts of each decommissioning task. The evaluation uses current analysis data and methodology.

The evaluation of decommissioning safety is divided into three parts: occupational safety, public safety, and transportation safety. Radiation doses and industrial accidents involving decommissioning workers are estimated using information about the expected radiation dose rates discussed in Appendix D and the manpower requirements presented in Appendices I, J, and K of Volume 2 for the three alternatives of decommissioning the reference R&T reactors. Radiation doses to the public during decommissioning are determined using the routine and accidental atmospheric release scenarios presented in Appendix N and the radiation dose methodology presented in Appendix F of Volume 2. Radiation doses to transportation workers and to the public along the transport route are based on the radioactive material shipment requirements of each decommissioning alternative for each reactor and on the permissible radiation exposure rates for shipments of radioactive material.

A detailed probabilistic analysis of postulated accident scenarios during decommissioning is not within the scope of this study. However, selected accidents are considered that can affect both decommissioning workers and the public during decommissioning and transportation tasks.

The estimated occupational doses for the research reactor are about: 18 man-rem for DECON, 13 man-rem for preparations for safe storage, and about 17 man-rem for ENTOMB. For the test reactor, the estimated occupational

radiation doses are about: 322 man-rem for DECON, 112 man-rem for preparations for safe storage, and 425 man-rem for ENTOMB. Radiation doses for deferred decontamination of the reference R&T reactors are based on those for DECON and corrected for ^{60}Co decay during the safe storage period. The occupational doses are corrected for radioactive decay assuming that ^{60}Co controls the decay of the external radiation dose rate, using the time after shutdown at which each task is half completed (time-wise) and the decay half-life of ^{60}Co. Deferred decontamination of the reference research reactor is estimated to require a time span equivalent to DECON and to result in radiation doses to decommissioning workers of 1.5, 0.11, or <0.01 man-rem after safe storage periods of 10, 30, or 100 years, respectively. Deferred decontamination of the reference test reactor is estimated to require a time span equivalent to DECON and to result in radiation doses to decommissioning workers of 86, 6, or <1 man-rem after safe storage periods of 10, 30, or 100 years, respectively.

Public radiation doses are calculated for both the maximum-exposed individual and the population residing within 80 km of the site using the calculated atmospheric releases. Fifty-year committed radiation dose equivalents are calculated for DECON, preparations for safe storage and ENTOMB. Total SAFSTOR doses to the public are not reported since the active release of radionuclides during safe storage is expected to be negligible compared to the release during preparations for safe storage, and since the public doses from deferred decontamination are expected to be lower than the DECON doses reported because of radioactive decay. For the maximum-exposed individual at the reference research reactor, the 50-year committed radiation dose equivalents to lungs (in rem) from routine releases during the decommissioning alternatives are about: 1.3×10^{-9} for DECON, 3.8×10^{-10} for preparations for safe storage, and 8.9×10^{-10} for ENTOMB. At the reference test reactor, the doses to the lungs of the maximum-exposed individual (in rem) are about: 1.6×10^{-6} for DECON, 9.3×10^{-7} for preparations for safe storage, and 9.6×10^{-7} for ENTOMB. For the research reactor, the total 50-year population committed dose equivalents to the lungs (in man-rem) are about: 5.6×10^{-7} for DECON, 1.8×10^{-7} for preparations for safe storage, and 4.0×10^{-7} for ENTOMB. Similar doses to the lungs for the test reactor are about: 1.6×10^{-3} for DECON, 1.0×10^{-3} for preparations for safe storage, and 1.0×10^{-3} for ENTOMB.

12.1 TECHNICAL APPROACHES

The safety evaluation is divided into two areas of interest: radiological safety and nonradiological safety. Radiological safety is evaluated using a three-part technical approach. First, descriptions of the reference facilities are developed (see Section 8 and Appendices B and C). Second, the radionuclide inventories and external dose rates within each facility are characterized and quantified (also see Section 8). Finally, reference decommissioning tasks are defined for each reactor and alternative to permit calculation of radiation exposures (discussed in Appendices I, J, K, and N). The nonradiological safety evaluation is based on industrial and transportation accidents that result in injuries or fatalities. The technical approach is divided into two parts. First, the total labor requirements for each reactor and decommissioning alternative are analyzed and divided into categories of effort (discussed in Appendices I, J, and K); second, injuries and fatalities are calculated based on statistical information from the literature on accident frequencies for the different categories of effort.

Key assumptions are made during the safety evaluation to coordinate the parts of each of the technical approaches. Some of the major assumptions are:

1. The quantities, mixtures of radionuclides, and external dose rates are based on estimates made at real R&T reactors, as discussed in Section 8 and Appendices D and E. The estimated reference radionuclide mixtures at the time of final shutdown of the reference R&T reactors are mixtures containing: stainless steel activation products (including ^{60}Co), aluminum activation products, reinforced concrete activation products, hot-cell surface contamination, and mixed soil contamination.

2. The reactor equipment areas are kept relatively free of radioactive contamination during the operating lifetime to permit operational maintenance. As a result, expected radioactive contamination levels are generally modest and are reasonably consistent with the quality of operation experienced at modern R&T reactors.

The postulated accident that results in the largest atmospheric release of radioactivity for any decommissioning alternative at both reactors is the oxyacetylene explosion. Oxyacetylene gas is assumed to leak into the HEPA filters through the ventilation system where the explosion occurs. The force of the explosion is assumed to release the material collected on the HEPA filters. The accident is assumed to occur during the removal of the reactor vessels at both reactors. The calculated 50-year dose commitments to the lungs of the maximum-exposed individual from the postulated accidents are: 1.6×10^{-3} rem at the research reactor, and 1.7×10^{-4} rem at the test reactor. The larger 50-year dose commitment calculated for the reference research reactor relative to the reference test reactor (for the same type of postulated accident) is the result of using different reference radionuclide inventories (see Section N.2.2.5 in Apppendix N of Volume 2 for details).

These calculated public radiation doses are quite small because of: 1) the reduced inventories of radionuclides at the R&T reactors after the reactor fuel has been shipped and after localized chemical decontamination, 2) the carefully designed procedures that minimize atmospheric release, and 3) the use of existing process and HVAC systems to ensure proper air flows in isolated work areas.

Transportation of radioactive materials results in external radiation doses to the transportation workers and to the public along the transportation route. Again, since no transportation of radioactive materials is required during safe storage and since the transportation impacts for various decay periods are not estimated, total SAFSTOR doses are not reported. Instead, only the transportation doses associated with the radioactive materials shipped during preparations for safe storage are reported. External radiation doses (in man-rem) to truck transportation workers during radioactive waste shipments for the research reactor are calculated to be: 0.28 for DECON, 0.07 for preparations for safe storage, and 0.07 for ENTOMB. Doses to the population along the transportation route for the research reactor (in man-rem) are: 0.03 for DECON, 0.007 for preparations for safe storage, and 0.007 for ENTOMB. For the test reactor, doses to truck transportation workers in man-rem are: 22 for DECON, 13 for preparations for safe storage, and 19 for ENTOMB. Population doses for test reactor waste transport (in man-rem) are: 2.2 for DECON, 0.11 for preparations for safe storage, and 1.3 for ENTOMB.

12.2 OCCUPATIONAL SAFETY ASPECTS OF DECOMMISSIONING THE REFERENCE R&T REACTORS

Occupational safety for DECON, SAFSTOR, and ENTOMB is evaluated both for radiation exposure and for nonradiological industrial accidents at the reference R&T reactors.

Estimates of occupational radiation doses are based on the postulated radiation dose rates in various areas of the reference R&T reactors and on the estimated staff labor required to complete the decommissioning work. Summaries of the detailed information contained in Appendices I, J, and K are given in this section. This section also presents estimates of worker injuries and fatalities resulting from decommissioning the reference R&T reactors. These industrial accident estimates are based on nuclear industry experience.

12.2.1 Occupational Radiation Dose from Decommissioning Activities

Summaries of the estimated occupational radiation doses for DECON, SAFSTOR, and ENTOMB are given in Tables 12.2-1, 12.2-2, and 12.2-3, respectively, for the reference research reactor, and in Tables 12.2-4, 12.2-5, and 12.2-6 for the reference test reactor. These tables contain listings of the decommissioning tasks for each reactor, the associated estimated total man-hours of exposure to radiation, and the estimated total doses from external radiation.

The radiation doses to decommissioning workers are calculated as the product of the estimated radiation zone manpower requirements and the radiation dose rates postulated for each specific decommissioning task. The occupational dose estimates are based on the following basic assumptions: 1) personnel exposure to radiation while accomplishing a task is minimized by using temporary shielding and remote handling techniques and by staying out of radiation fields when not actively participating in the work, 2) the localized chemical decontamination campaigns are reasonably successful in reducing radiation dose rates, 3) careful, prompt accounting of radiation doses is maintained to rapidly identify jobs that are causing excessve dose accumulations so that corrective action can be taken, and 4) ^{60}Co is the dominant radioactive species contributing to occupational exposure.

3. Accidents that occur during plant operation are relatively minor with respect to radioactive contamination of normally clean surfaces. Any major contamination episodes are cleaned up immediately following the event.

4. Radiation protection techniques applied conform to the principle of keeping occupational radiation dose as low as reasonably achievable (ALARA).

5. All radioactive wastes shipped offsite are shipped in accordance with Department of Transportation regulations. Radioactive wastes are shipped 800 km by truck to a shallow-land burial ground.

6. The largest potential radiological consequence of a given decommissioning task is associated with performing that operation in the area with the largest inventory of radionuclides.

7. The maximum release from a specific decommissioning task applies to that task whenever it is used in the facility. In performing the dose calculations for releases of radionuclides from routine tasks, the estimated total releases for the entire decommissioning period are released at a uniform rate during a 1-year period.

8. All atmospheric releases contain the radionclide mixtures that are present at plant shutdown, with no credit taken for radioactive decay. (Radionuclide releases during deferred decontamination after a period of safe storage are not calculated in this analysis since radioactive decay will reduce the release amounts.)

9. A contamination control envelope has a transmission factor of 5×10^{-4} through the filtered exhaust and a leakage of 10%, which is used as a maximized value to account for routine ruptures or failures of the contamination control envelope.

Other specific assumptions used in calculating the occupational doses are found in Appendices I, J, and K. A complete discussion of the assumptions and methods used for the public and transportation radiation dose calculations is found in Appendix N.

TABLE 12.2-1. Estimated Occupational Radiation Doses from DECON at the Reference Research Reactor

Task Number[a]	Location/Task	Task Totals: Exposure (man-hr)	Dose (man-rem)	Decay Factor[b]	Corrected Dose[c] (man-rem)
	Reactor Building				
1.	Install HEPA Filters	277	0.277	1.00	0.227
2.	Comprehensive Radiation Survey	36	0.036	0.989	0.036
3.	General Cleanup	132	0.132	0.989	0.131
4.	Discharge and Ship Fuel	990	6.930	0.978	6.778
5.	Remove Beam Tube Caves	158	0.316	0.989	0.313
6.	Drain Pool Irradiation Facility	27	0.054	0.978	0.053
7.	Remove Reactor Core and Vessel Internals	114	0.456	0.968	0.551
8.	Drain Reactor Pool	24	0.48	0.957	0.046
9.	Remove Reactor Vessel	45	0.450	0.956	0.431
10.	Ship Reactor Core, Vessel and Internals	370	1.295	0.956	1.239
11.	Remove Contaminated Concrete	351	1.755	0.946	1.660
12.	Remove Reactor Building Equipment	450	2.700	0.946	2.554
13.	Remove Piping Drains and Sinks	231	0.231	0.936	0.216
14.	Remove and Decontaminate HVAC and Elec.	507	0.254	0.926	0.238
15.	Final Radiation Survey	66	0.017	0.916	0.016
	Annex Building				
16.	Decontaminate Hot Cell	219	2.219	0.978	2.170
	Heat Exchanger Building				
17.	Remove Heat Exchanger	19	0.019	0.936	0.018
	Pump House				
18.	Decontaminate Walls and Floor	898	0.898	0.968	0.869
19.	Remove Retention Tank, Piping and Equip.	41	0.082	0.957	0.078
	Radiation Center Building				
20.	Remove Piping and Equipment	36	0.036	0.946	0.034
21.	Package and Ship Contaminated Materials and Radioactive Wastes	386	0.772	0.957	0.739
	Subtotals	5327			9.298
22.	Ancillaries				
	Routine Radiation Surveys	239			0.005
	Totals[d]	5564			18

(a) For buildings and areas, tasks are numbered either in the order in which decommissioning activities take place or to facilitate the cross-referencing and referral of specific tasks throughout the study.
(b) Based on the half-life of ^{60}Co; calculated at the midpoint of the task times shown in Figure I.1-1.
(c) The number of significant figures shown is for computational accuracy and does not imply precision to the nearest millirem.
(d) Dose totals are rounded to the nearest whole number.

TABLE 12.2-2. Estimated Occupational Radiation Doses Accumulated During Preparations for Safe Storage at the Reference Research Reactor

Task Number[a]	Location/Task	Task Totals: Exposure (man-hr)	Dose (man-rem)	Decay Factor[b]	Corrected Dose[c] (man-rem)
	Reactor Building				
1.	Comprehensive Radiation Survey	36	0.036	0.989	0.036
2.	General Cleanup	132	0.132	0.989	0.131
3.	Discharge and Ship Fuel	990	6.930	0.978	6.778
4.	Remove Beam Tube Caves	158	0.316	0.989	0.313
5.	Drain Pool Iradiation Facility	27	0.054	0.989	0.053
6.	Seal Biological Shield Penetrations	96	0.768	0.989	0.760
7.	Cover and Seal Reactor Pool and Pool Irradiation Facility	45	0.225	0.989	0.223
8.	Drain Reactor Pool	24	0.048	0.978	0.047
9.	Decontaminate Steel Structures Equipment Concrete: Apply Protective Paint	71	0.142	0.978	0.139
10.	Remove and Decontaminate HVAC	507	0.254	0.968	0.246
11.	Isolate and Seal Equipment-Doors-Duct. Install HEPA Filtered Vents	226	0.113	0.957	0.108
12.	Deactivate Unnecessary Utilities	143	0.072	0.957	0.069
13.	Install Intrusion, Radiation Monitoring and Fire Alarm Systems	135	0.135	0.957	0.129
14.	Final Radiation Survey	66	0.017	0.946	0.016
	Annex				
15.	Decontaminate Hot Cell	219	2.219	0.989	0.016
	Heat Exchanger Building				
16.	Remove Heat Exchanger and Piping	93	0.093	0.978	0.091
	Pump House				
17.	Decontaminate Walls and Floor	898	0.898	0.967	0.869
18.	Remove Retention Tank-Piping and Equipment	41	0.082	0.957	0.079
	Radiation Center Building				
19.	Remove Piping and Equipment	36	0.036	0.967	0.035
	All Buildings				
20.	Package and Store Contaminated Material and Radioactive Wastes	227	0.554	0.967	0.536
	Subtotals	4219			12.853
21.	Ancillaries				
	Routine Radiation Surveys	238	0.238	0.96	0.230
	Totals[d]	4457			13

(a) For buildings and areas, tasks are numbered either in the order in which decommissioning activities take place or to facilitate the cross-referencing and referral of specific tasks throughout the study.
(b) Based on the half-life of ^{60}Co; calculated at the midpoint of the task times shown in Figure I.1-1.
(c) The number of significant figures shown is for computational accuracy and does not imply precision to the nearest millirem.
(d) Dose totals are rounded to the nearest whole number.

TABLE 12.2-3. Estimated Occupational Radiation Doses from ENTOMB at the Reference Research Reactor

		Task Totals			
Task Number[(a)]	Location/Task	Exposure (man-hr)	Dose (man-rem)	Decay[(b)] Factor	Corrected Dose[(c)] (man-rem)
	Reactor Building				
1.	Install HEPA Filters	227	0.227	1.00	0.227
2.	Comprehensive Radiation Survey	36	0.360	0.989	0.356
3.	General Cleanup	132	0.132	0.989	0.131
4.	Discharge and Ship Fuel	990	6.930	0.973	6.742
5.	Remove Rector Core and Vessel Internals	114	0.456	0.968	0.441
6.	Drain Pool Irradiation Facility (PIF)	27	0.054	0.989	0.053
7.	Extend PIF Walls to Reactor Platform	88	0.176	0.978	0.172
8.	Remove Beam Tube Caves	158	0..316	0.978	0.309
9.	Ship Reactor Core and Internals	370	1.295	0.957	1.230
10.	Remove Piping-Drains and Sink to PIF	231	0.231	0.957	0.221
11.	Drain Reactor Pool (RP)	24	0.048	0.946	0.046
12.	Remove Reactor Building Equipment to RP	450	2.700	0.957	2.556
13.	Seal Biological Shield Penetrations	96	0.192	0.957	0.184
14.	Cover and Seal RP and PIF with ENTOMBMENT Structure Cap	45	0.090	0.946	0.097
15.	Remove and Decontaminate HVAC	507	0.254	0.946	0.240
16.	Final Radiation Survey	66	0.034	0.936	0.032
	Annex				
17.	Decontaminate Hot Cell	219	2.219	0.978	2.170
	Heat Exchanger Building				
18.	Remove Heat Exchanger to RP	19	0.019	0.978	0.019
	Pump House				
19.	Decontaminate Walls and Floor	898	0.898	0.968	0.870
20.	Remove Retention Tank, Piping and Equipment to PIF	41	0.082	0.978	0.080
	Radiation Center Building				
21.	Remove Piping and Equipment to PIF	36	0.036	0.968	0.368
	All Buildings				
22.	Store Contaminated Material and Radioactive Wastes to RP and PIF	76	0.380	0.968	
	Subtotals	4850			
	Ancillaries				
23.	Routine Radiation Surveys	238	0.060	0.973	0.058
	Totals[(d)]	5138			17

(a) For buildings and areas, tasks are numbered either in the order in which decommissioning activities take place or to facilitate the cross-referencing and referral of specific tasks throughout the study.
(b) Based on ^{60}Co half-life, calculated at the midpoint of the task times shown in Figure K.1.1.
(c) The number of significant figures is for computational accuracy and does not imply precision to the nearest million.
(d) Dose totals are rounded to two significant figures.

