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DECOMMISSIONING HANDBOOK

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PREPARED FOR

U.S. Department of Energy

BY

Nuclear Energy Services, Inc.
Automation Industries

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DECOMMISSIONING HANDBOOK

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Prepared for

The U.S. Department of Energy
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ABSTRACT

This document is a compilation of information pertinent to the decommissioning of surplus nuclear facilities. It has been prepared by Nuclear Energy Services, Inc. for the U.S. Department of Energy. This handbook is intended to describe all stages of the decommissioning process including selection of the end product, estimation of the radioactive inventory, estimation of occupational exposures, description of the state-of-the-art in re decontamination, remote cutting of heavy metal components and structures, segmenting thick reinforced concrete structures, disposition of wastes, and estimation of program costs. Presentation of state-of-the-art technology and data related to decommissioning will aid in consistent and efficient program planning and performance. Particular attention is focused on available technology applicable to those decommisssioning activities that have not been accomplished before, such as remote segmenting and handling of highly activated 1100 MW(e) light water reactor vessel internals and thick-walled reactor vessels. Mechanical and torch cutting techniques are described, including recent developments in 'arc saw' technology. Applicability of the methods as a function of material composition, thickness, and configuration is discussed, cutting rates defined, and equipment and procedures described. Other pertinent factors covered include in-air and underwater applications, contamination control, and personnel protection. Similar information is presented for the fracturing, segmenting, and rebar cutting of thick concrete sections and for the removal of contaminated piping systems. A summary of available information associated with the planning and estimating of a decommissioning program is also presented. Summarized in particular are the methodologies associated with the calculation and measurement of activated material inventory, distribution, and surface dose level, system contamination inventory and distribution, and work area dose levels. Cost estimating techniques are also presented and the manner in which to account for variations in labor costs as impacting labor-intensive work activities is explained.

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CHAPTER 1

INTRODUCTION TO THE DECOMMISSIONING HANDBOOK

1.1 PURPOSE

The Decommissioning Handbook was conceived as a project under the Energy Research and Development Administration, now the Department of Energy (DOE), to develop a guide containing state-of-the-art information for the decommissioning of nuclear facilities. With the formation of DOE, the Handbook became the responsibility of the Surplus Facilities Management Program (SFMP), which is part of the Office of Remedial Actions under the Assistant Secretary Nuclear Energy, Office of Nuclear Waste Management. The primary function of SFMP is the safe management and decommissioning of DOE-owned surplus faciltities, and the Handbook fulfills an SFMP objective of making decommissioning technology available to the nuclear industry.

The objective of the Handbook is to bring, under one cover, information pertinent to the planning logic that must underlie a decommissioning program; descriptions of the mechanical and chemical processes available for decommissioning and presently considered state-of-the-art; and presentations of the factors and methods of assessing environmental impacts and the costs of decommissioning. In order for the document to have a broad range of usefulness, the technical coverage is intended to include the more complex considerations of removal and disposition of large light water reactor pressure vessels as well as treatment of contaminated systems and structures.

1.2 BACKGROUND

Decommissioning of both reactor and nonreactor nuclear facilities is under active consideration throughout the entire international community. The ultimate disposition of these facilities is being studied and evaluated for options ranging from in-situ protective storage to complete removal of the facility from the site. There is also active thought being given to the reuse of the facilities -

in some cases implying a perpetual dedication of the plant site to nuclear applications. This approach is also being considered for reactor plants whereby at the end of their design operating life certain components and equipment, for example those adversely affected by neutron bombardment, would be replaced and the facility recommissioned for further operation.

Perhaps the most significant area of thought pertaining to decommissioning is the active consideration being given to the subject in the plant design phase. It is apparent that design efforts are underway to reduce the volume occupied by plant facilities, reduce structural masses, improve facility access, and provide for better shielding of operators. The primary importance of many of these design changes is to enhance plant operation, while others are solely intended for facilitation of plant decontamination and removal. A recent conference in Paris, France addressed this topic.* Although many of the ideas presented have yet to reach the "drawing board," the attention given the subject by designers and plant owners bodes well for those concerned with the ultimate disposition of nuclear facilities.

There are a number of characteristics of nuclear facilities that introduce unique problems in the ultimate handling and disposition of plant equipment and structures. They include such construction features as extremely thick clad pressure vessels and heavily reinforced massive concrete structures; extensive radioactive contamination within systems and on structural surfaces; and, in the case of reactors, extremely high activation levels in the region of the nuclear core.

Although many nuclear facilities, including reactors, have been decommissioned, the large size of present-day reactors overshadows this experience. It is one of the aims of this handbook to provide basic information derived from proven experience to aid the designers, owners, and regulators of these facilities in developing confidence and direction towards the eventual accomplishment of decommissioning programs.

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* Organization for Economic Cooperation and Development (OECD) Nuclear Energy Agency (NEA) Specialist Meeting on Decommissioning Requirements in the Design of Facilities, Paris, France, March 17-19, 1980.

1.3 HANDBOOK ORGANIZATION

Chapters 2 and 3 address the planning stage in that they include a description of decommissioning alternatives and some thoughts on the logic of selecting a particular option.

Chapter 4 provides a methodology for estimation of the radioactive inventory in a nuclear facility. This is perhaps the most important preliminary activity in any decommissioning program since accurate knowledge of the residual nuclides as to composition, quantity, and distribution is imperative in preparing for detailed work activities as well as evaluating the adequacy of the end product and its associated protective storage structure. Quantitative estimation of both activation and contamination by-products is considered.

Chapters 5, 6, 7, and 8 present state-of-the-art summaries of the technologies available for plant decontamination, segmenting of activated metals, removal of large concrete structures, and removal of contaminated fluid systems.

Chapter 9 discusses the disposition of both the liquid and solid wastes generated by decommissioning programs.

Chapter 10 includes a qualitative discussion of the environmental impacts associated with decommissioning, and finally, Chapter 11 presents a detailed methodology for the preparation of decommissioning cost estimates.

It is hoped that the information presented in this document will be of some assistance to individuals who are addressing the decommissioning of nuclear facilities. We realize there are significant on-going programs which will be of direct value in expanding the information reservoir presented herein. It is intended that revised editions of the Handbook will be issued to accomodate this data.

CHAPTER 2

DESCRIPTION OF DECOMMISSIONING OPTIONS

2.1 INTRODUCTION

The ultimate disposition of a nuclear facility after cessation of operations will result in either (1) the retention of certain radioactive materials in-situ or (2), the transfer of all radioactive materials from the original site to an approved burial ground.

Any decommissioning program that results in a retained on-site radioactive inventory will require protective storage to assure public health and safety. The facility owner has a considerable range of choices in establishing the boundaries of the protective storage areas. For example, a reactor facility could be left completely intact, less all special nuclear materials, and each building containing radioactive materials would be considered a protective storage area; or the protective storage area might be limited to the reactor building provided all radioactive material outside of that structure has either been decontaminated, removed for off-site disposal or removed and relocated to the reactor building; or the boundary of the protected area could be confined to certain contiguous structures within the reactor building such as the containment or the biological shield within the containment. In addition to this choice of structural form, the facility owner may also remove certain items of the residual radioactive inventory for off-site disposal, e.g., reactor vessel internals, contaminated piping runs, or activated concrete. This partial removal could permit unrestricted use of a section of the facility or eliminate long-lived nuclides from the inventory. It is obvious that there are many possible forms of "protective storage".

2.2 PROTECTIVE STORAGE AND REMOVAL

There have been numerous titles given to the basic forms of protective storage and facility removal. In fact, it seems that any group that has studied the subject has been honor-bound to create a new set of nomers. These will be reported in this chapter for information. Simply stated, they all can be summarized by the following alternative approaches:

1. Permanent in-situ protective storage of all or part of the residual radioactive inventory.
2. Temporary protective storage of all or part of the residual radioactive inventory followed by (3) below.
3. Removal of all potentially hazardous residual radioactivity to an off-site waste storage facility and release of the site for unrestricted use.

The most long-standing reference defining decommissioning alternatives is Regulatory Guide 1.86, Termination of Operating Licenses for Nuclear Reactors[1]. The definitions as stated in Regulatory Guide 1.86 are as follows:

2.2.1 Mothballing

Mothballing of a nuclear reactor facility consists of putting the facility in a state of protective storage. In general, the facility may be left intact except that all fuel assemblies and the radioactive fluids and waste should be removed from the site. Adequate radiation monitoring, environmental surveillance, and appropriate security procedures should be established under a possession-only license to ensure that the health and safety of the public is not endangered.

2.2.2 In-Place Entombment

In-place entombment consists of sealing all the remaining highly radioactive or contaminated components (e.g., the pressure vessel and reactor internals) within a structure integral with the biological shield after having all fuel assemblies, radioactive fluids and wastes, and certain selected components shipped off-site. The structure should provide integrity over the period of time in which significant quantities (greater than Table 2.1 levels) of radioactivity remain with the material in the entombment. An appropriate and continuing surveillance program should be established under a possession-only license.

TABLE 2.1

REGULATORY GUIDE 1.86 TABLE 1
ACCEPTABLE SURFACE CONTAMINATION LEVELS

Nuclide(a)	Average(b,c)	Maximum(b,d)	Removable(b,e)
U-nat, U-235, U-238, and associated decay products	5,000 dpm a/100 cm^2	15,000 dpm a/100 cm^2	1,000 dpm a/100 cm^2
Transuranics, Ra-226, Ra-228 Th-230, Th-228, Pa-231, Ac-227, I-125, I-129	100 dpm/100 cm^2	300 dpm/100 cm^2	20 dpm/100 cm^2
Th-nat, Th-232, Sr-90, Ra-223, Ra-224, U-232, I-126, I-131, I-133	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 Sr-90 and others noted above.	5,000 dpm $\beta\gamma$/100 cm^2	15,000 dpm $\beta\gamma$/100 cm^2	1,000 dpm $\beta\gamma$/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 should apply independently.

(b) As 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 square meter. For objects of less surface area, the average should be derived for each such 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 is determined, the pertinent levels should be reduced proportionally and the entire surface should be wiped.

2.2.3 Removal of Radioactive Components and Dismantling

All fuel assemblies, radioactive fluids and waste, and other materials having activities above accepted unrestricted activity levels (Table 2.1) should be removed from the site. The facility owner may then have unrestricted use of the site with no requirements for a license. If the facility owner so desires, the remainder of the reactor facility may be dismantled and all vestiges removed and disposed of.

2.2.4 Conversion to a New Nuclear System or a Fossile Fuel System

This alternative, which applies only to nuclear power plants, utilizes the existing turbine system with a new steam supply system. The original nuclear steam supply system should be separated from the electric generating system and disposed of in accordance with one of the previous three retirement alternatives.

2.3 COMPARISON OF ALTERNATIVES

Table 2.2 presents a comparison of the titles of Regulatory Guide 1.86 to those presented in various studies.

The mothballing category of alternatives are all consistent with the basic definition of Regulatory Guide 1.86. Facility equipment is left in an inoperative condition; residual radioactivity is stabilized; structures are left intact with uncontrolled access prevented; the security of the facility is monitored and periodic surveillance performed.

All in-place entombment modes provide for the permanent in-situ retention of residual radioactivity within strong integral structures so that containment of the radioactive inventory is assured throughout the time period required for radioactive decay to reach unrestricted levels. This decommissioning alternative may be precluded for a reactor facility that has had a significant operating history due to the presence of long-lived ^{59}Ni and ^{94}Nb activation products in the vessel internals and reactor vessel wall belt line region. The time to achieve

TABLE 2.2

COMPARISON OF DECOMMISSIONING APPROACH TITLES

COMPARABLE TITLE	REFERENCE DOCUMENT
Regulatory Guide 1.86 Title: Mothballing	
Mothballing	AIF/NESP-009[2]
Stage 1	IAEA-179[3]
Option 1	IAEA Draft Report[4]
Safe Storage, Passive	NUREG/CR-0129[5], NUREG/CR-0130[6], and NUREG/CR-0672[7]
SAFSTOR	NRC Program Status Paper, May 1980[8]
Regulatory Guide 1.86 Title: Entombment	
Entombment	NUREG/CR-0129 and NUREG/CR-0278[9]
Stage 2	IAEA-179
Option 2	IAEA Draft Report
ENTOMB	NRC Program Status Paper, May 1980
Regulatory Guide 1.86 Title: Removal of Radioactive Components and Dismantling	
Prompt Removal/Dismantling	AIF/NESP-009
Dismantlement	NUREG/CR-0130, NUREG/CR-0278, and NUREG/CR-0672
Immediate Dismantlement	NUREG/CR-0219
Stage 3	IAEA-179
Option 3	IAEA Draft Report
DECON	NRC Program Status Paper, May 1980
Regulatory Guide 1.86 Title: No Equivalent Title	
Safe Storage, Custodial	NUREG/CR-0129, NUREG/CR-0130, and NUREG/CR-0672
Safe Storage, Layaway	NUREG/CR-0278
Safe Storage, Hardened (temporary)	NUREG/CR-0129, NUREG/CR-0130, and NUREG/CR-0672
Entombment (temporary)	AIF/NESP-009
Mothballing - Delayed Removal/ Dismantling Combination	AIF/NESP-009
Entombing - Delayed Removal/ Dismantling Combination	AIF/NESP-009
Safe Storage with Deferred Dismantlement	NUREG/CR-0129

unrestricted release would be inordinately long and structural integrity of the entombment could not be assured over the period. In this case, in-place entombment could only be pursued if the components, or parts thereof, containing the excessive activation were removed and disposed of at an off-site waste facility. Similarly excessively long-lived radioactive contamination could also limit the direct application of this approach for any dormant nuclear facility.

The removal approaches are all consistent and apply to the dismantling and removal of all residual radioactive material to a level that permits unrestricted release and use of the property and any facilities that remain on-site.

The new titles, which do not have an equivalent in Regulatory Guide 1.86, broaden the potential range of decommissioning approaches. For example, custodial or layaway safe storage infers minimal decommissioning effort with certain plant equipment (e.g., ventilation systems) continuing in operation. As such, there will be on-going need for some operational support. The temporary entombment and hardened safe storage alternatives result in secure structural boundaries around the residual radioactive inventory with the intention of eventual removal of the inventory for off-site disposal. This approach may be preferred to mothballing where higher confidence is needed to preclude unauthorized access to the residual activity, e.g., at a single reactor site.