TABLE 12.2-4. Estimated Occupational Radiation Doses from DECON at the Reference Test Reactor

Task Number[a]	Location/Task	Task Totals: Exposure (man-hr)	Dose (man-rem)	Decay Factor[b]	Corrected Dose[c] (man-rem)
	Reactor Building/ MUR/Primary Containment				
1.	Comprehensive Radiation Survey for Total Facility (i.e., all buildings)	528	2.64	0.995	2.626
2.	Discharge Fuel (including MUR)	66	0.75	0.988	0.741
3.	Prepare and Ship Spent Fuel	2 500	6.0	0.963	5.781
4.	General Cleanup and Equipment Inventory (i.e., all buildings)	924	1.848	0.986	1.823
5.	Drain, Clean, Dry Quadrants A, B, and D and Canals E and F	780	7.8	0.980	7.648
6.	Drain, Clean, Dry Canal H	180	1.8	0.946	1.702
7.	Remove, Package, and Ship MUR and Associated Hardware	576	10.0	0.944	9.436
8.	Drain, Clean, Dry Canal G	180	1.8	0.940	1.693
9.	Remove Loose Equipment in Q&Cs and Dry Annulus	936	9.36	0.937	8.774
10.	Drain and Flush PCWS	72	0.36	0.934	0.336
11.	Isolate RV and Add Deionized Water for Shielding	72	0.072	0.932	0.067
12.	Remove RV Internals and Ship Activited RV Internals	10 366	51.83	0.914	47.349
13.	Remove RV and Ship RV Segments	2 916	14.58	0.889	12.966
14.	Remove Bio-Shield Concrete	120	0.060	0.882	0.053
15.	Remove Fixed Equipment in CV (Except HVAC)	5 890	29.45	0.874	25.750
16.	Remove Fixed Equipment Outside CV	1 728	1.728	0.865	1.495
17.	Remove Quadrant Piping	360	0.72	0.863	0.622
18.	Segment and Remove Subpile Room	252	6.3	0.860	5.416
19.	Remove Lead Shield from Below Reactor Cavity	252	0.54	0.857	0.463
20.	Remove Pipes from Bio-Shield	1 000	1.6	0.852	1.363
21.	Remove PCWS Piping to PPH	2 820	5.64	0.839	4.733
22.	Remove RB/CV Contaminated Concrete	3 240	3.24	0.825	2.675
23.	Remove Q&C, and Miscellaneous Contaminated Drains	2 520	5.04	0.822	4.142

TABLE 12.2-4. (contd)

Task Number[a]	Location/Task	Task Totals: Exposure (man-hr)	Dose (man-rem)	Decay[b] Factor	Corrected Dose[c] (man-rem)
	Reactor Building/ MUR/Primary Containment				
24.	Remove Contaminated HVAC from RB/CV	960	2.4	0.810	1.943
25.	Final Radiation Survey	100	0.050	0.801	0.040
	Subtotal[c,d]	39 338	166		150
	Hot Laboratory Building				
1.	Decontaminate Hot Cells	624	17.119	0.973	16.656
2.	Remove and Package Hot Cell Equipment and Piping	2 146	21.46	0.956	20.506
3.	Remove and Package Hot Cell SS Cladding	480	4.8	0.942	4.519
4.	Remove Contaminated Concrete from Hot Cells	336	0.336	0.938	0.315
5.	Decontaminate the HLB (including cranes)	336	0.336	0.935	0.314
6.	Drain, Clean, Dry Canals J and K	360	3.6	0.933	3.360
7.	Remove Loose Equipment	913	1.826	0.926	1.691
8.	Remove Fixed and Permanent Equipment (except HVAC), Including the Hot Pipe Tunnel	2 146	7.15	0.900	6.436
9.	Remove SS Cladding from Decontamination Room 23	120	0.240	0.896	0.215
10.	Remove Hot Cell Windows	1 072	0.536	0.932	0.500
11.	Remove and Package HLB Contaminated Concrete	795	0.795	0.894	0.711
12.	Remove and Package Contaminated HVAC from HLB	1 200	4.8	0.860	4.126
13.	Final Radiation Survey	88	0.044	0.843	0.037
	Subtotals[c,d]	10 616	63		60
	Other Contaminated Structures and Areas				
1.	Radiation Survey and Inventory Update (i.e., all "other buildings/areas)	264	0.66	0.855	0.565
2.	Primary Pump House (PPH)				
	- Preparatory Tasks (see Table I.2-4)	420	2.1	0.852	1.789
	- Remove Fixed Equipment, Except HVAC (see Table C.3-5)	4 410	30.87	0.834	25.735
	- Decontaminate PPH and Remove Contaminated Concrete (see Table D.2-3)	180	0.18	0.818	0.147

TABLE 12.2-4. (contd)

Task Number[a]	Location/Task	Task Totals: Exposure (man-hr)	Dose (man-rem)	Decay[b] Factor	Corrected Dose[c] (man-rem)
	Other Contaminated Structures and Areas				
	- Remove and Package Contaminated HVAC (see Table C.5-1)	300	0.6	0.816	0.490
	- Final Radiation Survey	40	0.020	0.815	0.016
3.	Office and Laboratory Building (OLB)				
	- Preparatory Tasks (see Table I.2-4)	950	0.475	0.814	0.387
	- Remove Contaminated Hoods and Sinks (see Section C.3.5 of Appendix C)	519	0.260	0.810	0.211
	- Remove Contaminated Concrete (see Table D.2-3)	120	0.060	0.808	0.048
	- Final Radiation Survey	24	0.012	0.807	0.010
4.	Emergency Retention Basin (ERB) and Site Ditches:				
	- Drain the ERB	0	0	0	0
	- Remove and Package Contaminated Piping and Soil from ERB and Site Ditches (see Table C.4-1)	1 338	0.134	0.823	0.110
5.	Cold Retention Area (CRA):				
	- Remove Contaminated Concrete (see Table D.2-3) and Contaminated Soil (see Appendix C, Section C.4)	1 320	6.618	0.801	5.298
	- Final Radiation Survey	36	0.018	0.793	0.014
6.	Hot Retention Area (HRA):				
	- Preparatory Tasks (see Table I.2-4)	1 584	4.752	0.802	3.812
	- Remove and Package Contaminated Piping (see Table C.3-11)	1 008	5.04	0.796	4.013
	- Provide Tank Access to Eight HRA Tanks (see Appendix L, Section L.3.2.6)	0	0	0	0
	- Remove and Package HRA Tanks 1 through 8, Floor Plates, and Partitions (see Table C.3-10)	3 108	15.54	0.785	12.204
	- Uncover and Prepare HRA Tanks 9 through 12 for Shipment (see Table C.3-10 and Appendix L, Section L.3.2.6)	0	0	0	0
	- Remove Contaminated Concrete (see Table D.2-3)	180	0.180	0.7779	0.140
	- Final Radiation Survey	48	0.024	0.778	0.019

TABLE 12.2-4. (contd)

Task Number[a]	Location/Task	Task Totals Exposure (man-hr)	Dose (man-rem)	Decay[b] Factor	Corrected Dose[c] (man-rem)
	Other Contaminated Structures and Areas				
7.	Fan House:				
	- Preparatory Tasks (see Table I.2-4)	792	3.96	0.791	3.132
	- Remove Contaminated Concrete (see Table D.2-3)	240	1.2	0.789	0.946
	- Remove Fixed Equipment (see Table C.5-2)	2 520	6.3	0.781	4.918
	- Raze Stack, Segment and Package[e]	-	-	-	-
	- Final Radiation Survey	36	0.18	0.773	0.139
8.	Waste Handling Building (WHB):				
	- Preparatory Tasks (see Table I.2-4)	792	2.376	0.775	1.841
	- Remove Fixed Equipment, Including Evaporator (see Table C.3-4) and HVAC (see Table C.5-1)	2 376	2.376	0.767	1.823
	- Remove Contaminated Concrete (see Table D.2-3)	180	0.180	0.762	0.137
	- Final Radiation Survey	36	0.018	0.761	0.014
	Subtotals[c,d]	22 821	84		68
	Ancillaries				
1.	Radwaste Handling and Laundry Operations	3 178	14.7	0.876	12.877
2.	Routine Radiation Surveys	618	1.854	0.876	1.624
3.	Miscellaneous[f]	-	-	-	29.0
	Subtotals, Ancillaries[c,d]	3 796	17		44
	TOTALS[c]	76 571	330		322

(a) For buildings and areas, tasks are numbered either in the order in which decommissioning activities take place or to facilitate the cross-referencing and referral of specific tasks throughout the study.
(b) Based on the half-life of ^{60}Co; calculated at the midpoint of the task times shown in Figures I.2-1, I.2-2, and I.2-3.
(c) The number of figures shown is for computational accuracy and does not imply precision to the nearest millirem.
(d) Dose totals are rounded to the nearest whole number.
(e) The occupational dose for segmenting and packaging the stack is included in "removal of fixed equipment" for the Fan House.
(f) Consists of an allowance of 10% of the total explicitly estimated task radiation dose to account for any omissions and uncertainties in the analysis.

TABLE 12.2-5. Estimated Occupational Radiation Doses Accumulated During Preparations for Safe Storage at the Reference Test Reactor

Task Number[a]	Location/Task	Task Totals: Exposure (man-hr)	Dose (man-rem)	Decay[b] Factor	Corrected Dose[c] (man-rem)
	Reactor Building/ MUR/Primary Containment				
1.	Comprehensive Radiation Survey for Total Facility (i.e., all buildings)	528	2.64	0.995	2.627
2.	Discharge fuel (including MUR)	66	0.750	0.988	0.741
3.	Prepare and Ship Spent Fuel	2 500	6.0	0.963	5.781
4.	General Cleanup and Equipment Inventory (i.e., all buildings)	924	1.848	0.989	1.828
5.	Drain, Clean, Dry Quadrants A, B, C and D and Canals E and F	780	7.8	0.98	7.647
6.	Drain, Clean, Dry Canal H (SAFSTOR MUR)	300	3.0	0.945	2.835
7.	Drain, Clean, Dry Canal G	180	1.8	0.943	1.697
8.	Drain and Flush PCWS	72	0.36	0.942	0.339
9.	SAFSTOR Tasks within the CV and for the RB as Given in Tables J.2-3 and J.2-4 Respectively (except for Q&C work)	2 016	10.08	0.965	9.726
10.	Final Radiation Survey	40	0.2	0.940	0.188
	Subtotals[b,c]	7 406	35		34
	Hot Laboratory Building				
1.	Decontaminate Hot Cells	624	17.119	0.989	16.932
2.	Drain, Clean, Dry Canals J and K	360	3.6	0.977	3.516
3.	SAFSTOR Tasks for the HLB as Given in Table J.2-5 (except for hot cells and Canals J and K)	960	9.6	0.970	9.309
4.	Final Radiation Survey	40	0.2	0.963	0.193
	Subtotals[b,c]	1 984	31		30
	Other Contaminated Structures and Areas				
1.	Primary Pump House Preparatory Tasks (see Table J.2-6)	792	7.92	0.939	7.437
2.	Final Radiation Survey	16	0.16	0.936	0.150
3.	Cold Retention Area Remove Contaminated Concrete (see Table D.2-3) and Contaminated Soil (see Appendix C, Section C.4)	1 320	6.6	0.972	6.414
	- Final Radiation Survey	36	0.018	0.959	0.017
4.	Hot Retention Area Preparatory Tasks (see Table J.2-6)	1 584	4.752	0.941	4.473
	- Final Radiation Survey	24	0.072	0.936	0.067

TABLE 12.2-5. (contd)

Task Number(a)	Location/Task	Task Totals: Exposure (man-hr)	Dose (man-rem)	Decay(b) Factor	Corrected Dose(c) (man-rem)
	Other Contaminated Structures and Areas				
5.	Remove and Package Contaminated Piping and Soil from ERB and Site Ditches (see Table C.4-1)	1 338	0.134	0.961	0.129
6.	Office and Laboratory Building Preparatory Tasks (see Table J.2-6)	1 692	0.846	0.955	0.808
	- Final Radiation Survey	16	0.008	0.946	0.008
7.	Fan House Preparatory Tasks (see Table J.2-6)	792	3.96	0.934	3.697
	- Final Radiation Survey	36	0.180	0.931	0.168
8.	Waste Handling Building	792	2.376	0.934	2.218
	- Final Radiation Survey	36	0.072	0.930	0.067
	Subtotals(b,c)	8 474	27		26
	Ancillaries				
1.	Radwaste Handling and Laundry Operations	1 110	7.38	0.963	7.109
2.	SAFSTOR Contaminated Air Systems (see Section J.2.2.3)	660	3.3	0.945	3.118
3.	Install Intrusion Alarms	850	1.275	0.937	1.195
4.	Routine Radiation surveys	178	0.534	0.963	0.514
5.	Miscellaneous(d)	-	-	-	10.2
	Subtotals, Ancillaries(b,c)	2 798	13		22
	Totals(b)	20 662	106		112

(a) Based on the half-life of ^{60}Co; calculated at the midpoint of the task times shown in Figure J.2-1.
(b) The number of figures shown is for computational accuracy and does not imply precision to the nearest millirem.
(c) Dose totals are rounded to the nearest whole number.
(d) Consists of an allowance of 10% of the total explicitly estimated task radiation dose to account for any omissions and uncertainties in the analysis.

TABLE 12.2-6. Estimated Occupational Radiation Doses from ENTOMB at the Reference Test Reactor

Task Number[a]	Location/Task	Exposure (man-hr)	Dose (man-rem)	Decay[b] Factor	Corrected Dose[c] (man-rem)
	Reactor Building/ MUR/Primary Containment				
1.	Comprehensive Radiation Survey for Total Facility (i.e., all buildings)	528	2.64	0.995	2.626
2.	Discharge Fuel (including MUR)	66	0.75	0.988	0.741
3.	Prepare and Ship Spent Fuel	2 500	6.0	0.963	5.781
4.	General Cleanup and Equipment Inventory (i.e., all buildings)	924	1.848	0.986	1.823
5.	Drain, Clean, Dry Quadrants A, B, C and D and Canals E and F	780	7.8	0.980	7.648
6.	Place Radioactive Material in CV	9 000	90.0	0.886	79.778
7.	Drain, Clean, Dry Canal H	180	1.8	0.946	1.702
8.	Remove, Package, and Ship MUR and Associated Hardware	576	10.0	0.944	9.436
9.	Drain, Clean Dry Canal G	180	1.8	0.940	1.693
10.	Remove Loose Equipment in Q&Cs and Dry Annulus	936	9.36	0.937	8.774
11.	Drain and Flush PCWS	72	0.36	0.934	0.336
12.	Isolate RV and Add Deionized Water for Shielding	72	0.072	0.932	0.067
13.	Remove RV Internals and Ship Activated RV Internals	10 366	51.83	0.914	47.349
14.	Cut and Cap CV Penatrations	3 840	38.40	0.886	34.092
15.	Remove Fixed Equipment Outside CV	1 728	1.728	0.865	1.495
16.	Remove PCWS Piping to PPH	2 820	5.64	0.839	4.733
17.	Remove RB Contaminated Concrete	1 300	1.30	0.825	1.069
18.	Remove Miscellaneous Contaminated Drains	2 520	5.04	0.896	4.516
19.	Remove Contaminated HVAC from RB/CV	960	2.4	0.810	1.943
20.	Install Entombment Cap	7 000	35.0	--	35.0
21.	Final Radiation Survey	50	0.025	0.801	0.020
	Subtotals	46 398	238.8		250
	Hot Laboratory Building Total	10 616			60
	Other Contaminated Structures and Area	22 821			71
	Ancillaries	3 796			44
	ENTOMB TOTAL	83 631			425

(a) For buildings and areas, tasks are numbered either in the order in which decommissioning activities take place or to facilitate the cross-referencing and referral of specific tasks throughout the study.
(b) Based on the half-life of ^{60}Co; calculated at the midpoint of the task times shown in Figure K.2-1 in Appendix K.
(c) The number of figures shown is for computational accuracy and does not imply precision to the nearest millirem.

The radioactive materials that are the source of the radiation dose rate decay throughout the decommissioning period. Therefore, the estimated total occupational radiation dose for each task is corrected for radioactive decay between the time of final reactor shutdown and the time at which the task is one-half completed, using the half-life of ^{60}Co.

For DECON, the estimated total occupational radiation dose for the reference research reactor is about 18 man-rem, and for the reference test reactor it is about 322 man-rem. The DECON tasks at the reference research reactor that result in the largest occupational doses are: 1) discharge and ship fuel (6.8 man-rem); 2) remove Reactor Building equipment (2.6 man-rem); and 3) decontaminate the hot cell (2.2 man-rem). At the reference test reactor, the DECON tasks that result in the largest occupational doses are: 1) remove RV internals and ship activated RV internals (about 47 man-rem); 2) removed fixed equipment in the CV (about 26 man-rem); remove fixed equipment in the primary pump house (about 27 man-rem); and 4) remove and package hot-cell equipment and piping (about 21 man-rem).

The estimated total occupational radiation doses from preparations for safe storage are: about 13 man-rem for the reference research reactor, and 112 man-rem for the reference test reactor. Deferred decontamination of the reference research reactor is estimated to require a time span equivalent to DECON and to result in radiation doses to decommissioning workers of 1.5, 0.11, or <0.01 man-rem after safe storage periods of 10, 30, or 100 years, respectively. Deferred decontamination of the reference test reactor is estimated to require a time span equivalent to DECON and to result in radiation doses to decommissioning workers of 86, 6, or <1 man-rem after safe storage periods of 10, 30, or 100 years, respectively. For ENTOMB, the total occupational radiation doses are about 117 man-rem for the reference research reactor and about 425 man-rem for the reference test reactor.

The estimated average quarterly radiation doses to decommissioning workers for DECON, preparations for safe storage, and ENTOMB are shown in Table 12.2-7 for the reference research reactor and in Table 12.2-8 for the reference test reactor. These quarterly average doses are based on the accumulated occupational doses, after correction for radioactive decay.

TABLE 12.2-7. Estimated Quarterly Occupational Radiation Doses from the Various Decommissioning Alternatives for the Reference Research Reactor

Decommissioning Alternative	Estimated Total Dose (man-rem)	Hands-on Workers[a]: Total Work Time (man-years)	Hands-on Workers[a]: Average Dose (rem/quarter)	All Decommissioning Workers: Total Work Time (man-years)	All Decommissioning Workers: Average Dose (rem/quarter)
DECON	18.34[b]	2.63[c]	1.7	3.80[c]	1.2
SAFSTOR					
Preparations for Safe Storage	13.08[d]	2.03[e]	1.6	2.78[e]	1.2
Deferred Decontamination, After Shutdown, at Years Shown:					
10	1.5	Deferred decontamination is estimated to require a time span equivalent to DECON while utilizing about the same total number of decommissioning workers; therefore, the estimated quarterly occupational radiation doses for deferred decontamination are expected to be less than those quarterly occupational radiation doses given above for DECON.			
30	0.11				
100	<0.01				
ENTOMB					
Entombment	16.64[f]	2.43[f]	1.7	3.2	1.3
Deferred Decontamination		For the purposes of this study, the intention is to leave the structure intact until the radioactivity has decayed to release levels (nominally, 100 years); therefore, occupational radiation dose estimates are not analyzed for this activity.[g]			

(a) Includes utility operators, laborers, and craftsmen.
(b) Based on Table I.1-13 in Appendix I.
(c) Based on Table I.1-4.
(d) Based on Table J.1-17 in Appendix J.
(e) Based on Table J.1-4.
(f) Based on Table K.1-3 in Appendix K.
(g) It should be recognized that there is no fixed number of years for nuclear research reactor facilities to be entombed; it depends on the facility-specific radionuclides and how long they take to decay to unrestricted use levels. For the purposes of this study, all ENTOMB time periods given are for illustration only.

TABLE 12.2-8. Estimated Quarterly Occupational Radiation Doses from the Various Decommissioning Alternatives for the Reference Test Reactor

Decommissioning Alternative	Estimated Total Dose (man-rem)	Hands-on Workers[a] Total Work Time (man-years)	Hands-on Workers[a] Average Dose (rem/quarter)	All Decommissioning Workers Total Work Time (man-years)	All Decommissioning Workers Average Dose (rem/quarter)
DECON	322[b]	66[c]	1.2	106.3[c]	0.76
SAFSTOR					
Preparations for Safe Storage	112[d]	16.5[e]	1.7	32.1[e]	0.87
Deferred Decontamination, After Shutdown, at Years Shown:					
10	86	Deferred decontamination is estimated to require a time span equivalent to DECON while utilizing about the same total number of decommissioning workers; therefore, the estimated quarterly occupational radiation doses for deferred decontamination are expected to be less than those quarterly occupational radiation doses given above for DECON.			
30	6				
100	<1				
ENTOMB					
Entombment	425(f)	66[g]	1.6	106.3[g]	1
Deferred Decontamination		For the purposes of this study, the intention is to leave the structure intact until the radioactivity has decayed to release levels (nominally, 100 years); therefore, occupational radiation dose estimates are not analyzed for this activity.[g]			

(a) Includes utility operators, laborers, and craftsmen.
(b) Based on Table I.2-20 in Appendix I.
(c) Based on Table I.2-6.
(d) Based on Table J.2-23 in Appendix J.
(e) Based on Table J.2-4.
(f) Based on Table K.2-4 in Appendix K.
(g) Assumed to be the same as for DECON (See Section K.2.1 in Appendix K for details).
(h) It should be recognized that there is no fixed number of years for nuclear research reactor facilities to be entombed; it depends on the facility-specific radionuclides and how long they take to decay to unrestricted use levels. For the purposes of this study, all ENTOMB time periods given are for illustration only.

The surveillance and maintenance staff is exposed to the residual radiation levels present in the reference R&T reactors during the safe storage period. During this period, the radiation levels continually decline by radioactive decay. The dominant isotope during the safe storage period is assumed to be ^{60}Co. Table 12.2-9 is a summary of the estimated man-hours of labor and man-rem of occupational radiation dose accumulated for safe storage periods of 10, 30, 50, and 100 years at the reference R&T reactors.

TABLE 12.2-9. Summary of the Estimated Occupational Radiation Doses for Safe Storage of the Reference Research and Test Reactors

Time After Final Shutdown (years)	Reference Research Reactor Accumulated Radiation Dose (man-rem)[a]	Reference Test Reactor Accumulated Radiation Dose (man-rem)
10	0.53	0[b]
30	0.78	0
50	0.80	0
100	0.82	0

(a) The facility radiation levels are assumed to decay at a rate governed by the half-life of ^{60}Co.
(b) Based on the negligible radiation exposures reported for the surveillance, maintenance, and security forces during the past eight years of continuing care of the PBRF (see Section J.2.6.2 of Appendix J for details).

The estimated external occupational radiation doses for decommissioning the reference R&T reactors are summarized in Tables 12.2-10 and 12.2-11. For each reactor, the total occupational dose for DECON; a breakdown of SAFSTOR into preparations for safe storage, safe storage, and deferred decontamination; and ENTOMB are presented. Occupational radiation doses for deferred decontamination are calculated by reducing the DECON doses in proportion to the decay of ^{60}Co over the time period of interest. Thus, if a given task performed

TABLE 12.2-10. Estimated Occupational Radiation Doses from Various Decommissioning Alternatives for the Reference Research Reactor

Years After Reactor Shutdown	Occupational Radiation Dose (man-rem)					
	DECON	SAFSTOR: Preparations for Safe Storage	SAFSTOR: Safe Storage	SAFSTOR: Deferred Decontamination	ENTOMB	Totals
0	18.34	--	--	--	--	18.34
0	--	--	--	--	16.64	16.64
10	--	13.08	0.53	1.48		15.09
30	--	13.08	0.78	0.11		13.97
50	--	13.08	0.80	0.01		13.89
100	--	13.08	0.82	<0.01		13.91

TABLE 12.2-11. Estimated Occupational Radiation Dose from Various Decommissioning Alternatives for the Reference Test Reactor

Years After Reactor Shutdown	Occupational Radiation Dose (man-rem)					
	DECON	SAFSTOR: Preparations for Safe Storage	SAFSTOR: Safe Storage	SAFSTOR: Deferred Decontamination	ENTOMB	Totals
0	322	--	--	--	--	322
0	--	--	--	--	425	425
10	--	112	0[(a)]	86		198
30	--	112	0	6		118
50	--	112	0	<1		113
100	--	112	0	<1		113

(a) Based on the negligible radiation exposures reported for the surveillance, maintenance, and security forces during the past eight years of continuing care of the PBRF (see Section J.2.6.2 of Appendix J for details).

immediately after shutdown caused a radiation dose proportional to the amount of radioactive material present, N_0, that same task performed t years later during deferred decontamination would cause a dose proportional to the amount of radioactive material present at that time, $N(t) = N_0 e^{-\lambda t}$, where λ is the decay constant for ^{60}Co in years. This is a conservative assumption since the radiation levels at reactor shutdown are controlled by radionuclides with half-lives shorter than that of ^{60}Co.

The estimates of the occupational radiation doses are sensitive to management philosophy and to the decommissioning methods used. Administrative controls are assumed to be in place that keep radiation records for each individual and ensure that no one worker exceeds recommended limits. Estimates contained in Tables 12.2-10 and 12.2-11 are based on decommissioning methods that use shielding devices and highly trained technicians. Different basic assumptions, decommissioning procedures, or increased manpower may change these occupational radiation dose estimates significantly.

12.2.2 Industrial Safety

Injuries and fatalities can result among decommissioning workers because of industrial accidents, but proper management and safety practices can minimize the occurrence of such accidents. Estimates of injuries and fatalities during decommissioning are based on data collected by the U.S. AEC for the period 1943-1970.(1) Tables 12.2-12 and 12.2-13 list the estimated worker injuries and fatalities for the three decommissioning alternatives considered in this study for the reference research and test reactors, respectively. Total SAFSTOR injuries and fatalities are found by summing DECON and preparations for safe storage estimates. The work categories shown in the table divide the total effort into three categories of accident potential.(2)

For the research reactor, lost-time injuries and fatalities are calculated for DECON, SAFSTOR, and ENTOMB, respectively. For the test reactor, about 0.11, 0.19, and 0.0027 lost-time injuries and about 7.5 x 10^{-4}, 1.2 x 10^{-3}, and 1.8 x 10^{-4} fatalities are calculated for DECON, SAFSTOR (with a 30-year decay period), and ENTOMB, respectively. For the test reactor, about 2.5, 3.1, and 2.5 lost-time injuries and about 0.014, 0.018, and 0.014 fatalities are calculated for DECON, SAFSTOR (with a 30-year decay period) and ENTOMB, respectively.

Estimates of the number of injuries and fatalities that could occur among the maintenance and surveillance staff during various periods of safe storage at the reference R&T reactors are listed in Table 12.2-14. As shown in the table, far less than one injury and one death are calculated to occur during 100 years of safe storage.

TABLE 12.2-12. Estimated Occupational Lost Time Injuries and Fatalities from Decommissioning the Reference Research Reactor

Category of Effort	Frequency (Accidents/10^6 man-hrs) Lost-Time Injuries	Frequency Fatalities	DECON man-hrs(c)	DECON Lost-Time Injuries	DECON Fatalities	SAFSTOR (With 30-Years of Decay) man-hrs(d)	SAFSTOR Lost-Time Injuries	SAFSTOR Fatalities	ENTOMB man-hrs(e)	ENTOMB Lost-Time Injuries	ENTOMB Fatalities
Heavy Construction(f)	10	4.2×10^{-2}	5.2×10^{3}	5.2×10^{-2}	2.2×10^{-4}	9.2×10^{3}	9.2×10^{-2}	3.9×10^{-4}	1.2×10^{3}	1.2×10^{-2}	5.0×10^{-5}
Light Construction	5.4	3.0×10^{-2}	4.8×10^{3}	2.6×10^{-2}	1.4×10^{-4}	8.0×10^{3}	4.3×10^{-2}	2.4×10^{-4}	1.1×10^{3}	5.9×10^{-3}	3.3×10^{-5}
Operational Support	2.1	2.3×10^{-2}	1.7×10^{4}	3.6×10^{-2}	3.9×10^{-4}	2.7×10^{4}	5.7×10^{-2}	6.2×10^{-4}	4.2×10^{3}	8.8×10^{-3}	9.7×10^{-5}
			2.7×10^{4}	1.1×10^{-1}	7.5×10^{-4}	4.4×10^{4}	1.9×10^{-1}	1.2×10^{-3}	6.0×10^{3}	2.7×10^{-2}	1.8×10^{-4}

(a) Estimates of man-hours, injuries and fatalities are rounded to two significant figures.
(b) Lost-time injuries and fatility frequencies are from Reference 1.
(c) Estimates of man-hours of effort are based on information shown in Table I.1-4 of Appendix I.
(d) Estimates of man-hours of effort are based on information shown in Table J.1-3 of Appendix J, and information in Table I.1-4 of Appendix I.
(e) Estimates of man-hours of effort are based on information shown in Table K.1-1 of Appendix K.
(f) Heavy construction involves demolition tasks such as removal of piping, equipment, and concrete.

TABLE 12.2-13. Estimated Occupational Lost-Time Injuries and Facilities from the Reference Test Reactor(a)

Category of Effort	Frequency (Accidents/10^6 man-hrs)(b) Lost-Time Injuries	Frequency Fatalities	DECON man-hrs(c)	DECON Lost-Time Injuries	DECON Fatalities	SAFSTOR (With 30-Years of Decay) man-hrs(d)	SAFSTOR Lost-Time Injuries	SAFSTOR Fatalities	ENTOMB man-hrs(e)	ENTOMB Lost-Time Injuries	ENTOMB Fatalities
Heavy Construction(f)	10	4.2×10^{-2}	6.2×10^{4}	6.2×10^{-1}	2.6×10^{-3}	6.2×10^{4}	6.2×10^{-1}	2.6×10^{-3}	6.2×10^{4}	6.2×10^{-1}	2.6×10^{-3}
Light Construction	5.4	3.0×10^{-2}	3.2×10^{5}	1.7	9.6×10^{-3}	4.1×10^{5}	2.2	1.2×10^{-2}	3.2×10^{5}	1.7	9.6×10^{-3}
Operational Support	2.1	2.3×10^{-2}	8.0×10^{4}	1.7×10^{-1}	1.8×10^{-3}	1.4×10^{5}	2.9×10^{-1}	3.1×10^{-3}	8.0×10^{4}	1.7×10^{-1}	1.8×10^{-3}
Totals			4.6×10^{5}	2.5	1.4×10^{-2}	6.1×10^{5}	3.1	1.8×10^{-2}	4.6×10^{5}	2.5	1.4×10^{-2}

(a) Estimates of man-hours, injuries and fatalities are rounded to two significant figures.
(b) Lost-time injuries and fatility frequencies are from Reference 1.
(c) Estimates of man-hours of effort are based on information shown in Table I.2-7 in Appendix I.
(d) Estimates of man-hours of effort are based on information shown in Table J.2-4 of Appendix J, and in Table I.2-7 of Appendix I.
(e) Estimates of man-hours of effort are based on assumption that they equal those estimated for DECON.
(f) Heavy construction involves demolition tasks such as removal of piping, equipment, and concrete.

TABLE 12.2-14. Estimated Lost-Time Injuries and Fatalities from Safe Storage Tasks at the Reference R&T Reactors[a]

Reactor/Task	Estimated Man-hr/year[b]	Frequency (Accidents/10^6 man-hr)[c] Lost-Time Injuries	Fatalities	Time After Shutdown (years) 10 Injuries	10 Fatalities	30 Injuries	30 Fatalities	50 Injuries	50 Fatalities	100 Injuries	100 Fatalities
Research Reactor											
Surveillance	320	2.1	2.3×10^{-2}	1.1×10^{-4}	7.4×10^{-4}	3.3×10^{-4}	2.2×10^{-4}	5.5×10^{-4}	3.7×10^{-4}	1.1×10^{-3}	7.4×10^{-4}
Maintenance	760	5.4	3.0×10^{-2}	1.2×10^{-3}	2.3×10^{-4}	3.6×10^{-3}	6.9×10^{-4}	6.0×10^{-3}	1.2×10^{-3}	1.2×10^{-2}	2.3×10^{-3}
Accumulated Totals	1080			1.3×10^{-3}	3.0×10^{-4}	3.9×10^{-3}	9.1×10^{-4}	6.6×10^{-3}	1.5×10^{-3}	1.3×10^{-2}	3.0×10^{-3}
Test Reactor											
Surveillance	500	2.1	2.3×10^{-2}	1.0×10^{-3}	1.2×10^{-5}	3.2×10^{-3}	3.4×10^{-5}	5.2×10^{-3}	5.8×10^{-5}	1.0×10^{-2}	1.2×10^{-4}
Maintenance	1400	5.4	3.0×10^{-2}	7.6×10^{-3}	4.2×10^{-5}	2.3×10^{-2}	1.3×10^{-4}	3.8×10^{-2}	2.1×10^{-4}	7.6×10^{-2}	4.2×10^{-4}
Accumulated Totals	1900			8.6×10^{-3}	5.4×10^{-5}	2.6×10^{-2}	1.6×10^{-4}	4.3×10^{-2}	2.7×10^{-4}	8.6×10^{-2}	5.4×10^{-4}

(a) Estimated man-hours, injuries, and fatalities are rounded to two significant figures.
(b) Labor estimates during safe storage for the reference R&T reactors are derived from data presented in Table J.1-4 and Section J.2-3, respectively, in Appendix J.
(c) Lost-time injuries and fatality frequencies are from Reference 1.

12.3 PUBLIC SAFETY ASPECTS OF DECOMMISSIONING THE REFERENCE R&T REACTORS

The consequences of atmospheric releases of radioactivity during routine R&T reactor decommissioning tasks are determined by calculating radiation doses to the maximum-exposed individual and to the population residing within 80 km of the respective R&T reactor sites. Radiation exposure pathways considered for routine atmospheric releases are direct external exposure, inhalation, and ingestion of food products. The consequences of postulated accidents are determined by calculating inhalation radiation doses to the maximum-exposed individual. The radiation dose calculations for both the routine and accidental releases use the environmental information discussed in Appendix A and the radiation dose models and parameters discussed in Appendix F.

Details of the atmospheric release calculations and listings of decommissioning alternative-, building-, and task-specific radiation doses for each reference reactor are found in Appendix N. These calculations use current data and methodology to quantify the atmospheric releases and obtain results that are useful in comparing the decomissioning tasks and alternatives discussed in this study. Radiation doses are presented for DECON, preparations for safe storage, and ENTOMB. Total SAFSTOR doses to the public are not reported since the active release of radionuclides during safe storage is expected to be negligible compared to the release during preparations for safe storage, and since the public doses from deferred decontamination are expected to be lower than the doses estimated from DECON because of radioactive decay. The following sections contain summaries of the calculated radiation doses to the public for decommissioning the reference R&T reactors.

12.3.1 Public Radiation Doses from Routine Decommissioning Tasks

Loss of confinement of radioactive materials resulting in public radiation exposure is a primary safety concern during decommissioning. Atmospheric releases of radioactivity during decommissioning are calculated in Appendix N of Volume 2.

The primary sources of radioactive effluents from routine decommissioning tasks are: radioactive liquid aerosols during localized chemical decontaminations, vaporized radioactive metal during equipment or piping removal, and radioactive concrete dust during concrete removal. Equipment, piping, and concrete removal tasks are kept to a minimum during preparations for safe storage.

A complete discussion of methods used to calculate atmospheric releases during decommissioning is contained in Appendix N. The atmospheric releases are calculated for tasks during DECON, preparations for safe storage, and ENTOMB at the reference R&T reactors. Decommissioning tasks are considered for each major building or area at the R&T reactors. The atmospheric releases for each task are associated with specific reference radionuclide inventories (developed in Appendix E and summarized in Section 7). These mixtures describe the fractional contributions of various radionuclides in activated stainless steel, activated aluminum, activated concrete, surface contamination in the hot labs, and contaminated soil.

Tables 12.3-1 and 12.3-2 contain summaries of the calculated radiation doses to the maximum-exposed individual and to the population residing within 80 km of the reference research reactor. Tables 12.3-3 and 12.3-4 contain summaries of the calculated radiation doses to the maximum-exposed individual and population around the reference test reactor. These radiation doses are based on the calculated atmospheric releases of radioactivity for each decommissioning alternative, task, and building at each reactor. Both the first-year doses and the 50-year committed radiation dose equivalents to total-body and lungs are listed. The calculated doses for DECON and ENTOMB are quite similar, while the doses for preparations for safe storage are about four times lower. These radiation doses are all quite small by comparison to the range of annual radiation dose to an individual from natural background in the United States (from 80 to 170 mrem per year).[3] These calculated radiation doses are also smaller than the allowable radiation doses to the public from operating LWR facilities set forth in Appendix I of 10 CFR 50.[4]

TABLE 12.3-1. Summary of Calculated Radiation Doses to the Maximum-Exposed Individual from Atmospheric Releases During Routine Decommissioning Tasks at the Reference Research Reactor

Alternative/Building	First-Year Dose (rem)		Fifty-Year Committed Dose Equivalent (rem)	
	Total-Body	Lungs	Total-Body	Lungs
DECON				
Reactor Building	1.2×10^{-10}	4.1×10^{-10}	1.9×10^{-10}	1.0×10^{-9}
Annex Building	1.2×10^{-11}	5.1×10^{-11}	1.0×10^{-10}	2.0×10^{-10}
Heat Exchanger Building	2.2×10^{-13}	8.3×10^{-13}	2.2×10^{-13}	2.5×10^{-12}
Pump House	2.6×10^{-12}	9.6×10^{-12}	2.6×10^{-12}	3.0×10^{-11}
Radiation Center Building	5.1×10^{-13}	1.9×10^{-12}	5.1×10^{-13}	5.8×10^{-12}
Totals	1.6×10^{-10}	4.8×10^{-10}	3.0×10^{-10}	1.3×10^{-9}
SAFSTOR[a]				
Preparations for Safe Storage				
Reactor Building	1.3×10^{-11}	4.9×10^{-11}	1.3×10^{-11}	1.5×10^{-10}
Annex Building	1.2×10^{-11}	5.1×10^{-11}	1.0×10^{-10}	2.0×10^{-10}
Heat Exchanger Building	2.2×10^{-13}	3.8×10^{-13}	2.2×10^{-13}	2.5×10^{-12}
Pump House	2.6×10^{-12}	9.6×10^{-12}	2.0×10^{-12}	2.9×10^{-11}
Radiation Center Building	5.1×10^{-13}	1.9×10^{-12}	5.1×10^{-13}	5.8×10^{-12}
Totals	2.8×10^{-11}	1.1×10^{-10}	1.2×10^{-10}	3.8×10^{-10}
ENTOMB				
Reactor Building	5.8×10^{-11}	2.2×10^{-10}	5.8×10^{-11}	6.5×10^{-10}
Annex Building	1.2×10^{-11}	5.1×10^{-11}	1.0×10^{-10}	2.0×10^{-10}
Heat Exchanger Building	2.2×10^{-13}	8.3×10^{-13}	2.2×10^{-13}	2.5×10^{-12}
Pump House	2.6×10^{-12}	9.6×10^{-12}	2.6×10^{-12}	2.9×10^{-11}
Radiation Center Building	5.1×10^{-13}	1.9×10^{-12}	5.1×10^{-13}	5.8×10^{-12}
Totals	7.4×10^{-11}	2.8×10^{-10}	1.2×10^{-10}	3.8×10^{-10}

(a) Total SAFSTOR doses are not reported since the active release of radionuclides during safe storage is expected to be negligible compared to the release during preparations for safe storage, and since the public doses from deferred decontamination are expected to be lower than the doses from DECON because of radioactive decay.

TABLE 12.3-2. Summary of Calculated Radiation Doses to the Population from Atmospheric Releases During Routine Decommissioning Tasks at the Reference Research Reactor[a]

Alternative/Building	First-Year Dose (man-rem)		Fifty-Year Committed Dose Equivalent (man-rem)	
	Total-Body	Lungs	Total-Body	Lungs
DECON				
Reactor Building	3.5×10^{-8}	1.6×10^{-7}	5.0×10^{-8}	4.5×10^{-7}
Annex Building	3.5×10^{-9}	2.3×10^{-8}	3.0×10^{-8}	9.2×10^{-8}
Heat Exchanger Building	5.0×10^{-11}	3.2×10^{-10}	5.2×10^{-11}	1.1×10^{-9}
Pump House	5.8×10^{-10}	3.7×10^{-9}	5.9×10^{-10}	1.3×10^{-8}
Radiation Center Building	1.2×10^{-10}	7.5×10^{-10}	1.2×10^{-10}	2.6×10^{-9}
Totals	3.9×10^{-8}	1.9×10^{-7}	8.1×10^{-8}	5.6×10^{-7}
SAFSTOR[a]				
Preparations for Safe Storage				
Reactor Building	3.0×10^{-9}	1.9×10^{-8}	3.9×10^{-9}	6.6×10^{-8}
Annex Building	3.5×10^{-9}	2.3×10^{-8}	3.0×10^{-8}	9.2×10^{-8}
Heat Exchanger Building	5.0×10^{-8}	3.2×10^{-10}	5.0×10^{-11}	1.1×10^{-9}
Pump House	5.8×10^{-10}	3.8×10^{-9}	5.8×10^{-10}	1.3×10^{-8}
Radiation Center Building	1.2×10^{-10}	7.5×10^{-10}	1.2×10^{-10}	2.6×10^{-9}
Totals	7.2×10^{-9}	4.7×10^{-8}	3.4×10^{-8}	1.8×10^{-7}
ENTOMB				
Reactor Building	1.3×10^{-8}	8.5×10^{-8}	1.3×10^{-8}	2.9×10^{-7}
Annex Building	3.5×10^{-9}	2.3×10^{-8}	3.0×10^{-8}	9.2×10^{-8}
Heat Exchanger Building	5.0×10^{-8}	3.2×10^{-10}	5.0×10^{-11}	1.1×10^{-9}
Pump House	5.8×10^{-10}	3.8×10^{-11}	5.8×10^{-10}	1.3×10^{-8}
Radiation Center Building	1.2×10^{-10}	7.5×10^{-10}	1.2×10^{-10}	2.6×10^{-9}
Totals	1.7×10^{-8}	1.1×10^{-7}	4.4×10^{-8}	4.0×10^{-7}

(a) Doses are calculated to a total population of 1.4 million people residing within an 80-km radius of the site.
(b) Total SAFSTOR doses are not reported since the active release of radionuclides during safe storage is expected to be negligible compared to the release during preparations for safe storage, and since the public doses from deferred decontamination are expected to be lower than the doses from DECON because of radioactive decay.