The combination modes have been devised in recognition of two major factors:

1. Activation products in large reactors will be present in significant quantities in certain reactor vessel structures for thousands of years thus dictating some form of removal to a waste facility designed for that purpose;

2. Since ^{60}Co is the most significant nuclide contributing to occupational exposure and dismantling complexity and since it is relatively short-lived, delay will simplify the removal procedure. For example, it will have decayed to about 1/500 of its initial magnitude in about 50 years and to about 1/1,000,000 in 100 years.

The combination modes will require the same degree of plant surveillance, environmental monitoring, and facility maintenance during the delay period as would be required for a mothballing facility.

The NUREG series of references are part of the overall program of the U.S. Nuclear Regulatory Commission that address the decommissioning of all light water reactor fuel cycle facilities. The paper describing the NRC program status[8] gives an insight into the new decommissioning alternative titles as defined by the NRC.

IAEA-179[3] is a report concerning the program undertaken by the international Atomic Energy Agency for the development of a Code and Guide to the decommissioning of land-based nuclear reactors. This program has been terminated and the information generated will be presented in a nonbinding IAEA safety series report[4]. The reason for the change in terminology from "stage" to "option" is explained by a footnote that appears in Reference 4. It reads: "The term 'stage' has been used in prior IAEA committee meetings and draft reports since decommissioning became part of the Agency's waste management program. However, because the term 'stage' in English denotes a point or a period in a series, which is contrary to the intended meaning here, the term 'option' replaces the former word 'stage' here to provide a more accurate term. However, some member states may prefer to retain the use of the term 'stage'. In addition, it should be pointed out, that the term 'option' implies a freedom of choice of decommissioning alternative that may not be acceptable to the regulatory bodies of some member states".

There is a final alternative that has not been specifically identified in any of the reference documents. That is, permanent dedication of a site and its facility, or a part of the facility, to nuclear application. This has been achieved in isolated instances. There has been some discussion of the approach on a generic basis in the deliberations of the IAEA Committee which prepared IAEA-179. One possible consideration is the rejuvenation of a reactor plant. Another would be the refurbishment of a nuclear facility such as may occur at the Eurochemic fuel reprocessing plant in Belgium. It is expected that greater attention will be given to this consideration particularly as acceptable nuclear sites become more difficult to find.

2.4 REFERENCES

1. U.S. Nuclear Regulatory Commission: Termination of Operating Licenses for Nuclear Reactors, Regulatory Guide 1.86, (June 1974).

2. Manion, W.J. and LaGuardia, T.S.: An Engineering Evaluation of Nuclear Power Reactor Decommissioning Alternatives, Atomic Industrial Forum, Inc., AIF/NESP-009, (November 1976).

3. International Atomic Energy Agency: Decommissioning of Nuclear Facilities, IAEA-179, Vienna, (1975).

4. International Atomic Energy Agency: Factors Relevant to the Decommissioning of Land-Based Nuclear Reactors (Draft) Safety Series, Vienna, (1979).

5. Jenkins, C.E., Murphy, E.S., and Schneider, K.J., in Battelle Pacific Northwest Laboratories Report for the U.S. Nuclear Regulatory Commission: Technology, Safety and Costs of Decommissioning a Reference Small Mixed Oxide Fuel Fabrication Plant, NUREG/CR--129, (February 1979).

6. Smith, R.I., Konzek, G.J., and Kennedy, W.E., in Battelle Pacific Northwest Laboratories report for the U.S. Nuclear Regulatory Commission: Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station, NUREG/CR-0130, (June 1978).

7. Oak, H.D. et al. in Battelle Pacific Northwest Laboratories report for the U.S. Nuclear Regulatory Commission: Technology, Safety and Costs of Decommissioning a Reference Boiling Water Reactor Power Station, NUREG/CR-0672, (June 1980).

8. Calkins, G.D. in report for the Atomic Industrial Forum Workshop: Status of NRC Decommissioning Program, San Francisco, California, (May 1980).

9. Schneider, K.J., Jenkins, C.E., in Battelle Pacific Northwest Laboratories report for the U.S. Nuclear Regulatory Commission: Technology, Safety and Costs of Decommissioning a Reference Nuclear Fuel Reprocessing Plant, NUREG-0278, (October 1977).

CHAPTER 3

SELECTION OF DECOMMISSIONING ALTERNATIVE

3.1 INTRODUCTION

There are numerous factors that contribute to the decision on selection of a decommissioning alternative. Some of these are clear and unambiguous, such as availability of funds, while others can be quite subjective and argumentive, e.g., the aesthetic influence of a plant stack on the surrounding environment.

This chapter discusses the factors that influence the selection of a decommissioning approach and presents a logical method for arriving at this decision.

3.2 FACTORS INFLUENCING THE SELECTION

The influencing factors can be grouped in the following categories:

1. Public Health and Safety
2. Occupational Safety
3. Waste
4. Cost
5. Environmental Impact
6. Other Influences

Table 3.1 lists the specific factors of concern.

3.2.1 Comments of Factors

The occupational safety factors are easily evaluated and quantified. The radiation exposure to workers can be estimated based on a knowledge of the work area dose levels and the work activities comprising the alternatives being considered. Minimization of occupational exposure is considered a primary factor in comparison of alternatives.

TABLE 3.1

FACTORS INFLUENCING SELECTION OF DECOMMISSIONING ALTERNATIVE

Public Health and Safety

- Radiation Exposure:
  - Decommissioning Program
  - Transportation
  - Accident Consequences

Occupational Safety

- Radiation Exposure
- Personnel Safety
- Accident Analysis/Consequence

Environmental Impact

- Site Dedication
- Protected Storage Facility Form:
  - Aesthetic Impact
- Program Accomplishment Impact on:
  - Financing
  - Labor force
  - Housing/Schools
  - Traffic
  - Local economy
  - Use of materials and natural resources
- End-product/Site Use:
  - Interaction with Environment
- End-product/Facility Use:
  - Interaction with Environment
- Waste Type:
  - Radioactive
  - Non-radioactive
- Waste Volumes
- Repository Availability

Cost

- Program Costs:
  - Labor
  - Materials
  - Equipment
  - Rentals
  - Services
  - Waste Containers
  - Waste Transportation
  - Waste Burial/Disposal

Cost

- Program Costs: (Cont'd)
  - Taxes/Insurance
  - Management
- Protected Storage Costs:
  - Duration of Period
  - Facility Operation
  - Security/Surveillance
  - Environmental Monitoring
  - Facility Maintenance
  - Taxes/Insurance
  - Management
- Value of Site for Future Use:
  - Unrestricted/Restricted
- Value of Facility for Future Use:
  - Unrestricted/Restricted
- Availability of Funds
- Impact of Alternatives on:
  - Financing Methods
  - Regulatory Interaction

Other Influences

- Regulations:
  - Federal/State/Local

- Ease/Complexity of Decomissioning Process

- Compatability (of selected decommissioning alternative) with Intended Future Use of Site

- Required Duration of Protected Storage Period

- Availability of Management and Plant-Knowledgeable Personnel after Protected Storage Period

- Condition of Required Systems after Protected Storage Period

- Distance to Waste Disposal Site(s)

The only significant public health and safety concern is radiation exposure. In all cases the exposures can be quantified. All decommissioning studies to date have shown both the direct and airborne radiation doses to the public to be extremely minimal. In the case of reactors, the nonoccupational exposure is almost insignificant when compared to an operating plant. It is doubtful that the difference in estimated values of nonoccupational exposure between alternatives would be a determining factor in the selection process.

Environmental impact considerations also fall into the category of being quite small when compared to those of the operating plant. This evaluation was quantified for reactors in the Atomic Industrial Forum decommissioning study[1]. However, there will be significant differences among alternatives in this category and they are entirely site-specific. No general comments on comparisons are ventured.

The residual radioactive waste will be an important factor in the selection process. The quantity and characteristics of the nuclides as well as their location on-site or in-facility must be quantitatively evaluated for each alternative. These factors could provide overriding considerations particularly in precluding certain alternatives.

The cost category is quite amenable to quantitative analysis. It will be possible to make reasonably accurate estimates of the costs of the alternatives being considered. However, subjective factors in this category could be of greater import than estimated cost differences between alternatives. The availability of funds, and the influence of Public Service Commissions on allowable cost recovery methods and over what time period, could easily overshadow other cost considerations.

Where ^{60}Co and other relatively short-lived nuclides are major constituents of the residual inventory, it is obvious that a significant reduction in that inventory can be achieved with a period of protected storage. Balanced against this positive factor are the practical considerations associated with any required future removal operations. These include, for example, availability of plant qualified personnel and the operating condition of any required electrical and fluid systems after a protracted protected storage period. The post-storage work activities must be specifically identified during the evaluation process in order to ensure that the combination mode is considered for practicality as well as feasibility.

3.2.2 Selection Methodology

The general logic sequence to be followed in the selection process is as follows:

1. Selection of Technically Viable Alternatives

   This first step requires a detailed knowledge of the end-of-life residual radioactive inventory including activation and contamination products. This is the most important step since all relative evaluations are based on this quantitative data. The inventory must be specific as to nuclide composition, distribution, and magnitude in systems and components, upon structural surfaces and on or under the site terrain. Accuracy in this step cannot be over-emphasized. See Chapter 4, Estimation of Radioactive Inventory.

   With a good knowledge of the residual inventory, the family of viable alternatives can be established and others, not appropriate to the situation, eliminated.

2. Evaluation of Overriding Factors

   In an actual program, a decision would have to be made at this time and the optimum program acceptable to the regulatory bodies selected and defined. If this evaluation process occurs early in a planning stage or at least well in advance of plant shutdown, it may be appropriate to identify more than one alternative, allowing a more timely decision to be made after plant final shutdown.

3.3 REFERENCES

1. Manion, W.J., LaGuardia, T.S.: An Engineering Evaluation of Nuclear Power Reactor Decommissioning Alternatives, Atomic Industrial Forum, Inc., AIF/NESP-009, (November 1976).

CHAPTER 4

ESTIMATION OF RADIOACTIVE INVENTORY

4.1 INTRODUCTION

The radioactive inventory of a nuclear reactor or facility that is to be decommissioned can be divided into two categories:

1. The radioactivity induced by neutron activation of certain elements in a reactor vessel, reactor components and adjacent structures; and
2. The radioactive material deposited on the internal and external surfaces of various systems.

An accurate estimate of the total radioactive inventory is important because the amount and type of radioactivity in the facility can directly affect the choice of the method of decommissioning to be undertaken. Specifically, the radioactive inventory is required in order to:

1. Determine the decommissioning techniques to be utilized
2. Determine the man-rem exposures of the decommissioning work force
3. Determine the desirability of a delay period prior to performance of permanent decommissioning
4. Assess the need for decontamination
5. Determine shipping requirements for radioactive waste
6. Determine burial or disposal requirements
7. Determine non-occupational radiation exposures
8. Prepare environmental impact assessments.

Estimates of the radioactive inventory are arrived at by the use of both computational and direct measurement methods. Computer codes and mathematical models for calculating the radionuclide inventory are available, and are preferable to hand calculation methods. Direct measurement methods are generally more reliable and should be used whenever possible.

4.1.1 Classification of the Radioactive Inventory

1. Neutron-activated Products

Materials exposed to the neutron flux in a reactor become irradiated and are transformed into radioactive isotopes. The level and type of radioactivity found in neutron-irradiated material depends upon: (1) the constituent elements in the material; (2) the duration of exposure to the neutron flux; and (3) the energies of the incident neutrons. The induced radioactivity in a reactor vessel, reactor components and adjacent structures comes primarily from the radionuclides ^{60}Co, ^{14}C, ^{55}Fe, ^{63}Ni and ^{59}Ni.

2. Internal System and External Surface Contamination

Radioactive contamination of internal systems in nuclear reactor plants is caused by the deposition of neutron-activated metal particles and dissolved elements in the circulating water, and by the deposition of fuel element fission products released when there is a failure of the fuel cladding. External surface contamination in nuclear reactor plants is primarily due to leakage from primary and auxiliary systems.

The corrosion of metals in the primary water loop of nuclear power reactors produces crud particles that are transported by the water through the reactor core where they become radioactive as a result of neutron activation. The radioactive crud is eventually deposited on both in-core and out-of-core surfaces. Elements dissolved in the water are similarly activated in the core and deposited.

Fuel reprocessing and production facilities will have radioactive contamination in their internal systems, although in those parts of the plant where radionuclides are in acidic solutions, the deposition of radionuclides on internal surfaces may be minimal. In production, reprocessing and other nuclear facilities, tramp radionuclides are a major source of external surface contamination. Chemical "hot" labs also may have significant surface contamination.

4.1.2 Application of Radioactive Inventory Data

The radioactive inventory data will play a major role in the decision as to which mode of decommissioning (mothballing, entombment, removal/dismantling or any combination of these) is to be carried out. The radioactive inventory will also provide the information needed to plan the decommissioning activities, and has a direct bearing upon the scheduling and manpower requirements, particularly with respect to exposures in highly radioactive areas.

Personnel exposure during decommissioning are estimated from the contact exposure rates and the work area dose levels. This data is useful for preparing cost-effective procedures for keeping personnel exposures as low as reasonably achievable.

Contact exposure rates, plotted as a function of time, provide an indication as to how many years it will take before the simplified procedures of manual removal and dismantling can be initiated.

Radiological safety planning during decommissioning should incorporate the "as low as reasonably achievable" principle, as well as the radiation protection standards mandated in 10 CFR 20 and discussed in the NCRP Report No. 39.[1]

The degree of decontamination included in a decommissioning program will be a direct function of the type and magnitude of the contamination source. These characteristics will also determine the impact on occupational exposure of a major decontamination program versus a simple water flush of the piping systems.

Shipping requirements for radioactive materials are governed by the regulations of the Nuclear Regulatory Commission (in 10 CFR 71) and the Department of Transportation (in 49 CFR 173-178). The type and activity of radionuclides in contaminated or activated material from a nuclear facility will have a direct bearing on the manner in which the material must be shipped. The packaging required depends upon the radionuclides present, the specific activity of the materials, its surface contamination, the radiation dose rate and the weight of the material.