TABLE 12.3-3. Summary of Calculated Radiation Doses to the Maximum-Exposed Individual from Atmospheric Releases During Routine Decommissioning Tasks at the Reference Test Reactor

Alternative/Building	First-Year Dose (rem)		Fifty-Year Committed Dose Equivalent (rem)	
	Total-Body	Lungs	Total-Body	Lungs
DECON				
RB/MUR/CV	3.0×10^{-8}	1.1×10^{-7}	3.0×10^{-8}	3.2×10^{-7}
Hot Laboratory Building	4.3×10^{-9}	1.8×10^{-8}	3.8×10^{-8}	7.4×10^{-8}
All Other Buildings and Areas	1.5×10^{-7}	3.8×10^{-7}	2.7×10^{-7}	1.2×10^{-6}
Totals	1.8×10^{-7}	5.1×10^{-7}	3.4×10^{-7}	1.6×10^{-6}
SAFSTOR(a)				
Preparations for Safe Storage				
RB/MUR/CV	2.4×10^{-10}	8.9×10^{-10}	2.4×10^{-10}	2.7×10^{-9}
Hot Laboratory Building	5.5×10^{-10}	2.4×10^{-9}	4.6×10^{-9}	9.2×10^{-9}
All Other Buildings and Areas	1.3×10^{-7}	3.0×10^{-7}	2.4×10^{-7}	9.2×10^{-7}
Totals	1.3×10^{-7}	3.0×10^{-7}	2.4×10^{-7}	9.3×10^{-7}
ENTOMB				
RB/MUR/CV	1.7×10^{-9}	6.4×10^{-9}	1.7×10^{-9}	2.4×10^{-8}
Hot Laboratory Building	5.5×10^{-10}	2.4×10^{-9}	4.6×10^{-9}	9.2×10^{-9}
All Other Buildings and Areas	1.3×10^{-7}	3.0×10^{-7}	2.4×10^{-7}	9.2×10^{-7}
Totals	1.3×10^{-7}	3.1×10^{-7}	2.5×10^{-7}	9.6×10^{-7}

(a) Total SAFSTOR doses are not reported since the active release of radionuclides during safe storage is expected to be negligible compared to the release during preparations for safe storage, and since the public doses from deferred decontamination are expected to be lower than the doses from DECON because of radioactive decay.

TABLE 12.3-4. Summary of Calculated Radiation Doses to the Population from Atmospheric Releases During Routine Decommissioning Tasks at the Reference Test Reactor[(a)]

Alternative/Building	First-Year Dose (man-rem)		Fifty-Year Committed Dose Equivalent (man-rem)	
	Total-Body	Lungs	Total-Body	Lungs
DECON				
RB/MUR/CV	1.2×10^{-5}	8.0×10^{-5}	1.4×10^{-5}	2.4×10^{-4}
Hot Laboratory Building	3.1×10^{-6}	2.1×10^{-5}	2.6×10^{-5}	8.1×10^{-5}
All Other Buildings and Areas	9.5×10^{-5}	3.8×10^{-4}	1.8×10^{-4}	1.3×10^{-3}
Totals	1.1×10^{-4}	4.8×10^{-4}	2.2×10^{-4}	1.6×10^{-3}
SAFSTOR[(b)]				
Preparations for Safe Storage				
RB/MUR/CV	1.3×10^{-7}	8.9×10^{-7}	1.3×10^{-7}	2.9×10^{-6}
Hot Laboratory Building	3.8×10^{-7}	2.5×10^{-6}	3.2×10^{-6}	1.0×10^{-5}
All Other Buildings and Areas	8.2×10^{-5}	3.0×10^{-4}	1.7×10^{-4}	9.8×10^{-4}
Totals	3.0×10^{-4}	3.0×10^{-4}	1.7×10^{-4}	1.0×10^{-3}
ENTOMB				
RB/MUR/CV	9.5×10^{-7}	6.4×10^{-6}	9.5×10^{-7}	2.1×10^{-5}
Hot Laboratory Building	3.8×10^{-7}	2.5×10^{-6}	3.2×10^{-6}	1.0×10^{-5}
All Other Buildings and Areas	8.2×10^{-5}	3.0×10^{-4}	1.7×10^{-4}	9.8×10^{-4}
Totals	8.3×10^{-5}	3.1×10^{-4}	1.7×10^{-4}	1.0×10^{-3}

(a) Doses are calculated to a total population of 3.5 million people residing within an 80-km radius of the site.
(b) Total SAFSTOR doses are not reported since the active release of radionuclides during safe storage is expected to be negligible compared to the release during preparations for safe storage, and since the public doses from deferred decontamination are expected to be lower than the doses from DECON because of radioactive decay.

The release of radionuclides during safe storage is expected to be negligible compared to the release during preparations for safe storage. This is because of the rugged construction of the reference R&T facilities, the erection of rigid barriers preventing migration of radionuclides, and the limited human contact during surveillance and maintenance operations. Thus, no public radiation doses are calculated for safe storage. The calculated radiation doses for DECON are small, and since the radioactivity levels are significantly reduced by radioactive decay during safe storage, public radiation doses for deferred decontamination are expected to be insignificant.

12.3.2 Public Radiation Doses from Postulated Accidents During Decommissioning

The consequences of postulated decommissioning accidents that result in atmospheric releases of radioactivity are determined by calculating the inhalation dose to the maximum-exposed individual. DECON tasks are analyzed, and postulated accidents are discussed in Section N.2.2 of Appendix N. Using engineering judgment, a general estimate of the frequency of occurrence of the level of atmospheric release is made for each accident. The frequency of occurrence is judged to be "high" if the occurrence of a release of similar magnitude per year is greater than 10^{-2}, "medium" if between 10^{-2} and 10^{-5}, and "low" if less than 10^{-5}. While it is beyond the scope of this study to evaluate every potential accident for each decommissioning alternative at each reactor, an attempt is made to identify the most significant potential accidents associated with DECON tasks. Accidents during preparations for safe storage and ENTOMB are determined by direct comparison to DECON, with no attempt at further analysis. Several of the accidents postulated for DECON do not apply to the other two alternatives, since they do not involve the removal of activated concrete or components.

Summaries of the postulated accidents considered in this study are given in Tables 12.3-5 and 12.3-6. These accidents are listed in order of decreasing magnitude of atmospheric release. First-year radiation doses and fifty-year committed radiation dose equivalents are listed for the total-body and the lungs of the maximum-exposed individual. The accident that is postulated to result in the largest atmospheric release of radioactivity at both the

TABLE 12.3-5. Summary of Accidents and Radiation Doses to the Maximum-Exposed Individual During Decommissioning at the Reference Research Reactor

Accident	Reference Radionuclide Inventory[a]	Total Atmospheric Release (Ci/hr)[b]	Frequency of Occurrence[c]	First-Year Dose (rem)		50-Year Committed Dose Equivalent (rem)	
				Total-Body	Lungs	Total-Body	Lungs
Oxyacetylene Explosion	Table E.1-6	5.2×10^{-2}	Medium	4.4×10^{-5}	1.2×10^{-3}	6.3×10^{-5}	1.6×10^{-3}
HEPA Filter Failure[d]	Table E.1-6 Table E.1-6	2.6×10^{-4} 1.0×10^{-5}	Low	1.4×10^{-7} 8.4×10^{-9}	7.3×10^{-7} 2.4×10^{-7}	1.4×10^{-7} 1.2×10^{-8}	7.8×10^{-7} 3.1×10^{-7}
Severe Transportation Accident[d,e]	Table E.1-5	5.2×10^{-5}	Low	1.3×10^{-6}	4.1×10^{-4}	1.3×10^{-6}	8.3×10^{-4}
LPG Explosion[d]	Table E.1-5	1.4×10^{-5}	Low	7.6×10^{-9}	3.9×10^{-8}	7.7×10^{-9}	4.2×10^{-8}
Vacuum Filter-Bag Rupture[d,e]	Table E.1-6	1.8×10^{-6}	Medium	1.5×10^{-9}	4.3×10^{-8}	2.2×10^{-9}	5.6×10^{-8}
Minor Transportation Accident[d,e]	Table E.1-5	1.3×10^{-6}	Low	3.2×10^{-8}	1.0×10^{-5}	3.2×10^{-8}	2.1×10^{-5}
Accidental Cutting of Activated Al in Air[d]	Table E.1-6	2.9×10^{-7}	High	2.4×10^{-10}	6.9×10^{-9}	3.5×10^{-10}	9.1×10^{-9}
Contaminated Sweeping Compound Fire[d,e]	Table E.1-5	1.9×10^{-9}	Medium	1.0×10^{-12}	5.3×10^{-12}	1.0×10^{-12}	5.7×10^{-12}
Combustible Waste Fire[d,e]	Table E.1-5	9.0×10^{-10}	High	4.8×10^{-13}	1.5×10^{-10}	4.9×10^{-13}	3.2×10^{-10}

(a) These numbers refer to the tables of radionuclides shown in Appendix E.
(b) For comparison, all accidental releases are assumed to occur in a 1-hr period.
(c) The frequency of occurrence considers not only the probability of the accident, but also the probability of an atmospheric release of the calculated magnitude. The frequency of occurrence is listed as "high" if the occurrence of a release of similar magnitude is $\geq 10^{-2}$ per year, as "medium" if between 10^{-2} and 10^{-5}, as as "low" if $<10^{-5}$.
(d) The accident shown applies to both DECON and SAFSTOR.
(e) The accident shown applies to both DECON and ENTOMB.

TABLE 12.3-6. Summary of Accidents and Radiation Doses to the Maximum-Exposed Individual During Decommissioning at the Reference Test Reactor

Accident	Reference Radionuclide Inventory[a]	Total Atmospheric Release (Ci/hr)[b]	Frequency of Occurrence[c]	First-Year Dose (rem)		50-Year Committed Dose Equivalent (rem)	
				Total-Body	Lungs	Total-Body	Lungs
Oxyacetylene Explosion	Table E.2-1	5.6×10^{-2}	Medium	3.0×10^{-5}	1.6×10^{-4}	5.3×10^{-4}	1.7×10^{-4}
LPG Explosion[d]	Table E.2-1	6.5×10^{-3}	Low	3.1×10^{-6}	1.8×10^{-5}	3.6×10^{-6}	2.0×10^{-5}
Severe Transportation Accident	Table E.2-1	1.0×10^{-3}	Low	2.5×10^{-5}	7.8×10^{-3}	2.5×10^{-5}	1.6×10^{-2}
HEPA Filter Failure[d]	Table E.2-1 Table E.2-1	5.2×10^{-4} 3.8×10^{-6}	Low	2.8×10^{-7} 3.2×10^{-9}	1.5×10^{-6} 9.1×10^{-8}	2.9×10^{-7} 4.6×10^{-9}	1.6×10^{-6} 1.2×10^{-7}
Accidental Cutting of Activated Stainless Steel[d]	Table E.2-1	8.8×10^{-5}	High	4.8×10^{-8}	2.5×10^{-4}	8.4×10^{-7}	2.6×10^{-7}
Vacuum Filter-Bag Rupture[d,e]	Table E.2-1	2.9×10^{-5}	Medium	1.6×10^{-8}	8.1×10^{-8}	2.8×10^{-7}	8.7×10^{-8}
Minor Transportation Accident	Table E.2-1	2.5×10^{-5}	Low	1.2×10^{-7}	3.8×10^{-5}	1.2×10^{-7}	8.0×10^{-5}
Contaminated Sweeping Compound Fire[d,e]	Table E.2-1	3.6×10^{-8}	Medium	1.9×10^{-4}	1.0×10^{-10}	3.4×10^{-10}	1.1×10^{-10}
Combustible Waste Fire[d,e]	Table E.2-1	1.8×10^{-8}	High	9.7×10^{-12}	5.0×10^{-11}	1.7×10^{-10}	5.4×10^{-11}

(a) These numbers refer to the tables of radionuclides shown in Appendix E.
(b) For comparison, all accidental releases are assumed to occur in a 1-hr period.
(c) The frequency of occurrence considers not only the probability of the accident, but also the probability of an atmospheric release of the calculated magnitude. The frequency of occurrence is listed as "high" if the occurrence of a release of similar magnitude is $>10^{-2}$ per year, as "medium" if between 10^{-2} and 10^{-5}, as as "low" if $<10^{-5}$.
(d) The accident shown applies to both DECON and SAFSTOR.
(e) The accident shown applies to both DECON and ENTOMB.

reference research and test reactors is an oxyacetylene gas explosion during reactor vessel segmentation tasks. This explosion is assumed to occur with enough force to cause failure of the HEPA filter system. It is calcuated that about 5.2×10^{-2} Ci of activated aluminum dust is released from the reference research reactor, and about 5.6×10^{-2} Ci of activated stainless steel dust is released from the reference test reactor as the result of this accident. This accident is estimated to have a "medium" frequency of occurrence. Transportation accidents are included in Tables 12.3-5 and 12.3-6, for comparison purposes, and they are discussed in Section 12.4

12.4 TRANSPORTATION SAFETY

Radioactive wastes collected during decommissioning are assumed to be shipped offsite as part of planned decommissioning tasks for each decommissioning alternative considered. All materials are assumed to be shipped by truck to a waste disposal site 800 km away. The method used to estimate radiation doses to transportation workers and to members of the public along the transportation route is based on information from Reference 5. The discussion of transportation accidents resulting in atmospheric releases of radioactivity is based on the methods contained in Reference 6. The following subsection contains a summary of the radiation dose calculations discussed in Section N.5 of Appendix N, as well as estimates of casualties resulting from traffic accidents during decommissioning transportation tasks. Radiation doses received by workers unloading the radioactive materials at a repository or disposal site are not estimated in this study, since they are assumed to occur at a separate licensed facility.

12.4.1 Radiation Doses from Routine Decommissioning Transportation Tasks

Department of Transportation (DOT) regulations[7] set the following exposure limits for shipments of radioactive material:

- 1000 mR/hr at 1 m from the external surface of any package transported in a closed vehicle
- 200 mR/hr at the external surface of the vehicle
- 10 mR/hr at any point 2 m from the vehicle

- 2 mR/hr at any normally occupied position in the vehicle.

Each shipment is assumed to contain enough radioactive material to result in the maximum exposure rates allowed by the above regulations.

Radioactive waste shipment requirements at the reference R&T reactors for the three decommissioning alternatives are discussed in Section 10. The number of shipments and calculated radiation doses for the reference R&T reactors are shown in Tables 12.4-1 and 12.4-2, respectively.

The largest doses occur for DECON at the reference test reactor, since this alternative requires the most waste shipments. Doses of 22 man-rem to transporation workers and 2.2 man-rem to the public are calculated to result. Similar doses for preparations for safe-storage and ENTOMB at the reference test reactor are about 50% and 90% of the doses calculated for DECON.

12.4.2 Radiation Doses from Postulated Transportation Accidents

Transportation accidents have a wide range of severities. Most accidents occur at low vehicle speeds and have relatively minor consequences. In general, as speed increases, accident severity also increases. However, accident severity is not a function of vehicle speed only. Other factors such as the type of accident, the kind of equipment involved, and the location of the accident can have an important bearing on accident severity.

Furthermore, damage to a package in a transportation accident is not directly related to accident severity. In a series of accidents of the same severity, or in a single accident involving a number of packages, damage to packages may vary from none to extensive. In relatively minor accidents, serious damage to packages can occur from impacts on sharp objects or from being struck by other cargo. Conversely, even in very severe accidents, damage to packages may be minimal.

Probabilities of truck accidents and the calculation of airborne concentrations of radioactivity from such accidents are discussed in Section N.5 of Appendix N. Most of the information about moderate and severe accidents is obtained from Reference 8. The radioactive materials that are transported in Type B packages (the highly activated reactor core internals) are in solid, noncombustible forms that are not likely to become airborne in an accident.

TABLE 12.4-1. Calculated Radiation Doses from Routine Radioactive Waste Transportation for the Reference Research Reactor

Alternative/Group	Radiation Dose Per Shipment (man-rem)[(a)]	Number of Shipments[(b)]	Total Population Dose Per Group (man-rem)[(c)]
DECON			
Truck Drivers	6.7×10^{-2}	4	2.7×10^{-1}
Garagemen	3.3×10^{-3}	4	1.3×10^{-2}
Total Worker Dose			2.7×10^{-1}
Onlookers	5.0×10^{-3}	4	2.0×10^{-2}
General Public	1.8×10^{-3}	4	7.2×10^{-3}
Total Public Dose			2.7×10^{-2}
SAFSTOR[(d)]			
Preparations for Safe Storage			
Truck Drivers	6.7×10^{-2}	1	6.7×10^{-2}
General Public	3.3×10^{-3}	1	3.3×10^{-3}
Total Worker Dose			7.0×10^{-2}
Onlookers	5.0×10^{-3}	1	5.0×10^{-3}
General Public	1.8×10^{-3}	1	1.8×10^{-3}
Total Public Dose			6.8×10^{-3}
ENTOMB			
Truck Drivers	6.7×10^{-2}	2	1.3×10^{-1}
Garagemen	3.3×10^{-3}	2	6.6×10^{-3}
Total Worker Dose			1.4×10^{-1}
Onlookers	5.0×10^{-3}	2	1.0×10^{-3}
General Public	1.8×10^{-3}	2	3.6×10^{-3}
Total Public Dose	1.8×10^{-3}	2	1.4×10^{-2}

(a) Based on one-way trips of 800 km.
(b) Based on the waste disposal requirements discussed in Appendices I, J, and K.
(c) All doses are rounded to two significant figures.
(d) There are no shipments of radioactive materials made during safe storage; therefore, only the doses from shipments made during the preparations for safe storage are analyzed. Since the total number of radwaste shipments made during deferred decontamination is expected to be fewer than the number of shipments made during DECON, the radiation doses for deferred decontamination are not analyzed.

TABLE 12.4-2. Calculated Radiation Doses from Routine Radioactive Waste Transportation for the Reference Test Reactor

Alternative/Group	Radiation Dose Per Shipment (man-rem)[a]	Number of Shipments[b]	Total Population Dose Per Group (man-rem)[c]
DECON			
Truck Drivers	6.7×10^{-2}	310	2.1×10^{1}
Garagemen	3.3×10^{-3}	310	1.0×10^{0}
Total Worker Dose			2.2×10^{1}
Onlookers	5.0×10^{-3}	310	1.6×10^{0}
General Public	1.8×10^{-3}	310	5.6×10^{-1}
Total Public Dose			2.2×10^{0}
SAFSTOR[d]			
Preparations for Safe Storage			
Truck Drivers	6.7×10^{-2}	168	1.1×10^{1}
Garagemen	3.3×10^{-3}	168	5.5×10^{-1}
Total Worker Dose			1.2×10^{1}
Onlookers	5.0×10^{-3}	168	8.4×10^{-1}
General Public	1.8×10^{-3}	168	3.0×10^{-1}
Total Public Dose			1.1×10^{-1}
ENTOMB			
Truck Drivers	6.7×10^{-2}	191	1.3×10^{1}
Garagemen	3.3×10^{-3}	191	6.3×10^{0}
Total Worker Dose			1.9×10^{1}
Onlookers	5.0×10^{-3}	191	9.6×10^{-1}
General Public	1.8×10^{-3}	191	3.4×10^{-1}
Total Public Dose			1.3×10^{0}

(a) Based on one-way trips of 800 km.
(b) Based on the waste disposal requirements discussed in Appendices I, J, and K.
(c) All doses are rounded to two significant figures.
(d) There are no shipments of radioactive materials made during safe storage; therefore, only the doses from shipments made during the preparations for safe storage are analyzed. Since the total number of radwaste shipments made during deferred decontamination is expected to be fewer than the number of shipments made during DECON, the radiation doses for deferred decontamination are not analyzed.

Therefore, no accident analysis of Type B packages is considered. Instead, two more realistic accidents involving combustible radioactive wastes in Type A packages are defined. Both, however, are judged to have a low frequency of occurrence. The calculated radiation doses to the lung of the maximum-exposed individual, resulting from these accidents are shown in Tables 12.3-5 and 12.3-6 for the reference R&T reactors. These transportation accidents are ranked by decreasing order of magnitude of atmospheric release.

The severe transportation accident for each reference reactor is assumed to involve rupture and fire in 40 waste containers. The total atmospheric releases are calculated to be: 5.2×10^{-5} Ci for the reference research reactor and 1.0×10^{-3} Ci for the reference test reactor. The calculated 50-year committed dose equivalents to the lungs of the maximum-exposed individual are: 8.3×10^{-4} rem for the reference research reactor and 1.6×10^{-2} rem for the reference test reactor.

For the minor accident, only one package is assumed to rupture and burn. In this case, 1.3×10^{-6} Ci are released for the reference research reactor wastes and 2.5×10^{-5} Ci are released for the reference test reactor wastes. The resulting 50-year committed dose equivalents to the lungs are calculated to be 2.1×10^{-5} rem for the reference research reactor and 8.0×10^{-5} rem for the reference test reactor.

12.4.3 Casualties from Traffic Accidents

As with any transportation task, a certain potential for accidental injury or death exists from traffic accidents during decommissioning tasks.[5] Summaries of the casualties calculated to result during the transportation tasks considered in this study for the reference R&T reactors are shown in Table 12.4-3. As shown in this table, less than one lost-time injury and far less than one fatality are calculated to result during waste shipments for either of the reference reactors. This is because of the small amounts of wastes collected at these reactors during decommissioning, and the correspondingly small numbers of waste shipments required.

TABLE 12.4-3. Estimated Casualties from Truck Transportation Accidents During Decommissioning of the Reference R&T Reactors[a]

Reactor/Alternative	Accident Frequency (Accidents Per Vehicle km)	Injuries Per Accident	Fatalities Per Accident	Total Kilometers (Round Trips)	Transportation Casualties[b]	
					Injuries	Fatalities
Research Reactor						
DECON	1×10^{-6}	0.51	0.03	6.4×10^{3}	3.2×10^{-3}	1.9×10^{-4}
SAFSTOR[c]						
Preparations for Safe Storage	1×10^{-6}	0.51	0.03	1.6×10^{3}	8.2×10^{-4}	4.8×10^{-5}
ENTOMB	1×10^{-6}	0.51	0.03	3.2×10^{3}	1.6×10^{-3}	9.6×10^{-5}
Test Reactor						
DECON	1×10^{-6}	0.51	0.03	5.0×10^{-5}	2.6×10^{-1}	1.5×10^{-2}
SAFSTOR[c]						
Preparations for Safe Storage	1×10^{-6}	0.51	0.03	2.7×10^{5}	1.4×10^{-1}	8.1×10^{-3}
ENTOMB	1×10^{-6}	0.51	0.03	3.1×10^{5}	1.6×10^{-1}	9.2×10^{-3}

(a) Accident frequencies are from Reference 5.
(b) Casuality estimates are rounded to two significant figures.
(c) There are no shipments of radioactive materials made during safe storage; therefore, only the shipments of radioactive materials made during the preparations for safe storage are analyzed. The number of transportation casualties from radioactive material shipments is expected to be fewer from deferred decontamination than from DECON since the total number of shipments made will be fewer than for DECON.

REFERENCES

1. Operational Accidents and Radiation Exposure Experiences Within the U.S. AEC 1943-1970, WASH-1192, 1971.

2. American National Standards Institute, Method of Recording and Measuring Work Injury Experience, ANSI 216.1, 1967.

3. United Nations Scientific Committee on the Effects of Atomic Radiation, Ionizing Radiation: Levels and Effects, Volume 1, United Nations, pp. 29-63, 1972.

4. Code of Federal Regulations, Title 10, Part 50, Appendix I, "Numerical Guides for Design Objectives and Limiting Conditions for Operation to Meet the Criterion 'As Low As Practicable' for Radioactive Materials in Light-Water-Cooled Nuclear Power Reactor Effluents," Superintendent of Documents, GPO, Washington DC, 1977.

5. Directorate of Regulatory Standards, Environmental Safety of Transportation of Radioactive Materials to and from Nuclear Power Plants, WASH-1238, U.S. Atomic Energy Commission, Washington DC, 1972.

6. Technology for Commercial Radioactive Waste Management, DOE/ET 0028, Vol. 4, Chapter 6.2, Prepared by Pacific Northwest Laboratory for the U.S. Department of Energy, Richland, Washington, May 1979.

7. U.S. Code of Federal Regulations, Title 49, Parts 170-189, "Transportation," Superintendent of Documents, GPO, Washington, DC January 1977.

8. Environmental Aspects of Commercial Radioactive Waste Management, DOE/ET-0029, Volume 2, Chapter 7.3, Prepared by Pacific Northwest Laboratory for the U.S. Department of Energy, Richland, Washington, May 1979.

13.0 COMPARISONS WITH OTHER STUDIES

Studies on the decommissioning of licensed R&T reactors as a class are virtually nonexistent. Historically, it is only when a specific research or test reactor licensee is preparing either for the actual decommissioning of his facility or for an amendment to his existing license (e.g., to permit operation to an increased power level) that the decommissioning of R&T reactors is addressed. Each study is then undertaken with a variety of motives in mind, and the conclusions reached/reported tend to reflect the particular interests of the study sponsor and the purpose for which the study was intended to be used.

A review of the literature has identified no comparative studies on decommissioning licensed research reactors and only two brief studies on decommissioning licensed test reactors: an earlier study on the reference test reactor (PBRF)[1] and a limited study on the National Bureau of Standards Reactor (NBSR).[2] The earlier PBRF study is incomplete in that it dealt only with activities occuring a number of years following the initial cleanup. The NBSR is sufficiently different from the PBRF that to make direct comparisons of the two is of limited value. In the following subsections, each of these test reactor studies is described briefly. Some discussion of the results of these studies and a comparison with the results of this study (NRC-BNW) for the reference test reactor follow the descriptions.

13.1 REFERENCE 1: TELEDYNE ISOTOPES STUDY

J. E. Ross, et al., An Evaluation of the Options for Further Decommissioning of the Plum Brook Reactor Facility, Teledyne Isotopes for the National Aeronautics and Space Administration, July 1978.

This report was prepared for the National Aeronautics and Space Administration (NASA) for the purpose of evaluating alternatives for further decommissioning the PBRF.

In early January 1973, NASA discontinued operations and testing, and the PBRF was decommissioned by placing it in a state of protective storage (mothballing). All systems, support hardware, etc. were maintained assuming the reactor could be utilized at some future date if needed. In late 1977, NASA

decided to forego any plans for future operation of this facility. It was that decision which led to Teledyne's evaluation to determine options available for further decommissioning.

The studies and evaluations leading to the report were intended to meet the following objectives:

1. To list and define the options open to NASA in further decommissioning the PBRF.
2. To perform a cost evaluation for each of these options.
3. To prepare a preliminary study to determine the most cost-effective option, taking into consideration both initial costs to attain that alternative and recurring annual costs to maintain that alternative.

The primary radionuclides of concern in the PBRF closely parallel those of concern for most light water moderated reactors. Despite this similarity, the report cautions readers to consider the following before attempting to compare the report with others of similar purpose:

- The considerable effort and costs required to achieve the present state of decommissioning of the PBRF are not included in the report.
- PBRF has an extensive system of canals and storage pools, elaborate experiment support systems, and a large hot laboratory complex, which complicates further decommissioning efforts.
- Substantial decay of shorter-lived nuclides has occurred during the 5 years since PBRF operations were terminated.
- Conclusions reached in the report are based on conditions specific for the PBRF given the laws, regulations, practices, and conditions which existed when the report was published (1978).

The Teledyne study evaluates five decommissioning alternatives, each one assuming that the PBRF status as of mid-1978 (i.e., after 5 years of safe storage had elapsed) was the starting point. The potential alternatives evaluated are:

1. Safe storage with delayed decontamination (based on a continuation of the present safe storage condition).

2. Safe storage with delayed decontamination with a reduction in plant acreage.

3. Entombment with delayed decontamination.

4. Prompt decontamination with structures removed.

5. Prompt decontamination with the structures remaining.

A summary of the estimated costs for alternative number five is given in Table 13.1-1. In scope, this alternative is similar to deferred decontamination of the reference test reactor, as described in Appendix J of Volume 2.

13.2 REFERENCE 2: NBS REACTOR

NRC Docket No. 50-184, Final Safety Analysis Report on the National Bureau of Standards Reactor, NBSR 9, Addendum 1, November 1980.

This addendum to the NBSR Final Safety Analysis Report includes sections addressing financial responsibility, safe operation and maintenance of the facility, and reactor decommissioning.

The decommissioning section contains a brief analysis of the estimated costs for decommissioning of the NBSR. The costs estimates are based on the July 31, 1980, estimated costs identified by Argonne National Laboratory (ANL) for the decontamination and decommissioning of the CP-5 Research Reactor Facility (a nonlicensed government reactor).

The reported conclusion from this brief analysis is that the annualized cost of decommissioning the NBSR is essentially the same as that of continued operation. The following assumptions were used by the NBSR staff in applying the ANL estimates to generate the estimates given in Table 13.2-1 for the NBSR decommissioning:

- All costs are in FY-1980 dollars.
- Decommissioning is expected to take 3 years and to start about 2 years after final fuel removal.

TABLE 13.1-1. Summary of Estimated Costs for Further Decommissioning of the PBRF Via Prompt Dismantlement with the Structures Remaining[a]

Cost Category	Alternative 5 ($ thousands)[b]
Task Labor[c]	433
Undistributed Labor[d]	3,217
Materials, Supplies and Other Expenses	250
Radioactive Waste Disposal[e]	509
Subcontracted Tasks[f]	634
Maintenance	--
Surveillance	--
Natural Gas	48
Electricity	24
Nitrogen Gas	--
Franchise Tax[g]	19
Subtotal	5,134
G&A @ 15%[h]	770
Subtotal	5,904
Fixed Fee @ 7%[i]	413
Total	6,317

(a) Data from Reference 1, p. 5-2.
(b) 1978 costs. Does not include the costs incurred in 1973 for the preparations for safe storage of the PBRF.
(c) Task labor is that which is related to specific tasks necessary to remove radiological and nonradiological systems and components prior to demolition.
(d) Undistributed labor consists of project management, project engineering, radiological services, and facility support services.
(e) Includes packaging and preparing radioactively contaminated/activated components for shipment; transportation to a licensed burial ground; burial costs; cask leasing and use charges; and demurrage on trailers.
(f) For the most part, subcontracted tasks are for building or facility demolition after all vestiges of radioactivity are removed by the prime contractor.
(g) Prime contractor costs for Ohio Franchise tax is included at the present rate (1978) of 4.7% of profit.
(h) G&A is General and Administrative and is estimated at 15%.
(i) Fixed fee under the assumed Cost Plus Fixed Fee Contract is estimated at 7%.

TABLE 13.2-1. Cost Estimates for Decontamination and Decommissioning of the NBS Reactor

Cost Category	Estimated Costs ($ thousands)
Preliminary Engineering & Design	400
Fuel Disposal	120
Heavy Water Reprocessing	400
Site Preparation	290
Ancillary Structures	40
Structure Components	3 200
Control Blades, Experimental Facilities, Shield Plug, Thermal Shield, Tank, Thermal Column, Biological Shield, etc.	
Process Systems	280
Electrical, Instruments, Cooling Systems, Rabbit System, Ventilation, Fuel Pool, etc.	
Repair and Refurbishment	320
Final Decontamination	160
Subtotal	5 210
Engineering Design & Inspection (24% of Construction)	900
Contingency (25% of Construction & Engineering)	1 180
1st Year	1 600
4 Subsequent Years	2 940
Total	11 830

- Upon completion of decommissioning, the 20-ton overhead crane becomes available for unrestricted use.
- Costs for remodeling are not included.
- Deconstruction costs in the Washington, D.C. area are assumed to be 20% higher than in the Chicago, Illinois, area.

No decommissioning alternatives other than DECON were considered in the NBSR addendum, with work assumed to start 2 years after final fuel removal. No details are provided on work descriptions, occupational radiation exposure estimates, or material disposal data. Thus, comparisons of cost estimate bases are not possible.

The brief analysis given states that the similarity between the ANL CP5 facility and the NBSR facility "adds greatly to the confidence to be placed in using their cost estimates as a basis for estimating NBSR decommissioning costs."

13.3 PRESENT REFERENCE TEST REACTOR STUDY

The costs of DECON estimated in this study for the reference test reactor (i.e., the PBRF on an assumed generic site) are summarized in Table 13.3-1, for comparison with the costs estimated in the earlier Teledyne study on PBRF and in the NBSR study, presented in the preceding sections.

The costs given in Table 13.3-1 for the reference test reactor can be broken down further into approximate estimates of costs per major component using the following two-step derivation:

1. $$\text{Estimated Monthly Labor Costs (EMLC) for DECON} = \frac{\text{Total Labor Cost for DECON}}{\text{Total Decommissioning Workers' Person-Months For All DECON Tasks}} = \frac{\$0.0154\text{ M}}{\text{month}}$$

2. $$(\text{EMLC}) \times \left(\text{Total Task Time In Person-Months Per Major Component}\right) + \left(\text{Estimated Radioactive Waste Disposal Costs/Component}\right) = \text{Approximate Cost Per Major Component}$$

The EMLC for all DECON tasks is about \$0.015 million. This monthly labor cost includes both management and support personnel as well as the decommissioning workers. In general, all DECON tasks are labor intensive (~69% of the total DECON cost), but radioactive waste disposal costs (~21% of the total DECON cost) must also be included in this first-order approximation of decommissioning costs for major components in the reference test reactor. Application of this methodology to the major components in the reference test reactor yields the results given in Table 13.3-2.

Since this study uses 1981 costs, no cost escalation is applied to the results presented in Table 13.3-2. The aforementioned methodology appears reasonable based upon the constant labor force postulated for DECON (see Section I.2.2.4 of Appendix I for details).

TABLE 13.3-1. Summary of Estimated Costs of DECON for the Reference Test Reactor

Cost Category		Estimated Costs ($ millions)(a,b)	Percent of Total
Disposal of Radioactive Materials			
Neutron-Activated Materials			
Reference Test Reactor	0.131		
Mock-Up Reactor (MUR)	0.004		
Contaminated Materials	2.338		
Radioactive Wastes	0.099		
Total Disposal Costs		2.572	20.7
Staff Labor		8.63	69.3
Energy		0.076	0.6
Special Tools and Equipment		0.361	2.9
Miscellaneous Supplies		0.203	1.6
Specialty Contractors(c)		0.616	4.9
Nuclear Insurance		--(d)	--
License Fees		--(e)	--
Subtotal		12.458	100.0
Contingency (25%)		3.115	
Total, DECON Costs		15.573	
Other Possible Costs			
Spent Fuel Shipment		0.204	
Facility Demolition and Site Restoration		2.289	
Subtotal		2.493	
Contingency (25%)		0.623	
Total, Other Possible Costs		3.116	

(a) 1981 costs used.
(b) The number of figures is shown for computational accuracy and does not imply precision to the nearest $1,000.
(c) Includes selected demolition, explosives, temporary radwaste, and environmental monitoring services.
(d) Indemnity fees are currently $100/yr for each license (i.e., the test reactor license and the MUR license) at the reference test facility and are not included in this study since they represent only small fraction of 1% of the total decommissioning cost.
(e) Because the reference test reactor is assumed to be federally owned, these fees are not applicable.

TABLE 13.3-2. Estimated Major Component Cost Breakdowns for Decommissioning the Reference Test Reactor

Major Component	Estimated Cost ($ millions)[a] Labor[b]	Radioactive Waste Disposal[c]	Miscellaneous	Estimated Total Cost ($ millions)	Percent of Total DECON Cost[d]
RB/CV	4.3	0.71	1.47	6.5	42
HLB	1.4	0.14	0.46	2.0	13
Other Bldgs.					
PPH, OLB, FH, WHB	1.6	0.28	0.56	2.5	16
Site:					
ERB, CRA, HRA	1.4	2.1	1.02	4.5	29
Totals	8.7	3.3	3.5	~15.5	100

(a) 1981 costs used (includes 25% contingency).
(b) Based on Table 13.3-1 and Figures I.2-1, -2, -3 in Appendix I.
(c) Based on Tables I.2-7 and I.2-11 in Appendix I and Table D.2-3 in Appendix D.
(d) Total DECON cost, including 25% contingency, is $15.6 million (see Table 13.3-1 for details).

A discussion of the preceding test reactor studies is given in the following subsections.

13.4 DISCUSSION OF TEST REACTOR DECOMMISSIONING STUDIES

The only item that can be compared between the preceding three studies on test reactors is cost. Examination of Tables 13.1-1, 13.2-1, and 13.3-1 makes it apparent that while attempts to compare individual cost items are essentially impossible, the adjusted grand totals are of the same order of magnitude, in the range of $13 to $16 million. Adjusting the NBSR study costs for escalation from 1980 to 1981 costs results in a total cost of about $13 million, close to the total amount estimated in the present reference test reactor study.

Each study gives a total cost for decommissioning, but the development of the cost segments making up that total varies markedly among the studies, so that the segments cannot easily be examined on a common basis. Therefore, we have interpreted Tables 13.1-1 and 13.2-1, as given in Table 13.4-1, to

TABLE 13.4-1. A Comparison of Test Reactor Decommissioning Costs Resulting from Three Separate Studies

Cost Category	Decommissioning Costs ($ millions) NBSR Study[a] (1980 costs)	PBRF Teledyne Study[b] (1978 costs)	Reference Test Reactor NRC-BNW Study[c] (1981 costs)
Labor	3.5	3.7[b]	10.8
Radioactive Waste	5.8	0.5[b]	3.2
Other	2.5	2.1[b]	1.6
Totals	11.8	6.3[b]	15.6
Escalation to 1981 Costs	~13	8.2[d]	15.6
Assumed Modifying Factor[f]	N/A[e]	[6.7][f]	N/A
Grand Totals	~13	~15[g]	~16

(a) Based on Table 13.2-1.
(b) Based on Table 13.1-1. These cost estimates are for further decommissioning PBRF after approximately 5 years of safe storage.
(c) Based on Table 13.3-1 (includes 25% contingency).
(d) Does not include the costs incurred in 1973 for the preparations for safe storage of the PBRF.
(e) N/A is not applicable.
(f) Since only limited quantitative cost data are available regarding the placement of PBRF into safe storage in early-1973, it is assumed for purposes of comparison of the three studies that the 1981 cost estimates for preparations for safe storage of the reference test reactor (see Appendix J for details) can be used to approximate within an order of magnitude what the original PBRF safe storage costs were (in 1981 dollars).
(g) It should be recognized that this total is an estimate by the author and is not the Teledyne Isotope total; it is the result of an estimate by the author, after applying various modifying factors, to illustrate comparative values.

simplify cost comparisons between the three test reactor studies, based on major cost categories--labor, disposal of radioactive materials, and other (i.e., the remaining cost categories for each study).