Burial or disposal requirements also depend upon the radionuclides present, the specific activity, surface contamination and radiation dose rates. An accurate inventory of radionuclides is necessary to demonstrate compliance with current regulations covering the disposal of radioactive materials. The inventory may, in some cases, show that burial of certain material is not necessary because of low radiation levels. In such cases, substantial financial savings may be realized.

An accurate radioactive inventory estimate is necessary to determine the non-occupational radiation exposure due to transport of the wastes to controlled burial grounds, and the non-occupational exposure from potential liquid and gaseous waste releases associated with decontamination activities. The inventory estimate is also needed to prepare the environmental impact assessments.

4.2 HOW TO ESTIMATE ACTIVITY LEVELS AND EXPOSURE RATES FOR NEUTRON-ACTIVATED PRODUCTS

4.2.1 General Procedure

An estimate of the activity levels in a nuclear reactor is obtained by calculating the activities of the radionuclides that have been formed by neutron activation during operation of the reactor. Such calculations require specific data on the size, weight and composition of the irradiated components, including any trace elements and impurities, plus data on the full operating history of the reactor, specifically power levels vs. time.

Using mathematical models that have been developed, these estimates are made prior to final plant shutdown to provide data needed for the early planning of the decommissioning program.

In most instances, it is preferable to perform the calculations on a computer. Several codes that have the capability to solve the multiple energy group equations are available for activation calculations. These codes are in the public domain and have been verified. In order to demonstrate how the calculations are carried out, an activation analysis model, suitable for hand calculation methods, is detailed in the following sections.

Contact exposure rates are calculated from the activity level estimates. It is recommended that the calculated estimates of activity levels and exposure rates be verified by direct measurements, where possible.

In certain instances, for example if the material composition of the irradiated component is not known, direct measurement techniques must be utilized to obtain the activity levels and exposure rates.

4.2.2 Radionuclides of Concern

Cobalt-60, a significant gamma emitter, is of primary concern in planning the decommissioning of a reactor. The dose levels of ^{60}Co gamma radiation from the carbon steel, stainless steel cladding and internal components of the reactor vessel will determine the amount of remote operation and worker shielding that is required. Other isotopes of concern are ^{63}Ni, ^{55}Fe, ^{59}Ni and ^{14}C. There are also trace isotopes, such as ^{94}Nb, depending on the composition of the stainless steels and impurities in the original materials.

Nickel-59 has not been of importance in previous reactor decommissionings because the reactors had not operated long enough to create significant quantities of this isotope. However, a commercial light water reactor (LWR) operated for 40 years at an 80% capacity factor will contain significant amounts of ^{59}Ni in certain reactor vessel internals. Therefore, this long-term, low-level activity must be taken into consideration. Carbon-14 is of concern for high temperature gas-cooled reactors (HTGR's). Other radionuclides encountered in neutron-irradiated material are found in Table 4.1.

For a decommissioning program, radionuclides with half-lives of one month or less are considered to be short-lived, and in most instances by the time decommissioning activities begin, these radionuclides have decayed to negligible levels.

Other radionuclides that also may be eliminated from consideration in the estimation of activity levels of irradiated material are:

1. Radionuclides with weak ionizing radiations and low specific activity
2. Those found in very low concentration (i.e. less than 1 ppm)
3. Those with large burnup cross sections.

Of importance, but not well-documented, is the activation of trace elements, such as ^{94}Nb, that may give rise to significant activity levels and thereby affect the selection of a decommissioning alternative. Trace elements are introduced from scrap metal added to virgin metal during manufacture. For example, niobium is added to steel to improve welding characteristics which, when diluted in the melt, remains in trace quantities. A typical composition[2] of a Type 304 stainless steel, including trace quantities, is shown in Table 4.2.

TABLE 4.1

TYPICAL RADIONUCLIDES OF CONCERN IN NEUTRON-ACTIVATED MATERIALS

	Isotope	Half-Life T 1/2 (yr)	Means of Production	Emission	Energy(MeV)
Carbon & Stainless Steel	14C	5730.0	N^{14}(n,p)	β^-	0.156
	49V	0.906	$Cr^{52}(p,\alpha)$	γ, β^-	0.6*
	54Mn	0.856	$Fe^{56}(d,\alpha)$	γ	0.835
	55Fe	2.6	$Fe^{54}(n,\gamma)$	γ	0.23*
	59Ni	$8 X 10^4$	$Ni^{58}(n,\gamma)$	ϵ	1.06*
	63Ni	100.0	$Ni^{62}(n,\gamma)$	β^-	0.066
	65Zn	0.667	$Zn^{64}(n,\gamma)$	$\gamma, \epsilon, \beta^+$	1.115, 1.352, 0.325
	58Co	0.194	$Mn^{55}(\alpha\ n)$	β^+, γ	0.474, 0.810
	60Co	5.263	$Co^{59}(n,\gamma)$	β^-, γ, γ	0.314, 1.17, 1.33
	93Mo	$3.5 X 10^3$	$Mo^{92}(n,\gamma)$	ϵ	Nb X-RAYS
	94Nb	$2 X 10^4$	$Nb^{93}(n,\gamma)$	β^-, γ, γ	0.49, 0.702, 0.871
	95Nb	0.096	Zr^{95}DECAY	β^-, γ	0.16, 0.765
	95Zr	0.175	$Zr^{94}(n,\gamma)$	β^-, γ, γ	0.396, 0.724, 0.756
Concrete	14C	5730.0	N^{14}(n,p)	β^-	0.156
	35S	0.238	$S^{34}(n,\gamma)$	β^-	0.167
	36Cl	$3.01 X 10^5$	$Cl^{35}(n,\gamma)$	β^-, ϵ	0.714, 1.18*
	37Ar	0.0953	$36Ar(n,\gamma)$	ϵ	0.81*
	39Ar	269.0	$Ar^{38}(n,\gamma)$	β^-	0.565
	40K	$1.28 X 10^9$	-	β^-, γ	1.314, 1.46
	41Ca	$8 X 10^4$	$Ca^{40}(n,\gamma)$	γ	K X-RAYS
	45Ca	0.446	$Ca^{44}(n,\gamma)$	β^-	0.257
	46Sc	0.229	$Sc^{45}(n,\gamma)$	$\beta^-, \beta^-, \gamma, \gamma$	1.48, 0.357, 0.889, 1.12
	54Mn	0.856	$Fe^{56}(d,\alpha)$	γ, ϵ	0.835, 0.829, 1.379
	55Fe	2.6	$Fe^{54}(n,\gamma)$	γ	0.23*
	59Fe	0.122	$Fe^{58}(n,\gamma)$	β^-, γ, γ	1.57, 1.1, 1.29
	58Co	0.194	$Mn^{55}(\alpha,n)$	β^+, γ	0.474, 0.81
	60Co	5.263	$Co^{59}(n,\gamma)$	β^-, γ, γ	0.314, 1.17, 1.33
	59Ni	$8 X 10^4$	$Ni^{58}(n,\gamma)$	ϵ	1.06*
	63Ni	100.0	$Ni^{62}(n,\gamma)$	β	0.067
	65Zn	0.667	$Zn^{64}(n,\gamma)$	$\gamma, \epsilon, \beta^+$	1.115, 1.352, 0.325
	94Nb	$2 X 10^4$	$Nb^{93}(n,\gamma)$	β^-, γ, γ	0.49, 0.702, 0.871
	95Nb	0.096	Zr^{95}DECAY	β^-, γ	0.16, 0.765
	93Mo	$3.5 X 10^3$	$Mo^{92}(n,\gamma)$	γ	Nb X-RAYS
Aluminum	46Sc	0.229	$Sc^{45}(n,\gamma)$	$\beta^-, \beta^-, \gamma, \gamma$	1.48, 0.357, 0.889, 1.12
	54Mn	0.856	$Fe^{56}(d,\alpha)$	γ	0.835
	55Fe	2.6	$Fe^{54}(n,\gamma)$	γ	0.23*
	54Fe	0.122	$Fe^{52}(n,\gamma)$	β^-, γ, γ	1.57, 1.1, 1.29
	60Co	5.263	$Co^{59}(n,\gamma)$	β^-, γ, γ	0.314, 1.17, 1.33
	65Zn	0.667	$Zn^{64}(n,\gamma)$	$\gamma, \epsilon, \beta^+$	1.115, 1.352, 0.325
	110mAg	0.69	$Ag^{109}(n,\gamma)$	β^-, γ**	.087, .6577

* Continuous spectrum of X-ray energies below this number, due to Bremmstrahlung.

** Energy of most probable energy β- and most probable energy γ given.

TABLE 4.2

TYPICAL WEIGHT PERCENT TRACE ELEMENTS IN TYPE 304 SS

Element	Wt %	Remarks
Lead (Pb)	0.002	
Tin (Sn)	0.01	
Cobalt (Co)	0.20	Can be reduced on Special Order
Copper (Cu)	0.15	
Zinc (Zn)	0.01	Removed by vaporization/ oxidation
Niobium (Nb)	0.01	Also called Columbium-removed by vaporization/ oxidation
Arsenic (As)	0.01	
Aluminum (Al)	0.01	
Molybdenum (Mo)	0.05	
Boron (B)	0.0005	Removed by vaporization/ oxidation
Titanium (Ti)	0.05	Removed by vaporization/ oxidation
Vanadium (V)	0.05	Removed by vaporization/ oxidation
Selenium (Se)	0.02	
Antimony (Sb)	0.01	
Nitrogen (N)	0.04	Range is 0.03 to 0.05 in electric furnace
Oxygen (O)	0.015	
Phosphorus (P)	0.03	Can go to 0.035
Sulfur (S)	0.015-0.025	Max is 0.03
Silicon (Si)	0.60/1.0 max	Added to heat
Manganese (Mn)	1.25/2.0 max	Added to heat
Hydrogen (H)	0.0007	
Carbon (C)	0.03/0.08 max	Depending on grade

Neutron activation of ^{93}Nb, which may be found in Type 304 stainless steel at concentrations of up to 160 ppm[3], produces ^{94}Nb which has a half-life of 20,000 years. At the 160 ppm concentration, the ^{94}Nb will dominate activity levels after about 100 years and must be taken into account when considering the delayed dismantling mode of decommissioning.

4.2.3 Computer Codes

A large number of numerical methods exist for activation analysis in the formal, publicly available computer codes. These codes are available through the Oak Ridge National Laboratory and the Argonne National Laboratory for direct use on several types of large computers. The use of computer codes, in place of hand calculations, becomes particularly advantageous when large numbers of nuclides or complex geometries are being considered. Once a component of interest has been identified for study, the task of performing an activation analysis by numerical methods can be broken down into three parts:

1. Determination of which elements present in the component lead to activated products of concern
2. Evaluation of the radiation environment to which the component has or will be exposed and the length of the exposure
3. Performance of calculations based on the above to establish which activated nuclei are present in the component and in what quantity.

The elemental composition of the material is determined from ASTM Specifications or from actual measured constituents. Specific nuclides may be chosen for analysis because of their large half-life, large cross section or abundance.

1. Determination of Neutron Flux by Computer

The neutron flux must be determined as a function of time, space and neutron energy. For power reactor applications, long operating time periods are usually encountered, during which it is possible to express the time dependence of the neutron fluence as a series of a few discrete intervals of constant value. The space and energy distribution of the neutron flux may be calculated using multigroup spatial codes in one, two or three dimensions. These codes vary in the mathematical approach and numerical method of solution.

The most widely used codes employ diffusion theory or transport theory as the mathematical representation of neutron interaction with matter. Of the two, diffusion theory codes are the simplest and most economical. Transport theory differs from diffusion theory in that it treats the angular dependence of neutron scattering. This difference makes transport theory codes more accurate but considerably more complex. For many applications involving activation analysis, diffusion theory codes provide adequate accuracy.

Input data to these codes consist of nuclear material properties in the form of cross sections and user-specified problem dependent data such as nuclide densities, material geometry, boundary conditions, and in the case of transport theory, desired angular quadrature and weights. Cross section input to diffusion or transport theory codes is in the form of multigroup (up to several hundred energy groups) microscopic cross sections, or few group macroscopic cross sections.

Nuclear cross section data can be obtained in raw form from the Evaluated Nuclear Data Files (ENDF/B4)[4] and transformed to usable, formatted multigroup sets (ANISN format for instance) using auxiliary codes such as ETOG[5] and AMPX[6]. Some codes already contain cross section files, such as KENO-IV[7] (which contains a 16 group Hansen-Roach cross section set), and ORIGEN. It should be noted that many one dimensional (1-D) spatial codes also calculate macroscopic material cross sections for input to other 2-D or 3-D spatial codes in addition to performing spatial flux and eigenvalue (criticality) calculations.

Numerical methods of solution vary among spatial codes. Diffusion codes typically use finite difference methods. Transport theory codes have various methods including P_n, S_n (discrete ordinates) and Monte Carlo. Of these solution methods, discrete ordinates and P_n methods provide economical and commonly used treatments while Monte Carlo (a statistical method) provides the ultimate flexibility in terms of geometry and overall problem solving capability. Monte Carlo is however, extremely expensive to run since it consumes large amounts of computer time. Complete explanation of all the above methods can be found in Bell and Glasstone.[8] Table 4.3 contains a list of some currently available codes and their method of solution.

2. Computer Activation Analysis

Once the neutron flux has been established, activation codes may be employed to determine the results of exposure. Input to activation codes includes information on neutron spatial flux levels as a function of time, initial nuclide atom densities, reaction cross section data, type of reactions to be considered and the time frame of interest. The output usually includes time dependent nuclide concentrations and photon yields of activation products. The differential equations governing time-dependent radiation production and decay processes are first order equations and are typically solved by matrix methods.

Reaction cross section data and decay constants for each nuclide being considered must be input to the activation codes. Some codes contain their own libraries of these data. One excellent example is the activation Code ORIGEN, which contains over 900 nuclides in its

TABLE 4.3

ACTIVATION CALCULATION COMPUTER CODES

Code Name	Calculational Method	Comments	Reference
ANISN	Discrete Ordinates	One-dimensional, anisotropic scattering	9
DTF-IV	Discrete Ordinates	Similar to ANISN	10
DOT	Discrete Ordinates	Two-dimensional, anisotropic scattering	11
TWOTRAN	Discrete Ordinates	Similar to DOT	12
MAC	Removal Diffusion	Uses Spinney formulation for removal cross section ΣR	13
NRN	Removal Diffusion	Uses concept of removal angle to define ΣR	14
MORSE	Monte Carlo	Multi-group neutron and gamma ray transport, flexible geometry	15
NAP	Neutron Activation	Up to 43 neutron groups: reaction cross sections can be calculated; up to 21 gamma groups	16
ACT-II	Neutron Activation	4 neutron groups, 4 gamma groups	17
ORIGEN	Neutron Activation	Uses recent data; one effective neutron group covering 3 ranges; 12 gamma groups	18

library with information on each isotope, regarding half-lives, decay schemes, reaction cross sections, fission yields and disintegration energies.