The largest cost items are staff labor, radioactive waste, and other (i.e., ancillary structures and/or areas). A comparison which can be drawn is that the overall cost of decommissioning for licensed test reactors having similar ancillary facilities will be very similar. In addition, these costs are not particularly sensitive to the authorized power level of the reactors (PBRF @ 60 MWt, NBSR @ 10 MWt), but are severely influenced by the size and nature of the ancillary facilities (hot cells, etc).

Thus, if one wishes to make decommissioning cost estimates for a specific reactor facility based on estimates given for another similar reactor facility, it is essential to compare the ancillary facilities carefully, since these facilities can contribute a significant fraction of the total decommissioning cost.

REFERENCES

1. J. E. Ross, et al., An Evaluation of the Options for Further Decommissioning of the Plum Brook Reactor Facility, Teledyne Isotopes for the National Aeronautics and Space Administration, July 1978.

2. NRC Docket No. 50-184, Final Safety Analysis Report on the National Bureau of Standards Reactor, NBSR 9, Addendum 1, November 1980.

14.0 FACILITATION OF DECOMMISSIONING

The primary objective of facilitating the decommissioning of nuclear research and test (R&T) reactor facilities is to reduce the radiation dose received by decommissioning workers. This radiation dose exists because the decommissioning process necessarily places the worker in proximity to radioactive material in order that the material may be removed or isolated effectively from the environment of man. Secondary objectives are: 1) to reduce the cost of decommissioning, 2) to reduce the volume of radioactive wastes, and 3) to reduce any radiation dose received by the public. The costs of decommissioning a nuclear facility are larger than the costs of decommissioning an equivalent non-nuclear facility because the radiation dose rates present in the nuclear facility at the time of decommissioning often require remote operations, contamination control, radiological surveillance, and radiological protection; because inefficiencies arise in using decommissioning personnel due to the radiation dose rates; because the radioactive wastes require special handling, packaging, and disposal; and because radioactive steel and concrete structures often require special dismantling techniques.

Criteria, considerations, and suggested techniques for facilitating the decommissioning of the reference R&T reactors are discussed in the following sections.

14.1 CRITERIA FOR EFFECTIVE DECOMMISSIONING FACILITATION

Experience has shown that steps can be taken to facilitate decommissioning. Some of the steps must be taken early in the design of a nuclear facility, while others may be taken during its operating lifetime or later during decommissioning. To be effective, a facilitation technique should reduce the radiation dose and/or the volume of radioactive waste at a reasonable cost. Ideally, an effective technique will provide similar benefits during the facility's operating years, as well as during decommissioning. Strategic decommissioning facilitation planning requires careful consideration to determine if a facilitation alternative will also facilitate maintenance.

A suggested methodology for facilitating decommissioning in light water reactors is developed in Reference 1. The methodology attempts to optimize costs versus radiation exposures in decommissioning and is directly applicable to the reference R&T reactors. Decommissioning facilitation techniques are described for light water reactors in general in Reference 2, for pressurized water reactors in Reference 3, and for boiling water reactors in Reference 4.

14.2 CONSIDERATIONS IN FACILITATING DECOMMISSIONING

This section contains a discussion of the regulatory considerations for facilitating the decommissioning of nuclear R&T reactor facilities and a discussion of the potential for dose reductions and cost savings.

14.2.1 Regulatory Considerations

Regulatory requirements pertinent to decommissioning are discussed in Section 6 of this study and also in Reference 5. There are presently no regulatory requirements specific to the facilitation of decommissioning R&T reactors. However, 10 CFR Part 50, Appendix F.4 states: "A design objective for fuel reprocessing plants shall be to facilitate decontamination and removal of all significant radioactive wastes at the time the facility is permanently decommissioned." The intent of this regulation can logically be extended to R&T reactors. Also, NRC Regulatory Guide 8.8, Information Relevant to Ensuring that Occupational Radiation Exposures at Nuclear Power Stations Will Be As Low As Is Reasonably Achievable, points out that "Design concepts and station features should reflect consideration of the activities of station personnel (such as ... decontamination and decommissioning) that might be anticipated and that might lead to personnel exposure to substantial sources of radiation."

The available regulatory guidance indicates that, to facilitate decomissioning, early attention should be given to the following: design, location, accessibility, and shielding of equipment and components; adequate record keeping, construction materials and their finishing; decontamination techniques; and special dismantling tools, techniques, and equipment. Thus decommissioning facilitation is an activity best begun at the time the nuclear facility is being designed, but can be carried out at any time up to the actual conclusion of decommissioning.

14.2.2 Radiation Dose Reduction Considerations

The reduction of occupational radiation dose to a practical minimum is an important consideration during decommissioning, just as it is during R&T reactor operation. The standard radiation control techniques of time, distance, and shielding are used during decommissioning. For example, the SAFSTOR decommissioning alternative is itself a decommissioning facilitation technique in that it allows time for radioactive decay, thereby reducing potential radiation dose to decommissioning personnel. Another example is the concentration of radiation sources in one place for easier shielding or remote handling. It should be recognized, however, that radioactivity is not reduced or eliminated by this concentration technique; radiation sources are merely rearranged for more convenient shielding and handling.

Recognizing where the greatest opportunities exist for reducing radiation dose is important. Since the bulk of the radioactive material in R&T reactors (following fuel removal) is in the reactor vessel and the vessel internals, the greatest opportunity for dose reduction lies in the efficient handling of these components. This material will be activated, as possibly will be some nearby concrete and structural components. Lesser amounts of radioactive material will be present as contamination in piping, in waste treatment areas, and in the experimental systems associated with the reference R&T reactors; therefore, lesser opportunities for reducing radiation dose are present in these areas.

14.2.3 Cost Savings Considerations

Costs associated with decommissioning facilitation alternatives include capital costs, costs of maintenance and operation (during both reactor operation and maintenance and decommissioning), and any cost savings during decomissioning. Cost savings may result from increased efficiencies in decommissioning or from reduced volumes of radioactive materials requiring disposal.

14.2.4 Cost-Benefit Considerations

One method of assessing decommissioning facilitation cost-benefit is to determine the cost per occupational man-rem saved. Such cost-benefits have been calculated for a PWR and lie in a range of zero cost to several million

dollars per man-rem saved.[2] Those decommissioning facilitation options that result in zero cost per man-rem saved are usually those that also result in the facilitation of maintenance during the operating years of the reactor. Options that facilitate both decommissioning and maintenance clearly are more advantageous than those that facilitate decommissioning only. This fact is as true for R&T reactors as it is for power reactors. Although downtime at R&T reactors is not as costly as it is at power reactors, it is still relatively costly to experimenters running tests, since fixed costs go on.

14.3 WAYS TO FACILITATE DECOMMISSIONING

This sections presents a discussion of possible decommissioning facilitation techniques. Most of the techniques are best implemented in the facility design phase before construction begins, but some may be delayed until just before decommissioning begins. In decommissioning, an opportunity exists only once to reduce radiation dose and cost, but in maintenance, an opportunity exists every year to reduce radiation dose and cost.

14.3.1 Improved Documentation

Documentation is the foundation of decommissioning facilitation. Improved documentation includes complete and accurate as-built drawings, construction photographs, maintenance records, and maintenance photographs; scale models and mock-ups; and clearly labeled equipment and piping. The larger and more complex the research or test reactor facility, the more important are these records. The records should emphasize weight, size, and location of all components and equipment, materials of construction, concrete pours, concrete penetrations, and the location of reinforcing steel embedded in concrete. Maintenance records can be useful to indicate such things as improved methods of equipment removal, shielding, and decontamination. Benefits accrue during both operation and decommissioning because of better planning possibilities; better informed (and therefore more efficient) personnel; and opportunities for dry runs on mock-ups. Improved documentation is particularly important for personnel involved in deferred decontamination, since it is unlikely that knowledgeable staff will be available for consultation after an extended storage period.

14.3.2 Improved Access

Access to contaminated equipment is improved in R&T reactor facilities by the installation of removable roof and wall panels. Improved access simplifies removal of contaminated equipment for maintenance or replacement during plant operation, as well as for disposal during decommissioning. Candidate equipment for such treatment includes contaminated tanks, demineralizers, filters, heat exchangers, and pumps. Occupational radiation doses would be reduced during both maintenance and decommissioning because these components could be removed or serviced more rapidly or could be remotely handled more easily than would otherwise be the case.

Shield wall and roof slabs could also be installed in modular form for easy removal during decommissioning.

14.3.3 Different Materials in the Reactor Vessel Internals

Removal of ^{59}Co from or substitution of zircaloy for the stainless steel used in the reactor vessel internals reduces the production of ^{60}Co as a neutron-activation product and greatly reduces the radioactivity of the reactor vessel internals following operation. Measurements made during the dismantlement of the Elk River Reactor showed a ten-fold difference in radiation dose rate between an upper core shroud assembly of stainless steel and a lower core shroud assembly of zircaloy, both of which were in similar neutron flux environments.(6) In addition to reducing radioactivity in the reactor vessel internals, this technique reduces ^{60}Co as a potential corrosion product in plant contamination.

The benefit of this technique to reactor operation and to decommissioning is substantially reduced radiation dose rates to the workers. In implementing this technique, care must be taken with respect to neutron physics considerations in the design of the vessel internals to ensure that the reactor performance is not adversely affected and that the neutrons do not cause increased activation in a less desirable area elsewhere.

14.3.4 Protection of Concrete Against Contamination

During dismantlement, contaminated concrete surfaces must be removed in order that the remaining concrete structure may be released for unrestricted use. A cost-effective method of protecting concrete surfaces from spills, seepage, and leaks of radioactive liquids is the application of an epoxy coating.[2] If concrete surfaces are protected with an epoxy coating and the coating is kept intact, radioactive contamination may be more easily removed during the facility's operating lifetime and during decommissioning, thus decreasing the associated radiation dose. Also, during decommissioning, most of the costs of concrete removal, handling, and disposal are avoided; and less disposal space is required.

14.3.5 Improved Shielding

The use of improved shielding reduces radiation dose to maintenance and decommissioning personnel and, at the same time, permits quasi hands-on work. Two possible alternatives are: 1) pipe and equipment shielding, and 2) a self-contained shielded vehicle with manipulator arms.

Presently, piping in power reactors is only insulated to maintain thermal efficiency. Lead shielding with an insulation gap would provide both radiation and thermal shielding. However, this would require stronger pipe supports. Although the general applicability of this shielding technique for dose reduction is considered to be quite limited for R&T reactors, its usefulness on a reactor-specific basis could be significant. Pipe shielding would reduce background radiation near valves and pumps, which require much maintenance in an operating plant, and thus benefit operation and maintenance as well as decommissioning.

Portable shields are used to provide temporary working areas in high radiation fields. However, a single-phase shield does not provide sufficient protection against reflected radiation. A shielded vehicle equipped with manipulator arms capable of performing functions similar to remote manipulators in hot cells could be used and would provide the desired protection during both maintenance and decommissioning activities. However, for maneuverability, this vehicle may require larger work areas and greater distances between

components. The vehicle would contain its own life-support systems and fail-safe power supplies to ensure that the operator could always safely leave high radiation areas. The vehicle would permit maintenance or decommissioning tasks to be carried out in higher radiation fields, for longer periods of time, and by fewer workers than would otherwise be possible.

Because of the high initial costs of shielding and shielded vehicles and the relatively low radiation levels found in R&T reactors, these alternatives may not be very cost effective in R&T reactor applications.

14.3.6 Reduction of Radioactive Waste Volume

The volume of contaminated waste to be stored or buried may be reduced by such techniques as mechanical compaction of compressible wastes, incineration of combustible materials, filtration, ion exchange, and evaporation of liquids, and cutting and packing of rigid materials.

Where compaction is feasible, dry solid wastes can be reduced in volume by approximately a factor of 5. Incineration can reduce the volume of combustible materials by an additional factor of 5. An incinerator unit includes a feed preparer, a burner fired by oil or gas, an afterburner, a heat exchanger, a HEPA filter chain, an exhaust stack with off-gas monitoring capability, and an ash collection and packaging facility. Extensive off-gas treatment is not usually necessary because of the low specific activity of the contaminated wastes and because of the absence of highly toxic constitutents. The advantages of incineration are: 1) a significant reduction in the volume of material that must be packaged and disposed of during both operation and decommissioning, and 2) a slight reduction in occupational and public radiation dose due to efficiencies in handling and transporting wastes. However, due to the small volumes of waste material at a research reactor, an incinerator may not be cost effective.

Water filtration and ion exchange systems are probably onsite (or can be brought to the site) as part of the radioactive waste handling system. These systems should be kept in use until the latter stages of decommissioning in order that water used in decontamination solutions and in fuel transfer canals and storage basins can be effectively decontaminated. As a final step, water may be evaporated in either permanent or portable units, with a volume reduction of 30 to 1.

Judicious cutting and packing of rigid components will also result in a waste volume reduction (see Section 14.3.9).

14.3.7 Electropolishing and Vibratory Finishing

Electropolishing is an excellent method for removing contamination from metal surfaces and for smoothing metal surfaces so that radioactive deposits will not adhere well.[7] In this technique, the object to be decontaminated serves as the anode in an electrolytic cell. The passage of an electric current from anode to cathode through the electrolyte results in the anodic dissolution of the surface material. Electropolishing removes surface layers of the metal, thereby both polishing the metal and removing undesireable overlying coatings. In-situ or batch application of electropolishing can be made in many situations, both during reactor maintenance and during decommissioning. In-situ applications of particular interest include electropolishing the interior of pipes and electropolishing flat or slightly curved surfaces, such as the interior surfaces of tanks. When using in-situ methods, arrangements must be made for collection or containment of the electrolyte. Batch electropolishing techniques are applicable to many metallic components such as tools, valves, ductwork, pipe segments, and other bulk metal pieces. The limitation on the size of components that can be electropolished in this manner is the size of the electrolyte tank.

Vibratory finishing has been shown to be an excellent way to remove surface contamination from non-metallic objects and to prepare metallic objects for electropolishing.[8] In this technique, components are placed inside a vibrating tub filled with loose ceramic or metallic media. The abrasive action of the vibratory media removes the surface contamination. A solution flows through the tub to flush away material removed by the vibrating media. Vibratory finishing is effective on glass, rubber, plastics, and metals.

Advantages of electropolishing and vibratory finishing include decontamination of slightly radioactive components to the extent that they can be reused, and reduction of the volume of severely contaminated material that otherwise would require deep geologic disposal. In both techniques, provision must be made for handling the secondary radioactive wastes from the solutions used in the decontamination process.

14.3.8 Remote-Controlled Equipment

The performance of radiation surveys, simple routine maintenance, and visual examination in areas of medium to high radiation dose rate causes inefficient use of personnel because of limited permissible residence time in these areas. The use of remote-controlled equipment to perform these functions would reduce personnel dose and provide more efficient use of personnel.

To be useful, a remote-control unit must be capable of carrying out these tasks with little maintenance. It must also be reasonably compact, inexpensive, readily decontaminable, and mobile (both the operating unit and the control console). Many non-nuclear jobs require a unit that can maneuver in limited space, operate in a range of temperatures and in hazardous locations (e.g., in little or no oxygen or under water), and perform boring jobs. In addition to these requirements, nuclear work requires operation in radiation fields. Reliability of such a unit is especially important, since a breakdown in service could not only delay a key operation, but could also compound the problem by requiring removal and repair of the unit, thus increasing the radiation dose to personnel.

A general-service, remote-control unit would contain a manipulator, a TV camera, a radiation monitoring device, and a hoist with an extendable mast. It would perform radiation surveys and normal inspections, place shielding, move or lift small objects (i.e., drums, liquid filters), operate valves, make connections, and tighten nuts. Unfortunately a robot that is practical for decommissioning power reactors might not be cost effective for decommissioning R&T reactors because of the high initial cost of the equipment and the relatively low dose rates present in these facilities.

In addition, it should be recognized that the usefulness of an industrial robot as a tool for R&T reactor decommissioning is limited because the robot is unable to climb over obstacles, and because its field of view, resolution, depth perception, and manual dexterity are limited. Robots especially designed for the environments anticipated at R&T reactors would require considerable development and a long lead time. In view of the relatively low risk involved for humans, there does not appear to be justification for developing robots specifically for use in decommissioning R&T reactors.

14.3.9 Other Ways to Facilitate Decommissioning

Brief summaries of other possible decommissioning facilitation techniques are presented in this section.

- Use of Deionized Water. Use of deionized water in dismantling the activated reactor core components will improve optical clarity and facilitate later waste water decontamination by ion exchange techniques.
- Bolted Reactor Core Construction. Bolted, rather than welded, construction techniques will facilitate the disassembly of highly activated reactor core components. Since access is usually severely restricted, bolts inserted from the top are easier to remove than those inserted from other directions. In those situations where bolting from below is necessary, drilling clear through is recommended. This facilitates dismantling later by providing a guide hole that can be seen and used from above to drill out the bolt. In addition, bolting, if planned in advance, allows disassembly of the core into optimum-sized pieces for packaging and disposal without further cutting.
- ALARA. Assigning an ALARA audit team to the project independent of the formal decommissioning organization could provide perspective that would result in radiation reductions and cost savings.
- Waste Tank Sizes. Where multiple tanks are required for the storage of radwastes, the tanks should be designed of such sizes and weights that they can be nested for transport on trucks and later disposal without sectioning of the tanks. The tops of all the tanks would be removed except for the smallest tank. The smallest tank would be packaged (nested) inside the next larger tank, etc., until all tanks were contained within the largest tank; then, the top of the largest tank would be welded back in place to provide the package used for transport. The limiting condition to consider for this technique would probably be the total weight involved. The space required for disposal of separate tanks would be substantially reduced.

14.4 CONCLUSIONS AND RECOMMENDATIONS

It is quite probable that the most effective decommissioning facilitation techniques that can be applied to existing R&T reactors are electropolishing, vibratory finishing, and incineration. Portable units of all three kinds can be brought to the facility. Electropolishing and vibratory finishing will be particularly effective if many small components are to be decontaminated and either made available for reuse in another test facility or recycled for other industrial uses. Incineration will be effective if there are particularly large volumes of combustible radwastes that must be removed.

In addition, increased use of modular-constructed shield walls and roof slabs would allow for more effective removal of contaminated equipment during decommissioning. Also, it is suggested that a standard decommissioning close-out data sheet be required to be completed about the same time as the final radiation survey. The proposed standard format should include decommissioning data in sufficient detail to be of subsequent benefit to other R&T reactor licensees whose facilities may be similar in part or in whole. Thus, it would provide the framework for an information data base upon which confident planning and preparation for future R&T reactor decommissioning could be accomplished.

REFERENCES

1. G. J. Konzek, "Optimization of Costs Versus Radiation Exposures in Decommissioning," Decontamination and Decommissioning of Nuclear Facilities, Proceedings of the American Nuclear Society Topical Meeting in Sun Valley, Idaho, September 16-20, 1979. Plenum Press, 1980.

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

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

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

5. A. H. Schilling, H. W. Lippek, P. D. Tegeler and J. D. Easterling, Decommissioning Commercial Nuclear Facilities: A Review and Analysis of Current Regulations, NUREG/CR-0671, U.S. Nuclear Regulatory Commission Report by Pacific Northwest Laboratory, August 1979.

6. Final Elk River Reactor Program Report, United Power Association, Elk River, Minnesota, 55330, November 1974.

7. R. P. Allen, H. W. Arrowsmith, L. A. Charlot and J. L. Hooper, Electropolishing as a Decontamination Process: Progress and Applications, PNL-SA-6858, Pacific Northwest Laboratory, April 1978.

8. M. W. McCoy, H. W. Arrowsmith and R. P. Allen, Vibratory Finishing as a Decontamination Process, Pacific Northwest Laboratory, PNL-3336, October 1980.

15.0 IMPACTS OF ALTERNATE STUDY BASES

In two previous studies on the decommissioning of commercial nuclear power reactors,[1,2] the impacts on cost and/or radiation dose of different plant sizes, increased radiation levels, different contractual arrangements, increased waste disposal costs, and different plant designs were examined. The impact on the total costs from decommissioning contaminated ancillary facilities was discussed previously in Section 13 for the reference test reactor. Proportionately, similar impacts could be expected on the total costs of decommissioning research reactors, depending on the type and number of contaminated ancillary facilities. Consequently, it is anticipated that the diversity of designs among licensed research and test (R&T) reactors precludes any reasonable scaling analysis based solely on authorized power level. Each particular class of reactor tends to be rather unique and scaling of costs across classes, based on authorized power level, cannot be accomplished in any meaningful way. Therefore, only increased radiation levels, different contractual arrangements, and increased waste disposal costs are readily amenable to examination for this study on R&T reactors.

15.1 IMPACT OF INCREASED RADIATION DOSE RATES

The design and the methods of operation of the reference research reactor are such that it is difficult to conceive of any way to significantly increase radiation dose rates estimated for decommissioning, barring fuel failures. In any case, it is expected that if continued operation of the reactor was planned, immediate cleanup would take place after a fuel failure. The subsequent impact on decommissioning could be expected to be positive, since the documented cleanup experience would be invaluable when formulating the facility decommissioning plan.

For the reference test reactor, again barring fuel failures, the most likely source for increased radiation dose rates is from increased deposition of activated corrosion products within the reactor coolant system. The assumption is made that the radiation dose rates from the reactor coolant piping, pumps, and

heat exchangers are greater than those postulated in Appendix I by a factor of three. Thus, those tasks listed in Table I.2-20 in Appendix I involving the reactor coolant system result in cumulative radiation doses that are increased by a factor of three. The cumulative radiation dose for the Reactor Building is increased by 8.4 man-rem, for the Primary Pump House by 55.0 man-rem, and for the Waste Handling Building by 3.6 man-rem, for a total increase of 67 man-rem, or about 21%. Based on the 106.3 man-years of direct staff labor given in Table I.2-6, the average annual dose to decommissioning workers is slightly over 3 rem. Increasing the cumulative dose by 67 rem raises the average annual dose to about 3.7 rem, still well below the 5 rem annual dose limit. Therefore, it is concluded that an increase in the radiation dose rates associated with the components of the reactor coolant system would have little impact on the decommissioning activities at the reference test reactor.

15.2 SENSITIVITY OF DECON COSTS TO DIFFERENT CONTRACTUAL ARRANGEMENTS

The effect on cost of using a decommissioning contractor to perform the decontamination and dismantlement tasks associated with DECON was examined for a large PWR[1] and a large BWR[2] in previous studies. The principal cost impacts involved increased direct labor overhead charges, the contractor's fee applied to direct labor and materials, and the mobilization/demobilization costs.

The staff labor costs estimated for the reference test reactor for DECON are listed in Table 15.1-1. The total work force is divided into Management and Support Staff from the owner's organization, and Contractor Staff. The principal impact is from a change in the overhead rates applied to the contractor labor, from 50% to 110% for nonsupervisory staff and from 70% to 110% for supervisory staff. Estimated labor costs are shown for both the owner-only approach and for the Owner-Contractor approach. The increased overhead rates increases the estimated labor costs from $8.63 million to $10.91 million, about 26%. The total estimated costs for DECON of the reference test reactor using the Owner-Only approach and the Owner-Contractor approach are shown in Table 15.1-2. Application of the contractor's 15% fee to the cost of equipment and supplies purchased during DECON as well as to the contractor labor and

TABLE 15.1-1. Estimated DECON Staff Labor Costs for the Reference Test Reactor Using the Owner-Only Approach and the Owner-Contractor Approach

Position	Staff Labor[b] (man-years)	Staff Labor Costs[a] ($ thousands) Owner-Only[c]	Owner-Contractor[d]
Management and Support Staff			
Decommissioning Superintendent	3.8	338.7	338.7
Secretary	10.0	242.0	242.0
Clerk	5.5	133.1	133.1
Contracts and Accounting Specialist	3.8	179.1	179.1
Control Room Operator	10.0	345.0	345.0
Industrial Safety Specialist	3.5	183.5	183.5
Quality Assurance Supervisor	3.8	198.4	198.4
Quality Assurance Engineer	3.7	173.6	173.6
Quality Assurance Technician	4.9	136.3	136.3
Consultants (Safety Review Committee)	2.0	200.0	200.0
Subtotals, Management and Support Staff	51.0	2 129.7	2 129.7
Contractor Staff			
Decommissioning Engineer	4.5	342.0	422.4
Assistant Decommissioning Engineer	4.1	214.9	265.4
Shift Engineer	7.2	375.9	464.2
Crew Leader	11.5	510.6	714.8
Utility Operator	25.6	821.8	1 150.5
Laborer	14.4	445.0	623.0
Craft Supervisor	4.7	220.5	272.3
Craftsman	26.0	834.6	1 168.4
Protective Equipment Attendant	4.2	116.8	163.5
Tool Crib Attendant	4.2	116.8	163.5
Security Supervisor	2.1	117.4	164.4
Security Shift Supervisor	10.2	371.3	458.6
Security Patrolman	28.4	721.4	1 010.0
Radioactive Shipment Specialist	3.1	121.9	170.7
Procurement Specialist	3.4	133.7	187.2
Clerk	3.5	84.7	118.6
Health and Safety Supervisor	4.5	269.1	332.3
Health Physicist	2.7	126.7	156.5
Senior Health Physics Technician	5.2	204.4	286.2
Health Physics Technician	11.7	351.0	491.4
Subtotals, Contractor Staff	181.2	6 500.5	8 783.9
Totals	232.2	8 630.2	10 913.6

(a) The number of figures shown is for computational accuracy and does not imply precision to the nearest $100.
(b) Data from Table I.2-6.
(c) Calculated as the product of the data given in the staff labor column and the corresponding salary data given in Table M.1-1 in Appendix M; rounded to next higher $100.
(d) Contractor labor costs are increased to reflect an overhead rate of 110%.

TABLE 15.1-2. Estimated DECON Costs for the Reference Test Reactor Owner-Only Approach or Owner-Contractor Approach

Cost Category	Costs ($ millions)[a,b] Owner-Only	Owner	Contractor
Disposal of Radioactive Materials	2.085	2.085	--
Shipping Containers	0.487	--	0.487
Staff Labor	8.63	2.130	8.784
Energy	0.076	0.076	--
Special Tools and Equipment	0.361	--	0.361
Miscellaneous Supplies	0.203	--	0.203
Speciality Contractors	0.616	--	0.616
Mobilization/Demobilization	--	--	0.546
Subtotal	12.458	4.291	10.997
Contractor Fee (15%)			1.650
			12.647
Total Contractor Costs			
Subtotals	12.458	16.938	
Contingency (25%)	3.115	4.235	
Total, DECON Costs	15.573	21.173	
Other Possible DECON Costs			
Spent Fuel Shipment	0.204		
Facility Demolition and Site Restoration	2.289		
Subtotal	2.493		
Contingency (25%)	0.623		
Total, Other Possible Costs	3.116		

(a) Costs are in 1981 dollars.
(b) The number of figures shown is for computational accuracy and does not imply precision to the nearest $1000.

specialty contractor costs is illustrated in the table, together with an estimate of the mobilization/demobilization costs for the decommissioning prime contractor. Using the Owner-Contractor approach results in an increase in the estimated costs from $15.57 million to $21.17 million, or about 36%.

15.3 SENSITIVITY OF DECON COSTS TO WASTE DISPOSAL CHARGES

During the past 4 years, the charge per unit volume for burial in a licensed burial ground has increased by over a factor of three. It is likely that these charge-rates will continue to increase as operating costs increase and as projected decommissioning costs for burial grounds become better defined.

Review of Tables I.2-9 through I.2-13 shows that burial costs comprise 12.5% of the estimated cost of DECON for the reference test reactor. Thus, for every 1% increase in the burial charge, the cost of DECON will increase 0.125%.

REFERENCES

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

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

16.0 GLOSSARY

Abbreviations, acronyms, symbols, terms, and definitions directly related to licensed research and test reactor facilities decommissioning are defined and explained in this section. The section is divided into two parts, with the first part containing abbreviations, acronyms, symbols and an SI (international system of units) conversion table, and the second part containing terms and definitions (including those used in special context for this study). Common terms covered adequately in standard dictionaries and commonly used chemical symbols are not included.

16.1 ABBREVIATIONS, ACRONYMS, SYMBOLS, AND SI UNITS

Abbreviations and Acronyms

AEC	Atomic Energy Commission
AGN	Aerojet General Nucleonics
ALARA	As Low As Reasonably Achievable[a]
ANSI	American National Standards Institute
CRF	Code of Federal Regulations
Ci	Curie[a]
cpm	Counts Per Minute(a, Count Rate)
CS	Carbon Steel
DF	Decontamination Factor[a]
DOE	Department of Energy
DOT	Department of Transportation
dpm (or d/m)	Disintegrations per Minute(a, Disintegration Rate)
EC	Electron Capture[a]
EFPY	Effective Full Power Year(s)

(a) See Section 16.2 for additional information or explanation.

EPA	Environmental Protection Agency
ERDA	Energy Research and Development Administration
FSAR	Final Safety Analysis Report
GEIS	Generic Environmental Impact Statement
Ge(Li)	Germanium-Lithium (detector)[a]
G-M	Geiger-Muller (detector)[a]
GVW	Gross Vehicle Weight
HEPA	High Efficiency Particulate Air (filter)[a]
HP	Health Physicist
HTO	Tritiated Water[a]
HVAC	Heating, Ventilation and Air Conditioning
IB	Inner Bremsstrahlung[a]
ICRP	International Commission on Radiological Protection
INEL	Idaho National Engineering Laboratory
kWt	Kilowatt, thermal
LLD	Lower Limit of Detection
LWR	Light Water Reactor
MeV	Million Electron Volts[a]
MPC	Maximum Permissible Concentration
mR	Milliroentgen, see also R (Roentgen)
mrad	Millirad, see also rad
mrem	Millirem, see also rem
MUF	Material Unaccounted For
MUR	Mock-Up Reactor

(a) See Section 16.2 for additional information or explanation.

MWe	Megawatts, electric
MWt	Megawatts, thermal
NASA	National Aeronautics and Space Administration
NaI	Sodium Iodide (detectors)
NRC	Nuclear Regulatory Commission
OSHA	Occupational Safety and Health Administration
OSTR	Oregon State TRIGA Reactor
PBRF	Plum Brook Reactor Facility
QA	Quality Assurance
QC	Quality Control
R	Roentgen[a]
rad[a]	Radiation Absorbed Dose
rem[a]	Roentgen Equivalent Man
SNM	Special Nuclear Material[a]
SS	Stainless Steel
TRIGA	Training, Research, Isotope Production, General Atomic Company

Symbols

α	Alpha Radiation[a]
β	Beta Radiation[a]
H^3	Tritium[a]
γ	Gamma Radiation[a]
χ	Chi, concentration (Ci/m^3)
Q	Released Quantity of Radioactive Material (Ci)
Q'	Release Rate of Radioactive Material (Ci/sec)

(a) See Section 16.2 for additional information or explanation.

x/Q' Chi-bar/Q prime, normalized average air concentration (Ci/m^3 per Ci/sec released, also written sec/m^3). Also called the annual average atmospheric dilution factor.

SI Units

SI units for use with radioactivity and ionizing radiations are as follows:

Quantity	New Named Unit and Symbol	In Other SI Units	Old Special Unit and Symbol	Relationship New to Old Units
Exposure	---	coulomb/kg (C/kg)	roentgen (R)	1 C/kg ≈ 3876 R
Absorbed Dose	gray (Gy)	joule/kg (J/kg)	rad (rad)	1 Gy = 100 rad
Dose Equivalent	sievert (Sv)	J/kg	rem (rem)	1 Sv - 100 rem
Activity	becquerel (Bq)	$seconds^{-1}$ (s^{-1})	curie (Ci)	1 Bq ≈ 2.70×10^{-11} Ci

16.2 GLOSSARY DEFINITIONS

A: See Mass Number.

Abnormal Environmental Occurrence: An event that 1) results in noncompliance with, or is in violation of, an environmental technical specification, or 2) results in uncontrolled or unplanned releases of chemical, radioactive, or other discharges in excess of federal, state, or local regulations. (See Technical Specifications.)

Acceptable Residual Radioactive Contamination Levels: Those levels of radioactive contamination remaining at a decommissioned facility or on its site that are acceptable to the NRC for termination of the facility operating license and unrestricted release of the site.

Activity: Sometimes used for the term "radioactivity." (See Radioactivity.)

Adsorption: Adhesion of ions or molecules to the surface of liquids or solid bodies with which they come in contact, adhering to a surface.

Agreement State: A state that has entered into an agreement with the NRC that transfers to the state regulatory responsibility

for byproduct material, source material, and quantities of special nuclear material insufficient to form a critical mass.

Airborne Radioactive Material: Radioactive particulates, mists, fumes, and/or gases in air.

Airborne Releases: The amount of a material of interest dispersed into the air inside a building.

ALARA: An operating philosophy to maintain exposure to ionizing radiation As Low As is Reasonably Achievable.

Alpha Decay: Radioactive decay in which an alpha particle is emitted. This transformation lowers the atomic number of the nucleus by two and its mass number by four.

Alpha Emitter: A radionuclide that characteristically undergoes transformation by emission of alpha particles.

Alpha Particle: A positively charged particle emitted by certain radioactive materials. It is made up of two neutrons and two protons; hence it is identical with the nucleus of a helium atom. It is the least penetrating of the three common types of radiation (alpha, beta, and gamma) emitted by radioactive material.

Anticontamination Clothing: Special clothing worn in a radioactively contaminated area to prevent personal contamination.

Atmospheric Release: The amount of a material of interest released to the atmosphere.

Atomic Number (Z): The number of protons in the nucleus of an atom; also its positive charge. Each chemical element has its characteristic atomic number, and the atomic numbers of the known elements form a complete series from 1 (hydrogen) through 105 (hahnium).

Background: Radiation originating from sources other than the source of interest (i.e., the reactor facility). Background radiation includes natural radiation (e.g., cosmic rays and radiation from naturally radioactive elements), as well as man-made radiation (e.g., fallout from atmospheric weapons testing).

Beta Decay: Radioactive decay in which a beta particle is emitted. This transformation changes only the atomic number of

the nucleus, raising or lowering the atomic number (Z) by one for emission of a negative or positive beta particle, respectively.

Beta Emitter: A radionuclide that characteristically undergoes transformation by emission of beta particles.

Beta Particle: An electron, of either positive or negative charge, that has been emitted by an atomic nucleus in a nuclear transformation.

Burial Ground: An area specifically designated for shallow subsurface disposal of solid radioactive wastes to temporarily isolate the waste from man's environment.

Byproduct Material: Any radioactive material (except source material and special nuclear material) obtained during the production or use of source or special nuclear material. Byproduct material includes fisson products and other radioisotopes.

Cask: A tightly sealing, heavily shielded, reusable shipping container for radioactive materials.

Cask Liner: A tightly sealing, disposable metal container used inside a cask for shipping radioactive materials.

Chelating Agent: A complexing agent that forms chelates. A chelating agent has two or more groups that attach to a single ion to form a stable (usually 5- or 6-member) ring. Organic chelating agents are compounds containing carbon, hydrogen, nitrogen, and oxygen.

Chemical Limits: Maximum chemical concentrations or quantities imposed upon gaseous or liquid effluents discharged from a facility to the environment, and consistent with known air- and water-quality standards.

Code of Federal Regulations (CFR): 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.

Complexing Agent: A chemical that combines with some ion to form a stable compound that no longer behaves like the original ion. The usual result of the complexing process is to increase the mobility of the complexed ion.

Contact Maintenance: "Hands-on" maintenance, or maintenance performed by direct contact of personnel with the equipment. Typically, most nonradioactive maintenance is contact maintenance.

Contamination: Undesired (e.g., radioactive or hazardous) material that is deposited on the surface of, or internally ingrained into, structures or equipment, or that is mixed with another material.

Contamination, Fixed: Radioactivity remaining on a surface after repeated decontamination attempts fail to significantly reduce the contamination level. Survey meter readings made on the surface generally indicate the level of fixed contamination.

Contamination, Removable: That fraction of the radioactive contamination present on a surface that can be transferred to a smear test paper by rubbing with moderate pressure.

Continuing Care Period: The surveillance and maintenance phase of safe storage or entombment, with the facility secured against intrusion.

Count Rate: The measured rate of the detection of ionizing events using a specific radiation detection device.

Curie: A unit of radioactivity, abbreviated Ci. One curie equals 3.7×10^{10} nuclear transformations per second. Several fractions of the curie are in common usage:

- Millicurie, abbreviated mCi. One-thousandth of a curie (3.7×10^{7} d/s).
- Microcurie, abbreviated μCi. One-millionth of a curie (3.7×10^{4} d/s).
- Nanocurie, abbreviated nCi. One-billionth of a curie (37 d/s).
- Picocurie, abbreviated pCi (replaces the term μμCi). One-millionth of a microcurie (0.037 d/s).

Decay, Radioactive: A spontaneous nuclear transformation in which charged particles and/or gamma radiation are emitted.

Decommissioning: The measures taken following a nuclear facility's operating life to safely remove the property from radioactive service and to dispose of radioactive materials.

The level of any residual radioactivity remaining on the property after decommissioning must be low enough to allow unrestricted use of the property.

DECON:	A decommissioning alternative that involves the immediate removal of all radioactive materials down to levels which are considered acceptable to permit the property to be released for unrestricted use.
Decontamination:	The removal of radioactivity from structures, equipment, or material by chemical and/or mechanical means.
Decontamination Agents:	Chemical or cleansing materials used to effect decontamination.
Decontamination Factor (DF):	The ratio of the initial amount (i.e., concentration or quantity) of an undesired material to the final amount resulting from a treatment process.
Deep Geologic Disposal:	Placement of radioactive materials in stable geologic formations far beneath the earth's surface, to isolate them from man's environment.
Design Basis Accident:	A postulated accident believed to have the most severe expected impacts on a facility. It is used as the basis for design and safety analysis.
Detergent:	A synthetic cleansing agent that resembles soap in its ability to emulsify oil and hold dirt in solution, and that contains surface active agents (surfactants) that do not precipitate in hard water.
Discount Rate:	The rate of return on capital that could be realized in alternative investments if the money were not committed to the plan being evaluated (i.e., the opportunity cost of alternative investments), equivalent to the weighted average cost of capital.
Disintegration, Nuclear:	The spontaneous (radioactive) transformation of an atom of one element to that of another, characterized by a definite half-life and the emission of particles or radiation from the nucleus of the first element.
Disintegration Rate:	The rate at which disintegrations (i.e., nuclear transformations) occur, in events per unit time (e.g., disintegrations per minute [dpm]).
Dismantlement:	Those actions required to disassemble and remove sufficient radioactive or contaminated material from a facility to permit release of the property for unrestricted use.

Dispersion: A process of mixing one material within a larger quantity of another, causing the first material to be diluted (i.e., reduced in concentration). For example, material released to the atmosphere is dispersed in (mixed with) air, reducing the released material's concentration with distance from the source.

Disposal: The disposition of materials with the intent that they will not enter a man's environment in sufficient amounts to cause a significant 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 ionizing radiation that is effective in the human body, in units of rems. Modifying factors associated with human tissue and body are taken into account. Equivalent dose is the product of absorbed dose, a quality factor, and a distribution factor. Referred to as Dose in this study.