The calculational sequence to determine the activation products is shown schematically in Figure 4.1. The application of available computer codes to activation analyses greatly simplifies the task of addressing complex geometries, multiple energy groups, constituent isotopes (normal and trace quantities) and each activated component.

4.2.4 Activation Analysis Model

A mathematical model, from which activity levels are calculated, will be developed in order to demonstrate the methodology used to perform these calculations. The example provided herein is for a manual calculation of neutron activation based on known fast and thermal neutron flux profiles. The methodology is applicable to both manual and computer solutions. Data required for the mathematical model are:

1. The facility operating history
2. Fast and thermal neutron flux profiles (two group solutions)
3. Size and weight of the irradiated components
4. Material composition of the components
5. Isotope cross sections and decay constants.

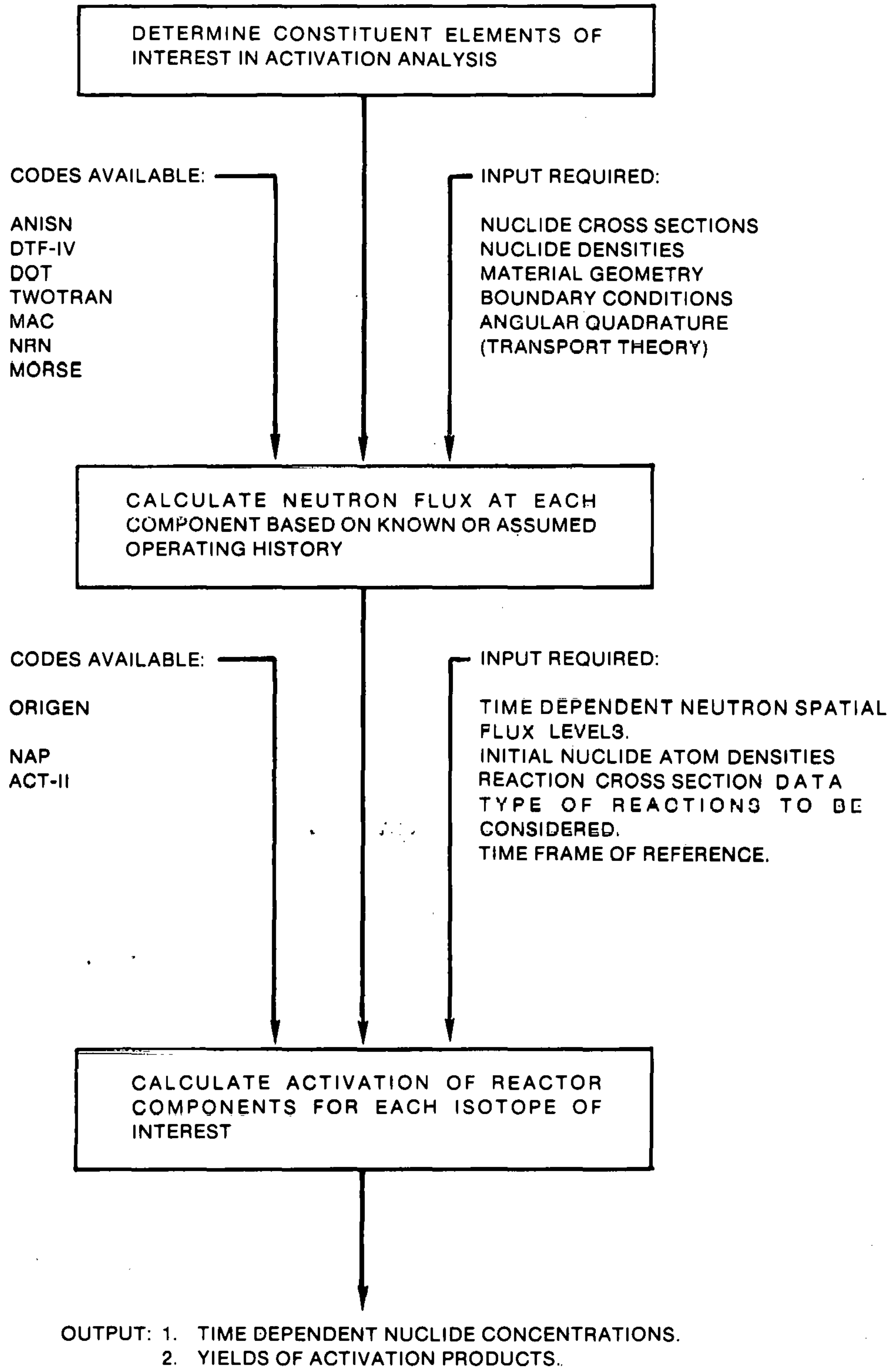
The equations of the mathematical formula are developed on a step-by-step basis, and sample calculations are given to illustrate the use of the model.

1. Obtaining Appropriate Data

A. The operating history of the reactor is of primary importance. The data may take the form of a histogram that displays the reactor operating flux levels during its power generating history.

FIGURE 4.1

SCHEMATIC DIAGRAM OF ACTIVATION ANALYSIS BY COMPUTER METHODS



The most appropriate method of compiling this data is to determine the number of operating periods of the reactor over its lifetime, and to calculate for each operating period the average reactor power level. From the histogram, a table containing the following information can be developed:

1. Duration thermal power generated in operating period
2. Total thermal power generated in operating period
3. Average thermal power generated in operating period
4. Length of operating period
5. Decay time from the end of each operating period to the date for which the activity levels are to be calculated.

One method of creating a histogram from the reactor operating data is to calculate the average power levels at which the reactor was operated over yearly intervals. However, it is necessary to always use the actual length of the operating period; for example, a reactor generating power at an average of 97% of its rated capacity for 10 months and zero power thereafter is said to have operated for 10 months at 97% of full power, not 12 months at 81% of full power.

B. The fast and thermal neutron flux profiles must be known to facilitate the calculation of neutron activation. The energy division between fast neutron and thermal neutron groups is not well-defined, and a certain amount of good judgment is needed to establish a boundary. In some cases, the dividing energy level is defined by the NSSS vendor. Past studies have used 1.855 eV as an upper limit for the thermal flux group.[19] Multi-group calculations can be made to improve accuracy, but these calculations are more difficult and require a computer.

Profiles of neutron fluxes for reactor internal components near the core can be obtained from:

1. The NSSS vendor's estimated values
2. The reactor's operating records
3. By calculation.

Flux profiles for components away from the core may not be as readily available however. They may be calculated using the NRN removal-diffusion computer code[14] or the ANISN (or DOT) computer codes[9].

For certain reactor components, it will be necessary to include a factor to correct for the decrease in flux level as a function of increasing distance from the core center. For example, a calculation of the activity due to the neutron activation of pressure vessel material at the internal and external radii may vary by an order of magnitude or more, depending upon material composition and thickness. It is possible to account for the decrease in flux level by incorporating attenuation factors into the calculations. To circumvent this difficulty it is suggested that either an average value of flux be used through the component, or the component be mathematically segmented radially for the calculations. For the reactor pressure vessel, this would mean mathematically segmenting the vessel into several thick concentric cylinders.

In general, large reactor components should be divided into segments to improve the accuracy of the activation calculations. There are no set criteria for selecting the number of segments, but accuracy improves as the number of segments is increased. In regions where the neutron flux is very high, smaller segments should be used to provide better resolution of the activity levels. An appropriate flux level is then assigned to each segment based on the position of the segment. Typical neutron flux distributions are shown in Figure 4.2. Figure 4.3 shows an example of a mathematical segmentation of a boiling water reactor vessel.

FIGURE 4.2 (A)

TYPICAL FLUX PER MEGAWATT - RADIAL DISTRIBUTION FORM

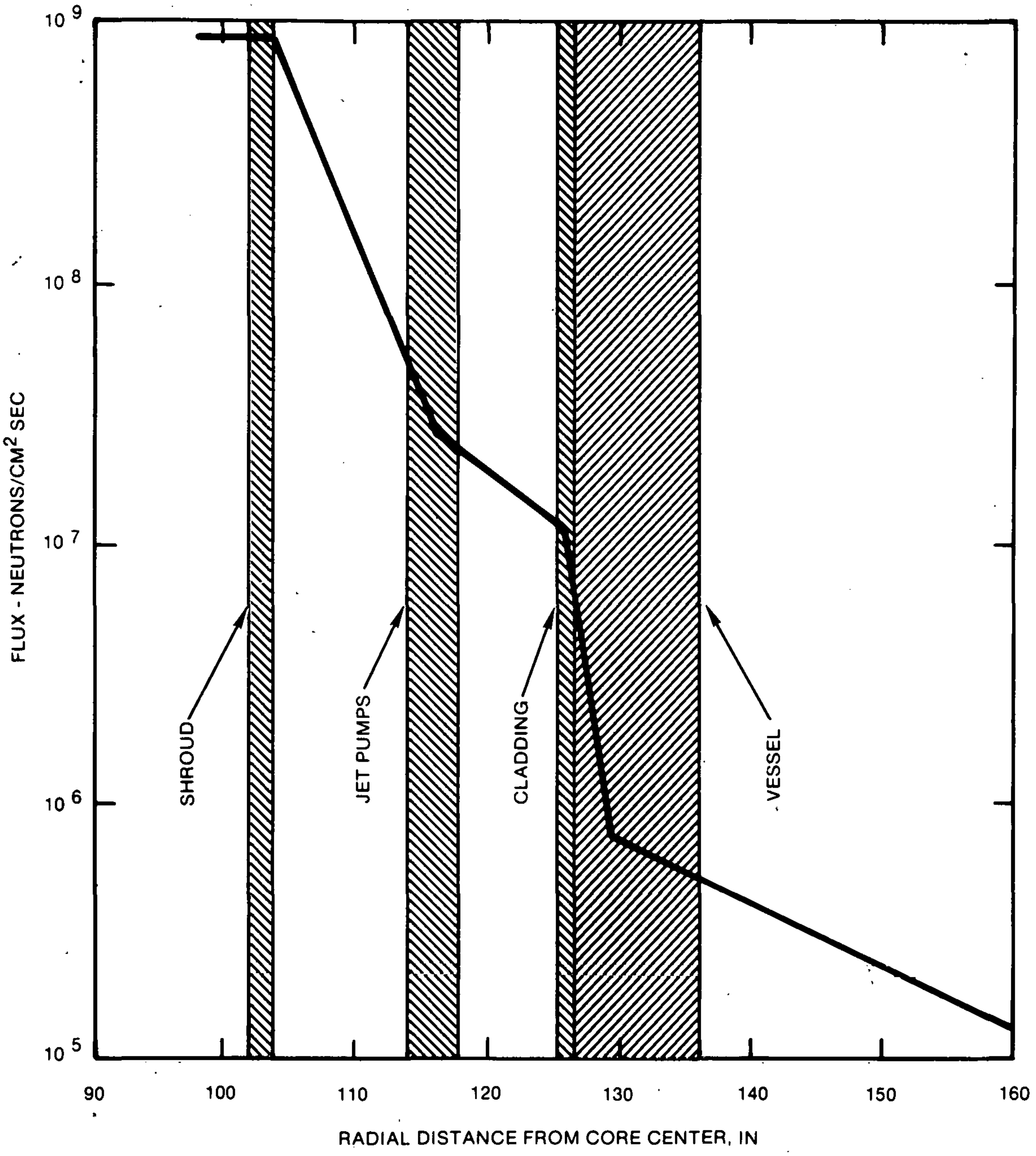


FIGURE 4.2 (B)

FLUX PER MEGAWATT - DOWNWARD DISTRIBUTION

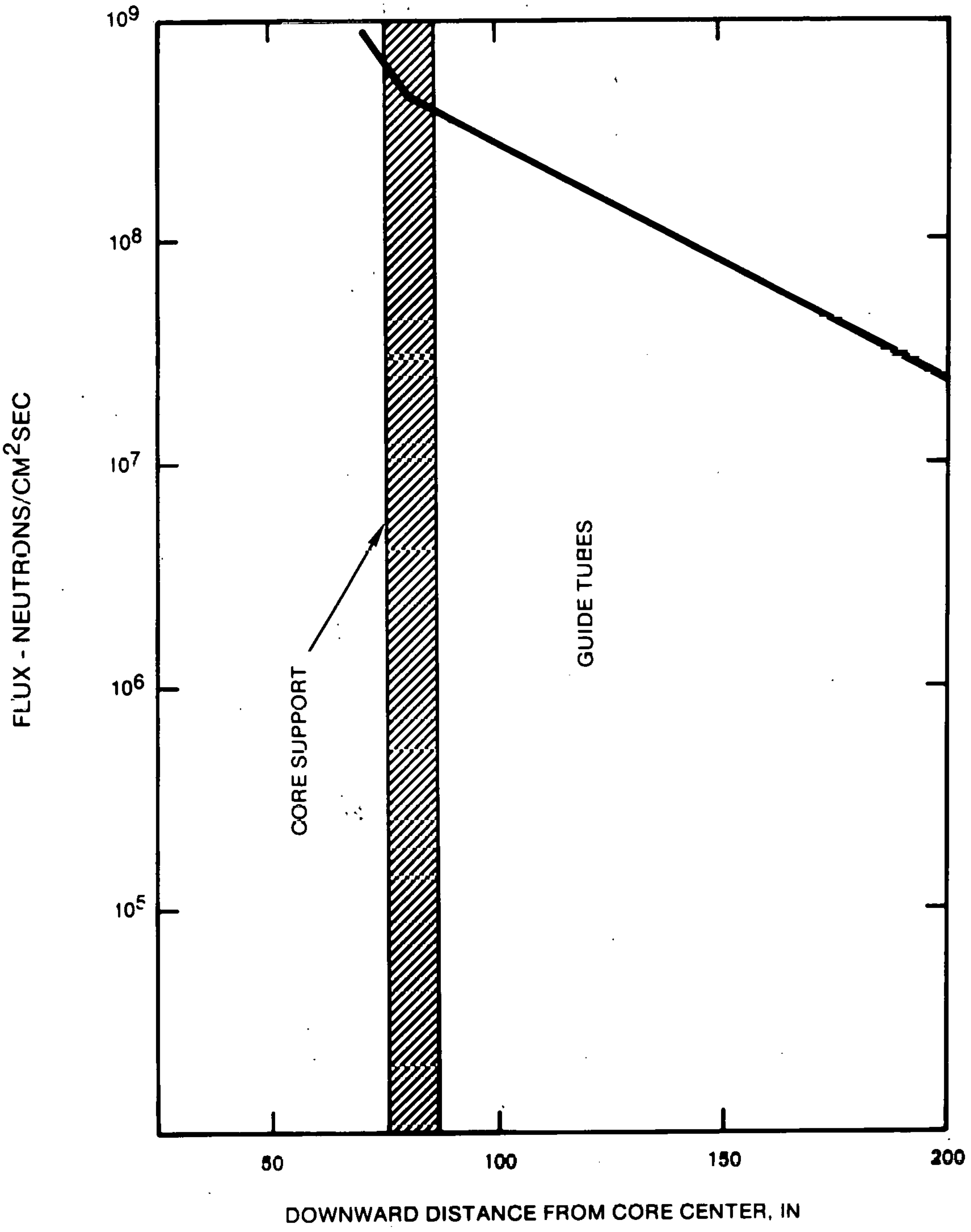


FIGURE 4.2 (C)

FLUX PER MEGAWATT - AXIAL DISTRIBUTION

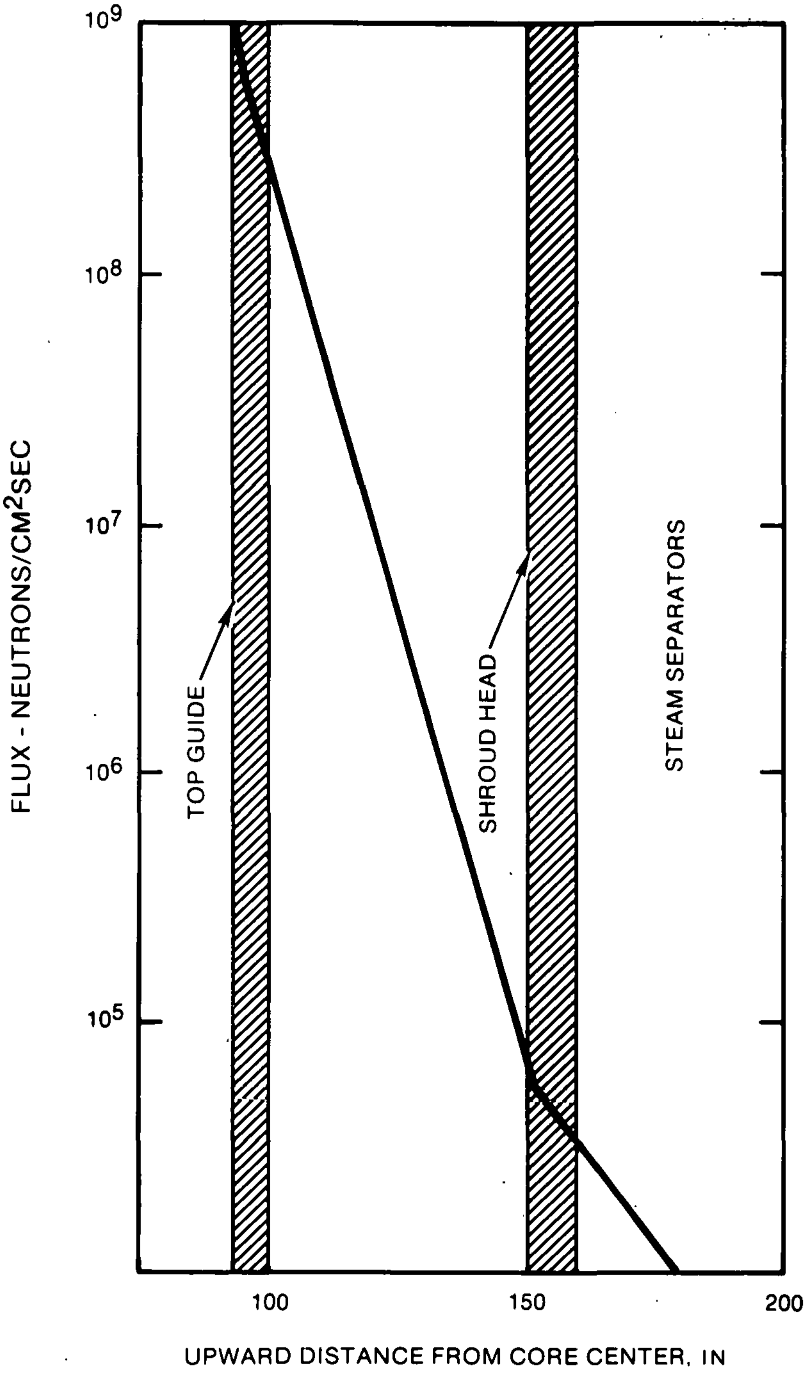
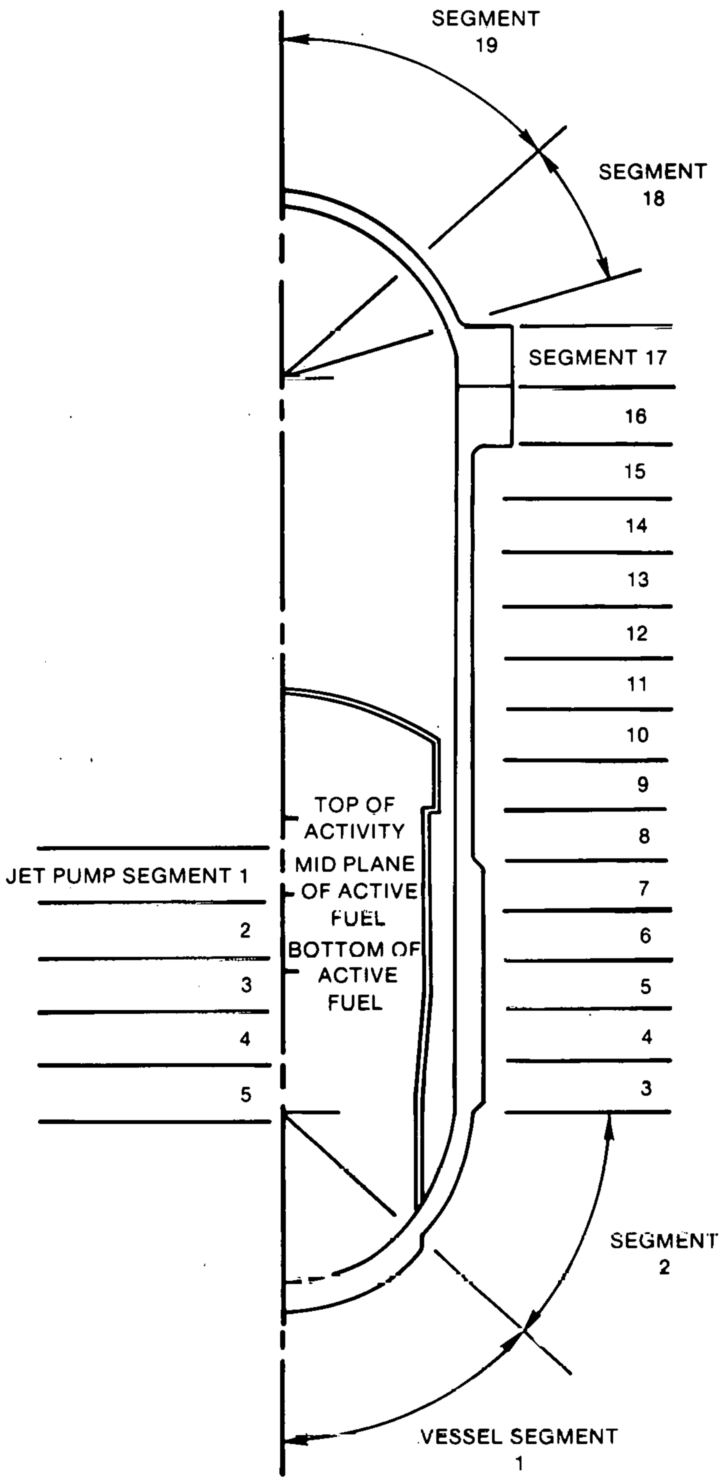


FIGURE 4.3

BOILING WATER REACTOR VESSEL - TYPICAL MATHEMATICAL SEGMENTATION



C. Data on the size and weight of the irradiated components should be obtained and tabulated. This data is usually available from the plant Safety Analysis Report (SAR), plant description, reactor vendor or reactor owners.

D. The original composition of the irradiated components, including trace elements and impurities, should be obtained whenever possible. Acquiring the data may involve some research work. For example, the supplier of the reactor component material may have detailed data on its composition that is more complete than the specification records provided with the shipment of the component to the facility. For the metallic structures with documented heat numbers, material composition is readily traced to facility records and possibly archive samples. If archive samples, or heat numbers are unavailable, then as a minimum the ASTM/ASME standards may be utilized to determine the major elemental composition. The cobalt content is of particular concern.

As noted in Section 4.2.2, trace elements with long-lived activity become important when the delayed-dismantling decommissioning alternative is being considered. Even though the majority of the radionuclides will have decayed to levels low enough to permit manual dismantling in about 100 years, very long-lived radionuclides of trace elements such as niobium may have appreciable levels at that time, and workers would have to be provided with proper shielding.

E. A library of isotope cross sections and decay constants must be compiled for each constituent isotope of the irradiated components. The neutron interactions to be considered are the fast and thermal neutron absorptions (n,γ), and the (n,2n), (n,p), (n,d) and (n,α) reactions. There is a wide variety of sources for information on neutron interactions. Some useful ones are: the Chart of the Nuclides[20], BNL-325[21], Roy and Hawton[22], Chattergee[23], and the Landbolt-Bornstein tables[24].

Radioisotopes with very short half-lives (on the order of one month or less) may be left out of subsequent calculations since their effect on the total activity is negligible.

Difficulties may arise in selecting the correct cross section for the fast flux in out-of-core internals because the neutron energy spectrum changes significantly as a function of the radial distance from the center of the core. As a starting point for the choice of the fast flux cross sections, one should use the most probable neutron energy to provide an estimate for determining the fast flux cross section. This will require knowing the most probable fast flux neutron energy as a function of radial distance from the center of the core. The information may be available from the reactor designer or it may be calculated as discussed in Section 4.2.4.

The most probable energy for the fast neutron flux within the core is on the order of 1 MeV. The most probable neutron energy for the fast neutron flux in the water just beyond the core shroud will be about 2 MeV, an increase because of the large removal cross section of hydrogen below 1 MeV. From the core shroud radially outward, the most probable energy in the fast flux group will start to drop as the inelastic scattering effects begin to dominate the neutron interactions. At the inner radius of the pressure vessel, the most probable energy may be 0.5 MeV or less. A schematic diagram of the manual activation analysis calculation is shown in Figure 4.4.

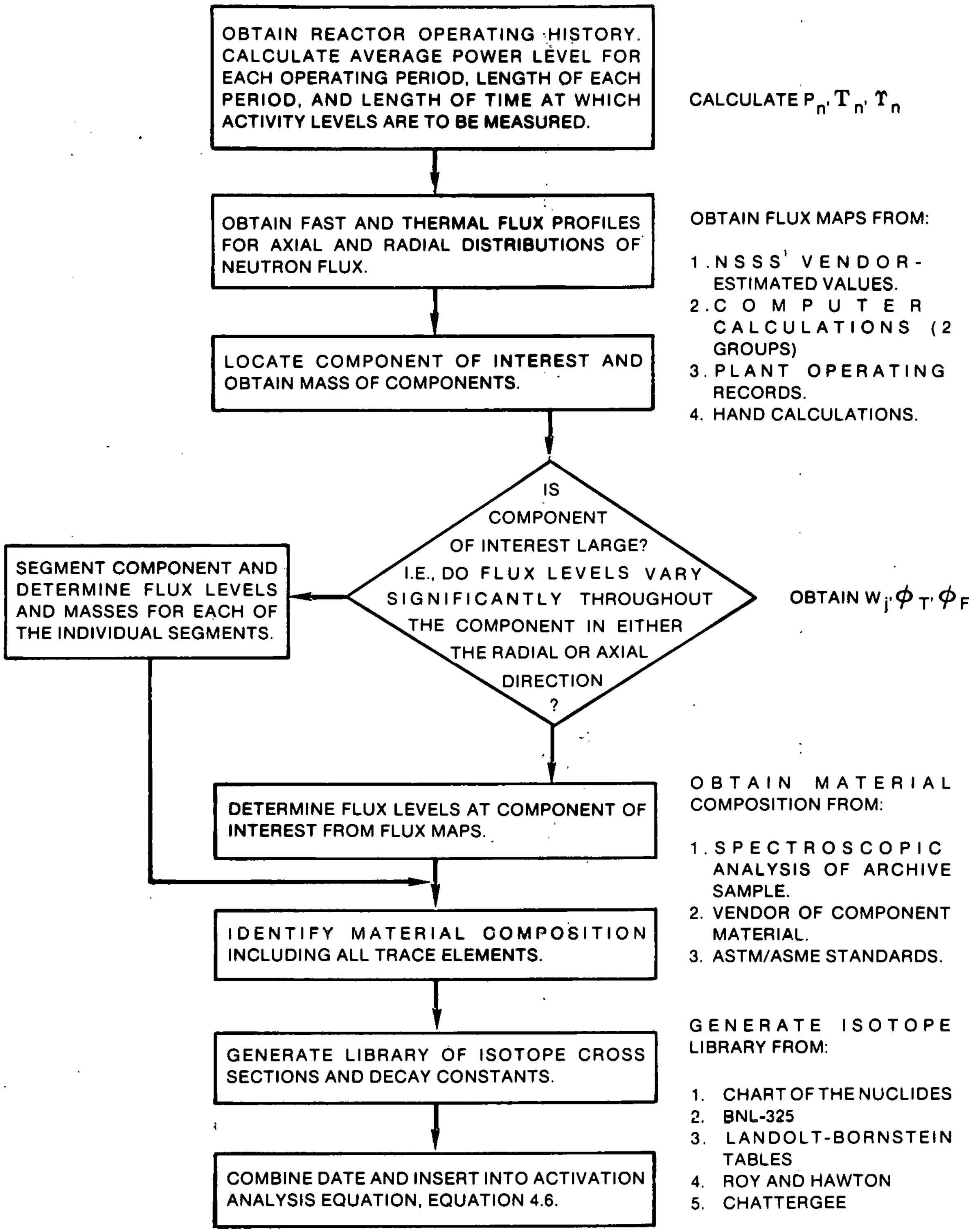
2. Activation Analysis Equations

During an operating period n with average power P_n and duration T_n, the rate of production of radionuclide i with decay constant λ_i is given by:

$$\frac{dN_i}{dt} = P_n \phi \Sigma_i V - \lambda_i N_i \qquad (1)$$

FIGURE 4.4

SCHEMATIC DIAGRAM OF MANUAL ACTIVATION ANALYSIS CALCULATION



where ϕ is the fast or thermal average neutron flux, V is the volume of the component (segment) and Σ_i is the macroscopic cross section for the production of radionuclide i. The equation is integrated over the duration of operating period n to give the number of atoms of nuclide i present at the end of the nth period:

$$N_i = \frac{P_n \phi \Sigma_i V}{\lambda_i} (1 - e^{-\lambda_i T_n}) \tag{2}$$

A measurement at time τ_n after the end of period n would show the number of atoms of nuclide i present as:

$$N_i = \frac{P_n \phi \Sigma_i V}{\lambda_i} (1 - e^{-\lambda_i T_n}) e^{-\lambda_i \tau_n} \tag{3}$$