Dose, Occupational: An individual's exposure to ionizing radiation (above background) as a result of his employment, expressed in rems.

Dose, Radiation: As commonly used, the quantity of radiation absorbed in a unit mass of a medium, frequently a human organ, expressed in rems.

Dose Rate: The radiation dose delivered per unit time, expressed in units of rems per hour.

Dosimeter: A device, such as a film badge or an ionization chamber, that measures radiation dose.

Electron Capture (EC): The capture of an orbital electron by the radioactive nucleus of an atom. This transformation decreases the atomic number of the nucleus by one.

Electron Volt: A unit of energy equal to the work done by the electric field when a charge of one electronic charge unit moves through a difference of potential of one volt. One electron volt (eV) equals 1.6×10^{-19} joules.

ENTOMB: A decommissioning alternative that involves the encasement and maintenance of property in a strong and structurally long-lived material (e.g., concrete) to assure retention until radioactivity decays to a level acceptable for releasing the facility for unrestricted use.

Environmental Surveillance: A program to monitor the impact of discharges from industrial operations on the surrounding region. As used in this study, it is the program to monitor the extent and consequences of releases of radioactivity or chemicals from the nuclear power plant.

Exhumation: The process of removing buried waste from the earth by digging.

Exposure: A measure of the ionization produced in air by x-ray 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 air in the volume element. The special unit of exposure is the roentgen. (See Roentgen.)

Facility: The physical complex of buildings and equipment on a research or test reactor plant site.

Fission: The splitting of a heavy atomic nucleus into two or more nearly equal parts (nuclides of lighter elements), accompanied by the release of a relatively large amount of energy and (generally) one or more neutrons. Fission can occur spontaneously, but usually it is caused by nuclear absorption of gamma rays, neutrons, or other particles.

Fission Products: The lighter atomic nuclides (fission fragments) formed by the fisson of heavy atoms. It also refers to the nuclides formed by the fission fragments' radioactive decay.

Food Chain: The pathways by which any material (such as radioactive material) passes through the environment through edible plants and/or animals to man.

Fuel Assembly: As used in this study, a single fuel rod or bundle of fuel rods (tubes containing nucler fuel) housed in a fixed geometry (e.g., in a metal channel or lattice plate(s).

Fuel Cycle: The series of steps involved in supplying fuel for nuclear reactors, handling the spent fuel and the radioactive waste, including transportation.

Fume Hood:	Ventilated containment space, enclosed on five sides, with the sixth side covered by a movable glass or plastic window to allow access and to maintain sufficient inflow or air and splash control to protect the worker from the hazardous materials handled inside.
Gamma Rays:	Short-wavelength electromagnetic radiation. Gamma radiation frequently accompanies alpha and beta emissions and always accompanies fission. Gamma rays are very penetrating and are best stopped or shielded against by dense materials such as lead or uranium. The rays are similar to x-rays, but are nuclear in origin, i.e., they originate from within the nucleus of the atom.
Gaseous:	Material in the vapor or gaseous state, but can include entrained liquids and solids.
Geiger-Muller (G-M) Detector:	A gas-filled tube used as a detector of beta particles and gamma rays. The tube acts as an ionization chamber and produces a voltage pulse each time an energetic particle or gamma photon deposits energy in the tube.
Germanium Lithium [Ge(Li)] Detector:	A solid-state detector of gamma radiation. The detector produces a voltage pulse proportional to the energy dissipated by the gamma photon in the germanium crystal.
Glove Box:	A box, usually made of stainless steel and large panes of glass or transparent rigid plastic, in which workers using gloves attached to, sealed, and passing through openings in the box can safely handle radioactive materials from the outside by inserting their hands into the gloves and manually performing manipulations.
Greenhouse:	In nuclear terms, a temporary structure, frequently constructed of wood and plastic, used to provide a confinement barrier between a radioactive work area and a nonradioactive area.
Half-Life, Biological:	The time required for a biological system (such as a man or animal) to eliminate, by natural processes, half the amount of a substance (such as a radioactive material) that it has absorbed.
Half-Life, Effective:	The time required for radioactivity contained in a biological system (such as a man or animal) to be reduced by half as a combined result of radioactive decay and biological elimination.
Half-Life, Radioactive:	The time in which half the atoms of a particular radioactive substance disintegrate to another 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 operating procedures for minimizing radiation exposures.
High Efficiency Particulate Air (HEPA) Filter	An air filter generally rated as being capable of removing at least 99.97% of the particulate material in an air stream.
High-Level Waste:	Radioactive waste from the first-cycle solvent extraction (or equivalent) during spent nuclear fuel reprocessing. Also applied to other concentrated wastes of various origins.
Hood:	See Fume Hood.
Hot Cell:	A heavily shielded enclosure in which radioactive materials can be viewed through shielding windows and handled remotely with manipulators to limit exposure to operating personnel.
Hot Spot:	An area of radioactive contamination of higher than average concentration.
HTO:	Chemical symbol for a molecule of water in which one of the ordinary hydrogen atoms has been replaced by an atom of tritium (tritiated water).
Immobilization:	Treatment and/or emplacement of materials (e.g., radioactive contamination) so as to impede their movement.
Inhibitor:	A chemical added to an acid wash solution to inhibit the corrosion reaction. Inhibitors are usually organic polar compounds having a carbon chain or ring with hydrogen atoms attached, and a polar group such as amino (NH_2^-), sulfonic (SO_3^-), or carboxy (CO_2^-).
Inner Bremsstrahlung:	Secondary electromagnetic radiation produced by deacceleration of charged particles passing through matter.
Intrusion Alarm:	A security device that detects intrusion into a protected area and initiates a visible and/or audible alarm signal.
Ion Exchange:	A chemical process involving the selective adsorption or desorption of certain chemical ions in a solution onto a chemical compound or solid material.

Isotope: Any of two or more forms of an element having the same or very closely related chemical properties but different radioactive properties. Isotopes of an element have the same atomic number but different atomic weights.

Kilohertz (kHz): A unit of frequency equal to one thousand vibrations per second.

Laboratory: A type of facility used for experimentation, observation, or practice in a particular field of study. The term "laboratory" is used broadly in this document to include parts of manufacturing facilities, research facilities, and academic or medical institutions.

License: Written authorization issued to the research or test reactor licensee by the NRC to perform specific activities related to the possession and use of byproduct, source, or special nuclear material.

Licensed Material: Byproduct material, source material, or special nuclear material received, possessed, used, or transferred under a license issued by the NRC or a state regulatory agency.

Licensee: The holder of a license issued by the NRC or a state regulatory agency to perform specific activities related to the possession and use of byproduct, source, or special nuclear material.

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.

Long-Term Care: The period following initial decommissioning activities during which institutional control of a facility or site is maintained. Activities performed during this period include environmental monitoring and routine surveillance and maintenance.

Low-Level Waste: Waste containing low but not hazardous quantities of radionuclides and requiring little or no biological shielding; low-level waste generally contains no more than 10 nanocuries of transuranic material per gram of waste.

Man-rem: Used as a unit measure of population radiation dose, 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 implied.

Mass Number (A): The number of nucleons (protons and neutrons) in the nucleus of a given atom.

Maximum-Exposed Individual: The hypothetical member of the public who receives the maximum radiation dose to an organ of reference. For the common case where exposure from airborne radionuclides result in the highest radiation exposure, this individual resides at the location of the highest airborne radionuclide concentration and eats food grown at that location.

Maximum Permissible Concentration (MPC): The average concentrtion of a radionuclide in air or water to which an individual may be continuously exposed without exceeding an established standard of radiation dose limitation.

MeV: Million electron Volts. One MeV is equal to 1.6×10^{-13} joules.

Monitoring: Making measurements or observations so as to recognize the status or adequacy of, or significant changes in, conditions or performance of a facility or area.

Neutron Source: Any material, combination of materials, or device that emits neutrons, including materials undergoing fission.

Normal Operating Conditions: Operation (including startup, shutdown, and maintenance) of systems within the normal range of applicable parameters.

Nuclear Reaction: A reaction involving a change in an atomic nucleus, such as fission, fusion, particle capture, or radioactive decay.

Nuclear Reactor: Any apparatus, other than an atomic weapon, designed or used to sustain nuclear fission in a self-supporting chain reaction. (See 10 CFR 140.3(f) and 10 CFR 170.3(d).)

Experimental Reactor: A reactor operated primarily to obtain reactor physics or engineering data for the design or development of a reactor or type of reactor. Reactors in this class include: zero-power reactor (may also be a research reactor), reactor experiment, and prototype reactor.

Heterogeneous Reactor:	A reactor in which the core materials are segregated to such an extent that its neutron characteristics cannot be accurately described by the assumption of homogeneous distribution of the materials throughout the core.
Homogeneous Reactor:	A reactor in which the core materials are distributed in such a manner that its neutron characteristics can be accurately described by the assumption of homogeneous distribution of the materials throughout the core.
Irradiation Reactor:	A reactor used primarily as a source of nuclear radiation for irradiation of materials or for medical purposes. Reactor types in this class include: isotope-production reactor, food-irradiation reactor, chemonuclear reactor, materials processing reactor, biomedical irradiation reactor, and materials testing reactor (may also be a research reactor).
Materials Processing Reactor:	A reactor employed for the purpose of changing the physical characteristics of materials by utilizing the reactor-generated ionizing radiation. Such characteristics may be color, strength, elasticity, dielectric qualities, etc. (See nuclear reactor, irradiation.)
Materials Testing Reactor:	A reactor employed for testing materials and reactor components in intense radiation fields.
Pool Reactor:	A reactor whose fuel elements are immersed in a pool of water which serves as moderator, coolant, and biological shield. (Also called swimming pool reactor.)
Pressurized Reactor:	A reactor whose primary liquid coolant is maintained under such a pressure that no bulk boiling occurs.
Pressurized-Water Reactor:	A reactor whose primary coolant, water, is maintained under such a pressure that bulk boiling does not occur.
Prototype Reactor:	A reactor that is the first of a series of the same basic design. Sometimes used to denote a reactor having the same essential features but of a smaller scale than the final series.
Pulsed Reactor:	A reactor designed to produce intense bursts of neutrons for short intervals of time.
Research Reactor:	A reactor used for scientific, engineering, or training purposes which operates at: 1. A thermal power level of 1 megawatt or less; or 2. A thermal power level of 10 megawatts or less and does not contain:

a. A flow loop through the core in which fueled experiments are conducted; or
b. A liquid fuel loading; or
c. An experimental facility in the core in excess of 16 in.^{2} (103.2 cm^2) in cross-section.

Test Reactor: A testing facility (i.e., a test reactor) is a nuclear reactor licensed for operation at:

1. A thermal power level in excess of 10 megawatts; or
2. A thermal power level in excess of 1 megawatt, if the reactor is to contain:
   a. A circulating loop through the core in which the licensee plans to conduct fueled experiments; or
   b. A liquid fuel loading; or
   c. An experimental facility in the core in excess of 16 in.^{2} (103.2 cm^2 in cross-section).

Packaging: The assembly of radioactive material in one or more containers and other components as necessary to ensure compliance with applicable regulations.

Possession-only License: An amended operating license issued by the NRC to a nuclear facility owner entitling the licensee to own but not operate the facility.

Power Reactor: A nuclear reactor used to provide steam for electrical power generation.

Present Value of Money: The present value of a future stream of costs is the present investment necessary to secure or yield the future stream of payments, with compound interest at a given discount or interest rate. Inflation can be taken into account in this calculation.

Protective Survey: See Radiation Survey.

Offsite: Beyond the boundary line marking the limits of plant property.

Onsite: Within the boundary line marking the limits of plant property.

Operable: Capable of performing the required function.

Overpack: Secondary (or additional) external containment or cushioning for packaged nuclear waste that exceeds certain limits imposed by regulation.

Package: The packaging plus the contents of radioactive materials.

Quality Assurance: The systematic actions necessary to provide adequate confidence that 1) a material, component, system, process, or facility performs satisfactorily or as planned in service, or 2) that work is performed according to plan.

Quality Control: The quality assurance actions that control the attributes of the material, process, component, system, facility, or work in accordance with predetermined quality requirements.

Rad: The unit of absorbed dose. The energy imparted by ionizing radiation to a unit mass of irradiated material at the place of interest. One rad equals 0.01 joules/kilogram.

Radiation: 1) The emission and propagation of radiant energy: for instance, the emission and propagation of electromagnetic waves or photons. 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 a dose in excess of 5 millirem in any one hour, or a dose in excess of 100 millirem in any 5 consecutive days. (See 10 CFR 20.202).

Radiation Survey: An evaluation of radiation and associated 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. Also called protective survey.

Radioactive Material: Any material or combination of materials that spontaneously emits ionizing radiation and has a specific activity in excess of 0.002 microcuries per gram of material. (See 49 CFR 173.389(e).)

Radioactive Series: A succession of nuclides, each of which transforms by radioactive disintegration into the next until a stable nonradioactive nuclide results. The first member is called the "parent," the intermediate members are called "daughters," and the final stable member is called the "end product."

Radioactivity: The property of certain nuclides of spontaneously transforming to other nuclides by emitting particles and/or gamma radiation. Also used to describe the number of

nuclear transformations occurring in a given quantity of material per unit time. Often shortened to "activity."

Radioactivity, Artificial: Man-made radioactivity produced by particle bombardment or electromagnetic irradiation, as opposed to natural radioactivity.

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.

Radioactivity, Natural: Radioactivity exhibited by more than 50 naturally occurring radionuclides.

Radiochemical: A molecule or a chemical compound or substance containing one or more radioactive atoms.

Radioisotope: A radioactive isotope of a chemical element. Each radioisotope decays with a characteristic half-life and with the emission of characteristic radiation.

Radiological Protection: Protection against the effects of internal and external human exposure to ionizing radiation and radioactive materials.

Reactor: See Nuclear Reactor.

Reactor Vessel: The principal vessel surrounding at least the reactor core.

Reagent: A chemical substance used to detect or measure another substance or to convert one substance into another by means of the chemical reaction that it causes.

Reflector: A material or a body of material which reflects incident radiation. In nuclear reactor technology, this term is usually restricted to designate part of a reactor placed adjacent to the core to scatter some of the escaping neutrons back into the core.

Regulatory Guides: Documents that describe and make publicly available 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 may be acceptable if they provide a basis for the findings requisite to the issuance or continuance of a permit or license by the NRC. (Government agencies other than the NRC have regulatory guides pertaining to nonnuclear matters.)

Rem: A unit of radiation dose equivalent. The dose equivalent in rem is numerically equal to the absorbed dose in rad 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. Used in the nuclear industry to reduce the occupational radiation doses to maintenance personnel.

Reporting Levels: Those levels or parameters called out in the environmental technical specifications, the dismantling order, and/or the possession-only license that do not limit decommissioning activities, but that may indicate a measurable impact on the environment.

Repository (Federal): A site owned and operated by the federal government for long-term storage or disposal of radioactive materials.

Research Reactor: See Nuclear Reactor, Research.

Restricted Area: Any area to which access is controlled for protection of individuals from exposure to ionizing radiation and radioactive materials.

Roentgen(R): The 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 Exposure.)

Roughing Filter: A prefilter with high efficiency for large particles and fibers but low efficiency for small particles. Usually used to protect a subsequent HEPA filter from high dust concentration.

SAFSTOR: A decommissioning alternative that involves those activities required to place (preparations for safe storage) and maintain (safe storage) a radioactive facility in such condition that the risk to safety is within acceptable bounds and that the facility can be safely

	stored for as long a time as desired. SAFSTOR is completed by subsequently decontaminating the facility to levels which permit release of the facility for unrestricted use (deferred decontamination).
Sealed Source:	Any radioactive material that is encased in a capsule designed to prevent leakage or escape of the radioactive material.
Scintillation Detector:	A crystal of phosphor used to detect ionizing radiation by the flash of light (scintillation) produced when the radiation enters the crystal. The crystal is normally coupled with a photomultiplier tube that detects and measures the scintillation.
Shield:	A body of material used to reduce the passage of ionizing 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). A shield may be required to protect personnel or to reduce radiation enough to allow use of counting instruments.
Site:	The geographic area upon which the facility is located, subject to controlled public access by the facility licensee (includes the restricted area as designated in the NRC license).
Site Stabilization:	The use of engineered procedures to restrict the migration of stored radioactive waste or contaminated soil and to protect the waste or soil from the effects of potential transport mechanisms.
Sodium Iodide [NaI(Tl)] Detector:	A scintillation detector consisting of a thallium-activated sodium-iodide crystal optically coupled to a photomultiplier tube. Used to detect and measure gamma radiation.
Solid Radioactive Waste:	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.
Source Material:	Thorium, natural or depleted uranium, or any combination thereof. Source material does not include special nuclear material. (See 10 CFR 40.4(h).)

Special Nuclear Material (SNM): Plutonium, ^{233}U, uranium containing more than the natural abundance of ^{235}U, or any material artificially enriched with the foregoing substances. SNM does not include source material. (See 10 CFR 40.4(i).)

Surface Contamination: The deposition and attachment of radioactive materials to a surface. Also, the resulting deposits.

Surfactant: A contraction of the phrase "surface active agent." A compound that is added to a chemical cleaning solution to reduce the surface tension of a liquid. Surfactants are usually organic molecules having long carbon-carbon skeletons plus a polar group containing atoms of nitrogen, oxygen, or sulfur.

Surveillance: Those activities necessary to ensure that the site remains in a safe condition (includes periodic inspection and monitoring of the site, maintenance of barriers preventing access to radioactive materials remaining on the site, and prevention of activities that might impair these barriers).

Survey Meter: An instrument used to monitor the presence of radioactivity by detecting the radiation (alpha, beta, or gamma) emitted during radioactive decay.

Technical Specifications: Requirements and limits encompassing environmental and nuclear safety that 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 into the operating and/or possession-only license issued by the NRC.

Test Reactor: See Nuclear Reactor, Test.

Transport Mechanism: Any mechanism that results in the movement of radioactivity away from a site where it is intended to be confined. Examples include water or wind erosion, percolation of water through the soil, the burrowing of animals, or human activity such as farming or excavation.

Transuranic Elements: Elements with atomic number (Z) greater than 92.

Tritium: A radioactive isotope of hydrogen having mass number 3. It decays by emitting a low-energy beta particle.

Unrestricted Release: Release of property from regulatory control such that subsequent use is no longer restricted in any way.

Waste Management: The planning and execution of essential functions relating to radioactive wastes, including treatment, packaging, interim storage, transportation, and disposal.

Waste, Radioactive: Equipment and materials (from nuclear operations) that are radioactive and have no further use. Also called radwaste.

X-Ray: A penetrating form of electromagnetic radiation emitted either when the inner orbital electrons of an excited atom return to their normal state (characteristic x-rays) or when a metal target is bombarded with high-speed electrons. X-rays are always nonnuclear in origin (i.e., they originate external to the nucleus of the atom).

GENERAL REFERENCES

American National Standard Glossary of Terms in Nuclear Science and Technology, American Nuclear Society, Hinsdale, Illinois, 1976.

Glossary of Nuclear Industry Terms, Standards and Specifications, Atomic Power Equipment Department, General Electric Company, San Jose, California, September 1969.

McGraw-Hill Dictionary of Scientific and Technical Terms, McGraw-Hill, Inc., New York, New York, 1976.

Radiological Health Handbook, Public Health Service Publication No. 2106, Revised Edition, U.S. Government Printing office, Washington, D.C., January 1970.

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Safety and Cost Information is developed for the conceptual decommissioning of two representative licensed nuclear research and test reactors. Three decommissioning alternatives are studied to obtain comparisons between costs (in 1981 dollars), occupational radiation doses, potential radiation dose to the public, and other safety impacts. The alternatives considered are: DECON (immediate decontamination), SAFSTOR (safe storage followed by deferred decontamination), and ENTOMB (entombment). The study results are presented in two volumes. Volume 1 (Main Report) contains the results in summary form. Volume 2 (Appendices) contains the detailed data that support the results given in Volume 1, including unit-component data.

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