The activity in Curies of radionuclide i from the neutron interaction in parent nuclide k in component (segment) j over n periods becomes:

$$A_{ijk} = K \phi_j \Sigma_{ijk} V_j \sum_n P_n (1 - e^{-\lambda_i T_n}) e^{\lambda_i \tau_n} \tag{4}$$

Where:

K = 1/(3.7 x 10^{10}) Curies/(disintegration/sec)

ϕ_j = fast or thermal average neutron flux in component j (neutrons/cm^2-sec-MW)

Σ_{ijk} = macroscopic cross section to product radioisotope i, in component j, from parent nuclide k (cm^{-1})

V_j = volume of component j (cm^3)

In Equation 4, the term Σ_{ijk} can be replaced by the following:

$$\Sigma_{ijk} = \frac{N_o}{A_k} f_{kj} \rho_j I_k \sigma_{ki} \tag{5}$$

Where:

N_o = 0.6023 x 10^{24} atoms/mole

A_k = atomic weight of parent isotope k (gr/mole)

f_{kj} = weight fraction of parent isotope k in component j

ρ_j = density of component j (gr/cm^3)

I_k = abundance of parent isotope k in parent element

σ_{ki} = microscopic cross section for the production of nuclide i by neutron interaction with isotope k (cm^2)

Finally, with W_j as the weight in grams of component j, we have:

$$A_{ijk} = K N_o W_j f_{jk} \frac{I_k}{A_k} \sigma_{ki} \phi_j \sum_n P_n (1-e^{-\lambda_i T_n}) e^{-\lambda_i \tau_n} \tag{6}$$

It should be noted in the above derivation, that the burnup reaction (activation of previously activated species) has been neglected. For many of the species that will be considered in an activation analysis, either the radionuclide i created by neutron interaction will itself have a small cross section for absorbing neutrons, or the granddaughter radionuclide has a short half-life as compared with the daughter radionuclide. Thus, for most calculations, burnup reactions may be neglected, which has the effect of making the calculations more conservative. If the burnup factor is to be included, it may be easily shown that Equation 6 becomes 6a:

$$A_{ijk} = K N_o W_j f_{kj} \frac{I_k}{A_k} \sigma_{ki} \phi_j \sum_n P_n \left\{ \frac{\lambda_i}{\lambda_i + P_n \phi_j \sigma_b} \right\} (1-e^{-(\lambda_i + P_n \phi_j \sigma_b) T_n}) e^{-\lambda_i \tau_n} \tag{6a}$$

where σ_b is the cross section for the burnup of radionuclide i.

3. Sample Activation Calculation for Materials of Known Composition

To illustrate the calculation procedure we shall consider the activity levels of specific isotope, ^{60}Co, the activation product of ^{59}Co. The activity level due to ^{60}Co shall be calculated for the core shroud of a large PWR at the most irradiated section, the core centerline. The activity level of ^{60}Co will be calculated at reactor shutdown following the procedure outlined above.

A. Obtain the Operating Histogram

For the hypothetical reactor, we shall assume a 40 year operating lifetime, at 0.80 plant capacity. The average gross thermal output of this reactor is 3411 MWt, and we have:

n = 40 operating periods
P_n = 3411 MWt for all n periods
T_n = 0.80 years for all n periods

B. Obtain Flux Profiles

Since we do not have flux profiles for our hypothetical reactor, we shall assume that the average thermal and fast neutron fluxes in a section of the core shroud at the core centerline are:

ϕ_T = 8.40×10^9 neutrons/cm^2-sec-MWt
ϕ_F = 1.94×10^{10} neutrons/cm^2-sec-MWt

In practice, care must be taken in selecting the average flux values especially through thick components such as the pressure vessel.

C. Determining Component Weights

We shall consider segmenting the core shroud and taking a cylindrical section from the core centerline that has the following dimensions:

Height of segment	101.60 cm
Inside radius of segment	168.54 cm
Outside radius of segment	171.40 cm

Using this data, the cylindrical section of core shroud has a volume of 3.103×10^5 cm^3. Since the core shroud is made of stainless steel that has a density of 8.027 grams/cm^3 (AISI Type 304), the weight of the cylindrical section is:

$$W_j = 2.491 \times 10^6 \text{ grams}$$

D. Material Composition

Since our reactor core shroud has not undergone a material analysis, we shall refer to Reference 2, Appendix B, and a value of 0.02 percent by weight of ^{60}Co will be used.

E. Isotope Library

Cobalt exists in nature as 100% ^{59}Co. From BNL-325, the thermal cross section is:

$$\sigma_T = 38 \text{ barns}$$

BNL-325 does not contain a large number of data points for the fast neutron absorption cross section. However, we shall use the assumptions made in Section 4.2.4(1), and from the data provided, use:

$$\sigma_F = 50 \text{ millibarns}$$

Other reactions that should be considered in this analysis are the ^{60}Ni (n,p) ^{60}Co, the ^{61}Ni (n,d) ^{60}Co, and the ^{60}Co(n,γ) ^{61}Co neutron interactions. The (n,p) and (n,d) reactions have measureable cross sections at energies above 1 MeV, but their contributions to the total activity is deemed negligible as their cross sections are quite small. The burnup reaction ^{60}Co (n,γ) ^{61}Co has a cross section of about 2 barns, but it will be neglected from the present calculation for simplicity.

F. Activity Calculation

Using Equation 6 developed in Section 4.2.4(2), we have the following variables defined:

$K = 1/(3.7 \times 10^{10})$ curies/(disintegration/sec)

$N_o = 0.6023 \times 10^{24}$ atoms/mole

$W_j = 2.491 \times 10^{6}$ grams

$f_{kj} = 0.0002$

$I_k = 1$

$A_k = 58.9332$ grams/mole

$\sigma_T = 38.0 \times 10^{-24} \text{cm}^2$

$\sigma_F = 50.0 \times 10^{-27} \text{cm}^2$

$\phi_T = 8.40 \times 10^{9}$ neutrons/cm^2-sec-MWt

$\phi_F = 1.94 \times 10^{10}$ neutrons/cm^2-sec-MWt

$P_n = 3411$ MWt for all 40 operating periods

$\lambda_i = 0.132$ years^{-1}

$T_n = 0.80$ years for all 40 operating periods

$\tau_1 = 39.0$ years

$\tau_2 = 38.0$ years

$\vdots$

τ_{39} = 1.0 year

τ_{40} = 0.0 years

Inserting these variables into Equation 6, we obtain:

A_{ijk} (thermal) = 120,800 Curies

A_{ijk} (fast) = 367 Curies

4.2.5 Calculation of Contact Exposure Rates

1. Definitions of Exposure and Dose Rate

It is important to make a distinction between an exposure rate and an absorbed dose rate. The term "exposure rate" is the incident rate of x-or γ-ray radiation on a body at any point. For personnel protection the exposure rate is used to determine the biological (or structural) damage that is called the absorbed dose.

The unit of radiation is the roentgen, which is that quantity of x or γ radiation such that the associated corpuscular emission per 0.001293 grams of air produces in air, ions carrying one eletrostatic unit (1 esu) of quantity of electricity of either sign. This means one roentgen will ionize 1 cubic centimeter of air at STP and will produce ions having a total charge on all ions of 1 esu. The rate of radiation emission (exposure rate) is expressed as R/unit of time (R/hr).

A more general unit of radiation is the rad, which is independent of both the type of radiation and the irradiated material. This unit expresses either an absorbed or delivered dose, and is defined as being equal to the absorption of 100 ergs/gram at the point of interest. The dose rate is expressed as rads/unit of time (rads/hr).

Since not all radiations have the same effect on body tissue, a quality factor (QF) or relative biological effectiveness (RBE) has been developed to account for these differences. It is the ratio of a dose of 250 kV x-rays to produce a given effect to that dose of comparison radiation to produce the same effect. Typical QF's are shown below:

Radiation	QF
X and γ rays	1
Electrons	1
Thermal neutrons	2-5
Fast neutrons (10 Mev)	5-10
Alpha	20
Protons (10 MeV)	10

The unit of biological dose is the roentgen equivalent man, or rem. It is defined as the dose in tissue that results in biological damage equivalent to that produced per rad of X-ray. Therefore:

rem = QF x dose in rads

Rem dosages of different radiations are additive. The rate of biological dose absorption is expressed in rems (or millirems) per unit time (mrem/hr). From the quality factors shown above, an exposure rate from x and γ rays of 1 R/hr will result in a dose rate of 1 rem/hr.

2. Definition of Contact Exposure Rates

The contact exposure rate is the radiation exposure rate from sources (piping, valves, tanks, vessels) measured or calculated at the surface of the component. In this handbook the contact exposure rate is defined as being the exposure rate at a distance of 1 centimeter from the source surface. Contact exposure rates calculated from the activity level data are used to estimate the occupational exposure of workers. Also, contact dose levels as a function of time for activated materials within a mothballed or entombed facility will be of value to the reactor owner in planning the scheduling of future actions, and determining the period of a possession-only license.

3. Contact Exposure Rate Equations

For most calculations of contact exposure rates from the pressure vessel and its internals, the use of thick-slab, distributed-volume source geometry is sufficient to produce relatively accurate results. However, the calculations may require the use of point, line, planar or cylindrical geometries instead. The selection of the appropriate geometry is based on the anticipated position and location of the personnel relative to the radioactive source.

The data required for the calculations are (1) the activity levels of the irradiated material, and (2) the attenuation characteristics of the material and of the transport media (air).

For unshielded, thick-slab, distributed-volume sources, the buildup gamma flux as given by Rockwell[25] is :

$$\phi_{ij} = \frac{S_{vj}B}{2\mu_j} \{1 - E_2 (\mu_j a)\} \tag{7}$$

Where:

ϕ_{ij} = gamma flux due to radionuclide i at the surface of component j (gamma/cm^2-sec)

S_{vj} = constant distributed volume source for component j (gamma/cm^3-sec)

μ_j = linear attentuation coefficient of component j (cm^{-1})

a = thickness of slab component j (cm)

E_2 = exponential integral function plotted in Reference 26

The variable B in Equation 7 is the Taylor form of the point buildup factor[27]; B is evaulated by:

$$B = A_1 e^{-\alpha_1 \mu t} + A_2 e^{-\alpha_2 \mu t} \tag{8}$$

$A_1, A_2, \alpha_1, \alpha_2$ = point buildup coefficients found in References 25, 27, and 28.

μ = linear attenuation coefficient of the material through which the gamma rays traverse.

t = thickness of the material.

The Taylor form, used in this manner, will produce conservative results. As an alternative to using the Taylor form, point exposure build-up factors may be found in Rockwell for various materials. The contact exposure rates due to the buildup gamma fluxes is given by Lamarsh[27] as:

$$\dot{X} = 0.0659\, E_o \left(\frac{\mu_a}{\rho}\right)_{air} \phi_{ij} \tag{9}$$

Where:

$\dot{X}$ = contact exposure rate (mR/hr)

E_o = energy of decay gamma ray (MeV)

$\left(\frac{\mu_a}{\rho}\right)_{air}$ = mass absorption coefficient of air (cm^2/gr)

Most survey equipment measures exposure rates as opposed to absorbed dose rates. The model presented above calculates exposure rates that may be correlated to absorbed dose rates by means of the following conversion for gamma or X-radiation:

$$\dot{D} = \frac{87.7}{100} \times \frac{\left(\frac{\mu_a}{\rho}\right)_t}{\left(\frac{\mu_a}{\rho}\right)_{air}} \times \dot{X} \tag{10}$$

Where:

$\dot{D}$ = contact dose rate (mrem/hr)

$\left(\frac{\mu_a}{\rho}\right)_t$ = mass absorption coefficient of tissue (cm^2/gr)

$\dot{X}$ = contact exposure rate (mR/hr)

4. Sample Contact Exposure Rate Calculation

To perform this sample calculation, we shall refer to the sample calculation used in the activation analysis in paragraph 4.2.4(3). The calculated activity must be redefined as a volumetric source term to introduce it into Equation 7. Since ^{60}Co has two gamma rays per disintegration, the mass of the segment of the core shroud is 2.491×10^6 grams, and the density of the metal in the pressure vessel is 8.027 gr/cm^3, and the total activity (fast plus thermal) is 121,255 Curies, the source term for Equation 7 becomes:

$$S_j = \frac{(1\ \gamma\ \text{pair/dis.})\ (121{,}167\ \text{Curies})\ (3.7 \times 10^{10}\ \text{dis/sec-Curie})\ (8.027\ \text{gr/cm}^3)}{(2.491 \times 10^6\ \text{grams})}$$

$$S_j = 1.445 \times 10^{10}\ \text{gamma pairs/cm}^3 - \text{sec}$$

The thickness of the core shroud is:

$a = 2.86$ cm

The energies of the two gammas of ^{60}Co, as given by the CRC Handbook of Chemistry and Physics,[29] are:

$$E_{\gamma 1} = 1.173\ \text{MeV}$$

$$E_{\gamma 2} = 1.332\ \text{MeV}$$

The linear attenuation values for these two gamma rays in stainless steel, AISI Type 304 are:

$$\mu_{\gamma 1} = 0.443\ \text{cm}^{-1}$$

$$\mu_{\gamma 2} = 0.415\ \text{cm}^{-1}$$

From Reference 27, the tabulated point buildup factors are:

$A_1(\gamma 1) = 23.688$

$A_2(\gamma 1) = -22.688$

$\alpha_1(\gamma 1) = -0.05834$

$\alpha_2(\gamma 1) = -0.02128$

$A_1(\gamma 2) = 22.522$

$A_2(\gamma 2) = -21.522$

$\alpha_1(\gamma 2) = -0.05602$

$\alpha_2(\gamma 2) = -0.01820$

Evaluating the exponential integrals using the tables in Etherington[26], and substituting the values into Equation 7, we obtain the buildup fluxes:

$\phi_{ij}(\gamma 1) = 2.078 \times 10^{10}$ gammas/cm^2-sec

$\phi_{ij}(\gamma 2) = 2.519 \times 10^{10}$ gammas/cm^2-sec

The values for the mass absorption coefficients in air for each of the ^{60}Co gamma ray energies are:

$\frac{\mu_a}{\rho}(1) = 0.0272$ cm^2/gr

$\frac{\mu_a}{\rho}(2) = 0.0264$ cm^2/gr

Substituting these mass absorption values into Equation 8 along with the buildup fluxes calculated above, we obtain the total contact exposure rate:

$$\dot{\chi} \quad = \quad 1.201 \times 10^5 \ \text{R/hr}$$

In the above calculation of the exposure rate due to ^{60}Co gammas from the activation of ^{59}Co in the core shroud, we have assumed a thick slab geometry for the source. For other physical component forms the appropriate source term geometry must be determined, which will lead to different forms of the buildup flux equation (Equation 7).

It should be noted that these calculations do not include the contact exposures due to the beta particles emitted by ^{60}Co. The estimates for the beta exposures are not necessary in most cases because the exposure contribution due to beta and other radiations are insignificant relative to the gamma exposure. Futhermore, the provisions made to shield personnel from some of the gamma radiation will effectively shield them from all beta radiation. The calculation of beta exposures is usually carried out only for inhalation and ingestion doses since direct beta exposures are shielded by just a few layers of dead skin.

However, the beta radioactivity due to activation of materials is important and must be considered in the release of materials for unrestricted use.

4.2.6 Direct Measurement Techniques for Activated Material

Direct measurements of activity levels and exposure rates of irradiated materials are an essential part of the radioactive inventory program.

Direct measurements are carried out:

1. When it is difficult to develop a mathematical model that will give an accurate estimate of the neutron activation of a component
2. When the composition of the material is unknown
3. In order to obtain benchmarks for the calculated activation and exposure levels, and
4. To confirm the accuracy of the calculated estimates.

Factors to be considered in selecting radiation survey instruments for determining contact exposure rates are:

1. Radiation energy levels and instrument sensitivity
2. Response time
3. Accuracy and precision
4. Measurement area environment (i.e. temperature, etc)
5. Type of radiation (neutron, gamma, beta, alpha).

A gamma ray spectrometer coupled to a multi-channel analyzer, is used to determine total gamma activity. It can also be used to determine the relative concentration of radionuclides.

1. How to Measure Dose Rates at Various Locations

Direct measurement of exposure rates in a reactor can only be made when all fuel has been removed from the core. One method is to place a detector at the inside wall of a thin-walled stainless steel tube that is sealed on the bottom. The bottom of the tube can be filled with lead shot to shield the detector from some of the back or bottom-scattered radiation. The tube is then inserted into the reactor vessel at several different locations and elevations of the vessel and internals to read the contact dose rate. The stainless steel tube wall will shield essentially all beta radiation from the detector. The resulting gamma exposure rate measurement can be used to benchmark or normalize the calculations, or may be used directly. Corrections may have to be made to account for water attenuation in water-moderated reactors and for distance from the component.

Geometry considerations must be taken into account when making direct measurements. If necessary, shielding should be provided to reduce background to a tolerable level.

2. Materials of Unknown Composition and Activity

For materials of known composition that cannot be readily modeled mathematically, direct measurement of their activity will provide the data needed for the radionuclide inventory.

For materials of unknown composition, the general procedure is to: (1) obtain direct exposure rate measurements; and (2) take small samples. The samples are subjected to beta and gamma ray spectroscopic analysis to determine the relative activity levels of the various radionuclides present. In carrying out the spectroscopic analysis, it is important to allow sufficient time for the decay of short-lived radionuclides so that they will not mask the activities of longer-lived, lower activity level radionuclides.

The sampling program should be drawn up to ensure that appropriate samples are obtained from the following locations:

1. Reactor vessel internals
2. Reactor vessel stainless steel cladding
3. Reactor vessel carbon steel shell
4. Biological shield concrete

Irradiated materials of unknown composition that may be sampled are small components such as nuts and bolts and concrete shield plugs.

The radioactive constituents of concrete will vary considerably depending on the type of aggregate that was used. The aggregate for construction is generally provided locally and is likely to be different in each region of the country. The concrete radionuclide inventory may be determined from the spectroscopic analysis and exposure rates of core samples. To estimate the activity at a location of interest, measure the exposure rate at a sample point (prior to sample removal) and the activity of the sample. The ratio of sample exposure rate to sample activity may be correlated to exposure rate measurements at any location of the same material. It is assumed that the isotopic distribution does not vary significantly within the same material of a given component. Furthermore, it is assumed that the ratio of thermal flux to fast flux is nearly constant as a function of axial and radial distance from the core center, and the thermalizing effect of water and steel does not distort the neutron flux energy distribution significantly in the component when two-group energy is used.

3. Benchmarking the Activation Analysis Calculations

The activation analysis and exposure rate calculations should be considered a method for estimating the radionuclide inventory and not an exact determination. Therefore, direct measurement benchmarking of calculated activation and exposure levels is desirable.

For a nuclear reactor, benchmark measurements of selected irradiated components prior to final plant shutdown may be accomplished during a maintenance or refueling shutdown. For test reactors or hot cells, the direct measurements may be made during maintenance work or even scheduled into the operating program.

However, these measurements can be made only when all fuel has been removed from the core. Therefore, after the plant has been shut down and the fuel and neutron sources have been removed, direct measurements at specific locations should be initiated in order to provide the required benchmarking data. The difference between the calculated levels and the measured levels can be used to normalize the dose estimates from the activation model. For benchmarking, only a few measurements need to be made at regions close to the activation calculation regions.

For example, if the pressure vessel activation was calculated by segmenting the vessel into several thick concentric cylinders, the corresponding calculated contact exposure rates, at the inner and outer surfaces of the vessel, should be benchmarked against measured exposure rates on these surfaces. The rates of the difference between actual and calculated exposure rates can be used to normalize the activation calculation.

4. Equipment for Direct Measurements

Gamma ray spectroscopic systems are used to determine the activity and radionuclide content of neutron-irradiated components. The detector measures the gamma ray energies, and the distribution of energies is recorded in a multi-channel analyzer. The identity and concentrations of the radionuclides present and their activity levels, can be computed from the collected data.

Instrument characteristics that must be taken into consideration in selecting radiation surveying equipment include:

A. Sensitivity

The instrument must be sufficiently sensitive to measure radiation at the desired level. It is important to match the capabilities of the equipment to the range of energy levels to be measured. The instruments must be used only for the type of radiation for which they are designed.

B. Response Time

It is suggested that instruments with slower response times be used because of the marked decrease in sensitivity of fast response instruments. Fast response instruments may not detect small areas of high contamination.

C. Accuracy and Precision

Most radiation measuring instruments have a limited span of energy over which they can accurately determine the radiation dose.

D. Ruggedness

The instrument must be able to withstand the environmental stresses to which it may be exposed, for example, high temperatures or high radiation levels.

Several manufacturers of nuclear instrumentation (Ortec, Canberra, Harshaw) have packaged systems that combine the detector, the analyzer and mini computer. The data is automatically analyzed and the list of radionuclides and their activity levels are printed out. The packaged systems may involve considerable expense. Before purchase is considered, it is worth checking to see if the facility to be decommissioned already has equipment for radionuclide analysis. In addition, it may be preferable to use an independent laboratory to perform the analyses.

There is a great variety of equipment for determining contact exposure rates. Low-level exposure rates (to 100 R/hr) may be measured by hand-held instruments, such as the "Cutie Pie" that is capable of detecting gamma or X-rays between 7 KeV and 2 MeV with an accuracy of ±10%. These instruments are also sensitive to alpha and beta radiations. Some instruments are provided with removable end caps that permit beta and alpha discrimination and electron equilibrium for high energy gamma radiation. Response times for these instruments may be as great as 20 seconds to reach 90% of true reading for exposure rates of about 0.1 mR/hr. Higher exposure rates reduce the response time significantly.

Remote radiation probes are available for exposure rate measurements above 100 R/hr. These probes are capable of measuring gamma exposure rates of up to 200 R/sec. The energy ranges are usually wide, from 50 KeV to 18 MeV.

4.2.7 Confirmation of Activity Levels and Exposure Rate Calculations

It is recommended practice that the calculated estimates of radionuclide inventory and exposure rates be verified by means of direct measurement. After final plant shutdown, a rigorous sampling and direct measurement program should be carried out to determine the actual radiation levels and dose rates.

Verification measurements should be made on the major components, and the results should be compared to the estimates arrived at by the calculation procedure. If there are inconsistencies between measured and calculated results, one should examine the calculation assumptions or model used so the measured data may be used to normalize the calculations.

4.3 HOW TO ESTIMATE INTERNAL SYSTEM AND EXTERNAL SURFACE CONTAMINATION

4.3.1 General Procedure

An estimate of the radionuclides deposited on the internal and external surfaces of various systems is prepared by:

1. Carrying out a complete radiation survey of the external surface contact exposure rates
2. Taking representative scraping samples from inside representative piping and components and analyzing the samples for radionuclide composition and concentration
3. Calculating the total deposited radionuclide inventory by correlating the surface exposure rates to the radionuclide content as determined by the scraping samples.

This procedure for estimating the deposited radionuclide inventory can be applied either prior to or after final facility shutdown. To obtain data prior to final shutdown, scraping samples and contact dose measurements can be taken during maintenance or refueling shutdowns. It is obvious that any plant operation after sampling may cause excessive redeposition and result in an inaccurate assessment of residual contamination.

4.3.2 Sources of Deposited Radionuclides

The sources of internal and external surface contamination are dependent on the type of facility (power reactor, hot cell, fuel reprocessing plant, etc.) and the operating history with respect to deposition and intentional or accidental releases. The potential sources and contamination mechanisms are widely varied for each facility type. For purposes of illustration this discussion will be primarily limited to a reactor facility, although in most cases, the inventory estimating methods are applicable to other facility types.

Continuous exposure of metals to high-temperature water in the primary and secondary coolant systems of a reactor results in corrosion and erosion of the metallic surfaces. The corrosion products pass through the core and become radioactive as a result of their interactions with neutrons.

In addition, fuel cladding failures may result in the release of fission products to the reactor coolant system. These corrosion and fission products form particulate crud deposits on the inner walls of the piping and components in the primary system. The crud deposits are the main source of radioactivity on primary loop surfaces.[30] In a fuel reprocessing facility the dissolved fission products and activated fuel cladding constitute the major source of system contamination.

External surface contamination is primarily due to leakage from the primary and auxiliary systems. Open surface reactor pools or fuel storage service pools containing contaminated water evaporate and release particulate contamination to the containment air, which subsequently settles out on structures, components, piping and electrical cable runs. Maintenance procedures, whereby contaminated systems must be drained for access, can spread additional contamination from accidental spills. The deposited radioactivity consists mainly of gamma emissions from ^{58}Co, ^{60}Co, ^{137}Cs, ^{55}Fe, ^{54}Mn. Fission products, uranium and plutonium, may also be present as noted earlier.

4.3.3 Measurement of Internal System Contamination

The objective of a contamination measurement program is to correlate the surface contact exposure rate with the data from samples (scrapings or smears) taken from the interior at that location. The measuring equipment required is the same as described in Section 4.2.6(4) of this chapter, for contact exposure rates. The hand-held "Cutie Pie" instrument is typically used. The system contact exposure rate must be measured with the system empty of fluid.

Pipe or component diameter and schedule (thickness) influence the contact exposure measurement by virtue of the geometry of the source (line or cylinder) and shielding provided by the pipe thickness. Accordingly, the effects of source geometry, material shielding and gamma flux attenuation must be included in evaluating contact exposure rate measurements.

Scraping samples should be of sufficient quantity to ensure accuracy in the gamma ray spectrographic analysis. Typically, a few milligrams per sample is sufficient.[31] If internal smears are taken for benchmarking, etc., they should be taken close to scraping sample locations whenever possible.

Scraping samples may be taken by removing the trim from a valve to expose contaminated surfaces, separating piping at a flange or opening manways or cover plates in components. The sample may be collected using a rotary file or scraper to remove a few mils of thickness from the surface. The chips should be bagged immediately and labeled with the system name, component identification, location and external exposure rate.

Scraping samples are analyzed in a gamma ray spectrometer coupled to a multi- channel analyzer. From the gamma ray spectrum obtained for each sample, the radionuclide content and the percent of total activity for each of the individual radionuclides may be determined.

All samples should also be checked for long-lived beta emitters such as ^{14}C that may prevail after the gamma emitters have decayed. To ensure that possible beta or gamma ray emitters are not being masked by the strong compton scattering radiations from ^{60}Co or ^{137}Cs, chemical separation by selective precipitation may be necessary, or a compton-suppressed spectrometer may be used. The resulting precipitates are analyzed with gamma and beta spectrometers.

The scraping samples provide data on the distribution of radionuclides in a specific pipe run. The external gamma contact exposure levels for that run are correlated to the radionuclide data in order to estimate the quantity of radionuclides present within that section of the pipe.

4.3.4 Calculating the Deposited Radionuclide Inventory

The inventory of radionuclides for internally contaminated systems may be estimated by correlating the exposure rates along the piping with its radionuclide composition as determined from the scraping samples. This correlation method provides a simplified technique for estimating the inventory and is developed by taking scraping samples from a particular piping section and determining the relative activity levels of each radionuclide in the section.

The methods for performing this correlation are outlined in the following paragraphs. Figure 4.5 is a block diagram of the procedure detailed below.

1. Determination of Radionuclide Content

The first step is to assemble the data on radionuclide content and relative activities acquired from the scraping samples and by direct measurement of exposure rates, as described in Section 4.3.3.

2. Development of Piping System Data

As a necessary aid to the estimation procedure, a table containing piping and insulation dimensions and attenuation and buildup factors should be prepared. To compile this table, a determination of potentially contaminated systems must be made. Items that should be included in this table are:

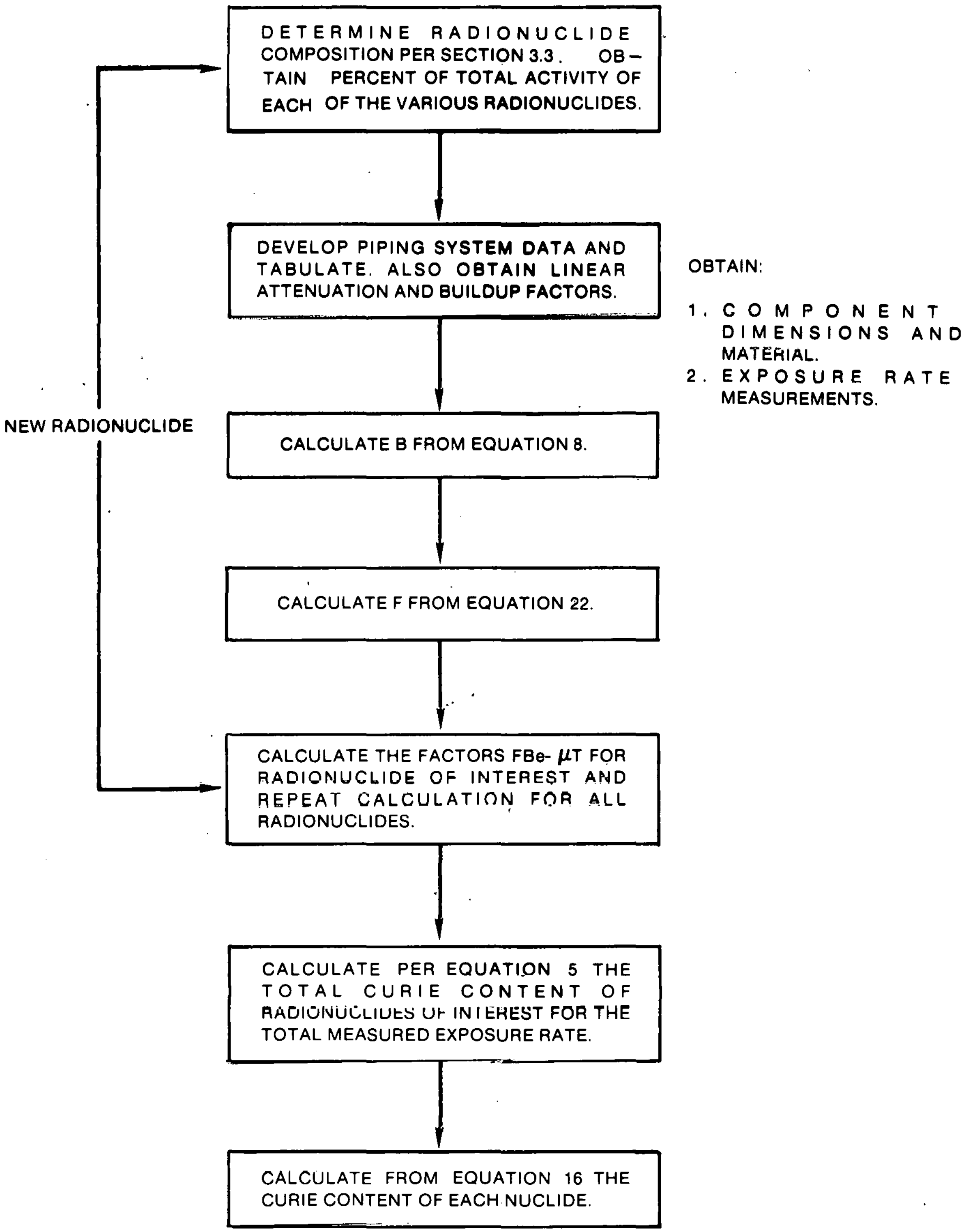
A. Location of system
B. Schedule (thickness) and radius of piping
C. Thickness, radius and composition of insulation
D. Attenuation and buildup factors of piping and insulation
E. External surface exposure rate of piping.

3. Development of the Calculational Models

Using exposure rate measurements from the survey of potentially contaminated system piping, and scraping sample data from specific pipe or component locations, an expression can be developed to estimate the curie content of activation products within a particular pipe run. This estimate is based upon the correlation of

FIGURE 4.5

FLOW DIAGRAM OF CURIE CONTENT CALCULATION



exposure rates measured along the surface of the pipe and the scraping sample data taken as described in the following paragraphs.

Radioactive products are deposited on pipe walls; thus the source of activity is in the form of a hollow cylinder or tube. The uncollided gamma flux near the side of a non-absorbing tubular source is given by Price, et.al.[32] as:

$$\phi_\gamma = S_A \Psi I(h, R) \tag{11}$$

Where:

ϕ_γ = uncollided gamma flux at the detector (gammas/cm^2-sec)
S_A = source strength per unit area of cylinder (gammas/cm^2-sec)
ψ = angle subtended from the detector to the ends of the tubular source (radians)
h = perpendicular distance from detector to the axis of the tube source (cm)
R = radius of the tube source (cm)
I(h,R) = an integral function plotted in References 21 and 22 equals I (h/R)

For a detector point near the surface of the pipe, the angle subtended will approach π radians. Thus, the exposure rate at a detector near the surface of the tubular source may be expressed as:

$$\dot{\chi} = \pi S_A I(h, R) F \tag{12}$$

Where:

$\dot{\chi}$ = exposure rate at detector near the surface of the tabular source (mR/hr)
F = flux to exposure conversion factor (mR/hr per gamma/cm^2-sec)

The exposure buildup and attenuation through the pipe wall and pipe insulation is:

$$\dot{\chi} = \pi S_a I(h, R) FBe^{-\mu t} \tag{13}$$

Where:

μt = thickness of the pipe wall and insulation in relaxation lengths

B = exposure buildup factor

Solving for the surface source strength S and converting to curies, we obtain:

$$\frac{C}{cm^2} = \frac{\dot{\chi}}{3.7 \times 10^{10} \pi I(h, R) FBe^{-\mu t}} \tag{14}$$

Equation 14 may be used to calculate the curie content in a tubular source when the exposure rate due to individual nuclides is known. Since this value is an unknown, the curie contents of individual nuclides must be expressed in terms of the total measured contact exposure rate. The total curie content for the i radionuclides emitting j gammas becomes:

$$\frac{C_t}{cm^2} = \frac{\dot{\chi}}{\sum_i f_i \, 3.7 \times 10^{10} \pi I(h, R) \sum_j F_j B_j e^{-\mu_j t}} \tag{15}$$

Where:

C_t = total curie content of all radionuclides

$\dot{\chi}_t$ = total exposure rate as measured in the survey

F_i = relative fraction of total activity for radionuclide i

Once C_T has been calculated, the curie content of each of the radionuclides, C_i, may be calculated by:

$$C_i = f_i C_t \tag{16}$$

An equation similar to Equation 15 may be developed to obtain the activity of activation products deposited on the inner surfaces of large components; such as the feedwater heater. The asymptotic expression for the flux of a large self-attenuating volume source is:

$$\phi = \tfrac{1}{2} S_v \lambda \tag{17}$$

Where:

ϕ = uncollided gamma ray flux on surface (gammas/cm^2-sec)

S_v = specific volume source strength (gammas/cm^3-sec)

λ = relaxation length of gammas within absorbing source (cm)

As before, the surface exposure rate may be expressed as:

$$\dot{\chi} = \tfrac{1}{2} S_v \lambda F \tag{18}$$

Where:

$\dot{\chi}$ = exposure rate at surface (mR/hr)

F = flux to exposure rate conversion factor (mR/hr per gamma/cm^2-sec)

Solving for the specific source strength:

$$S_v = \frac{2\dot{\chi}}{\lambda F} \tag{19}$$

The activity in the component in terms of curies is then:

$$C = \frac{2}{3.7 \times 10^{10}} \quad \frac{\dot{\chi} V}{2FB} \tag{20}$$

Where:

V = volume of component (cm^3)

As stated for Equation 14, Equation 20 is valid only when the exposure rate due to individual nuclides is known. The total curie content for the i radionuclides emitting j gammas is:

$$C_t = \frac{2}{3.7 \times 10^{10}} \quad \frac{\dot{\chi}_t V}{\sum_i \lambda_i \sum_j (F_j B_j)} \tag{21}$$

Curie contents of individual nuclides may then be calculated from Equation 16.

4. Sample Calculation

The aim of the sample calculation is to calculate ^{60}Co and ^{137}Cs curie contents in a 24 in. OD main steam pipe, which has a wall thickness of 1.219 in.

A. Radionuclide Composition

The first step in this procedure is to determine the isotopic composition of the crud deposited on the inside of the pipe. A spectrometric analysis is performed on a scraping sample from an appropriate section of the pipe as described in Section 4.3.3. Using data obtained in a previous study[31], we shall assume the spectrometric analysis reveals ^{60}Co as representing 95% of the total activity and ^{137}Cs as representing 5% of the total activity. There are no other radionuclides present.

B. Piping System Data

In this example, we shall simplify the problem by assuming pipe insulation has been removed. The inside radius of the pipe which is equal to the radius of our thin cylindrical source is 10.781 in. The pipe wall in 1.219 in. thick and is made of Type 304 stainless steel. For this calculation, we shall assume that the total contact exposure rate is 5 R/hr. From Reference 33 we find the value of I(h,R) to be 0.23.

The linear and mass attenuation coefficients, and the buildup parameters for each radionuclide, necessary to perform the calculations, are tabulated below.

For ^{60}Co:

$E_{\gamma 1}$ = 1.173 MeV (100%)
$E_{\gamma 2}$ = 1.332 MeV (100%)
$A_1\ (\gamma 1)$ = 23.688
$A_2\ (\gamma 1)$ = -22.688
$\alpha_1\ (\gamma 1)$ = -0.05834
$\alpha_2\ (\gamma 1)$ = -0.02128
$A_1\ (\gamma 2)$ = 22.522
$A_2\ (\gamma 2)$ = -21.522
$\alpha_1\ (\gamma 2)$ = -0.05602
$\alpha_2\ (\gamma 2)$ = -0.01820
$\mu\ (\gamma 1)$ = 0.443 cm^{-1}
$\mu\ (\gamma 2)$ = 0.415 cm^{-1}
$(\frac{\mu_a}{\rho})\ \gamma 1$ = 0.0272 cm^2/gr
$(\frac{\mu_a}{\rho})\ \gamma 2$ = 0.0264 cm^2/gr
f_i = 0.95

And for ^{137}Cs:

E_γ = 0.6616 MeV (93.5%)

A_1 = 29.303

A_2 = -28.303

α_1 = -0.06598

α_2 = -0.03329

μ = 0.606 cm^{-1}

$(\frac{\mu_a}{\rho})$ = 0.0294 cm^2/gr

f_i - 0.05

The buildup factors, B, are calculated using the Taylor form as found in Equation 8.

$$B = A_1 e^{-\alpha_1 \mu t} + A_2 e^{-\alpha_2 \mu t}$$

The flux to exposure factor F may be obtained by substituting Equations 9 and 11 into Equation 12, from which it may be found that:

$$F = (0.0659)(E_0)\left(\frac{\mu_a}{\rho}\right)_{air} \tag{22}$$

Performing the calculation using Equation 15 we find:

$$\frac{C_t}{cm^2} = 7.430 \times 10^{-5} \text{ curies/cm}^2$$

Now, using Equation 16 we find:

For ^{60}Co:

C_i = 7.059 x 10^{-5} curies/cm^2

For ^{137}Cs:

C_i = 3.715 x 10^{-5} curies/cm^2

4.3.5 External Surface Contamination

The sources of external surface contamination are primarily from leakage from the primary and auxiliary systems as discussed in Section 4.3.2 of this chapter. An accurate assessment of the surface contamination inventory is best obtained by direct measurement using alpha, beta, gamma survey instruments coupled with surface smears over a 100 cm^2 surface, as is standard practice at most facilities.

4.4 HOW TO ESTIMATE WORK AREA DOSE LEVELS

4.4.1 General Procedure

Work area dose levels are determined by direct measurement. For many of the radiation areas in power facilities, routine surveys of radiation levels are made and detailed records kept. When estimating the work area dose levels prior to final shutdown, the most recent survey results should be utilized.

For inaccessible areas, work area dose rates can be estimated by calculational techinques. After final plant shutdown, direct measurement of some of the previously inaccessible areas may be possible.

From the work area radiation levels measured and calculated after final shutdown, it is possible to estimate the work area dose levels at a time in the future when actual decommissioning work will commence.

The major steps in estimating work area dose levels are:

1. Defining the work area
2. Making an inventory of radioactive sources in the work area
3. Defining the source geometry.

4.4.2 Defining the Work Area

In planning the decommissioning program, it is necessary to identify all of the areas and activities where workers may be exposed to radiation. The work areas include the component dose rate and the room or area dose rate since the room may contain other radioactive sources not being decontaminated or removed that would contribute to the dose. Each activity to be performed in the room should be identified in advance to predict the period of exposure and expected occupational dose.

4.4.3 Radioactive Sources in the Work Area

In each of the work areas, all of the radioactive sources must be identified and located. The dose rate contributions from each of the sources are summed to find the total dose rate for the work area. Whenever possible the dose rate for work area should be determined by direct measurement.

4.4.4 Defining the Source Geometry

One of the more difficult tasks in estimating work area dose rates by calculation, is reducing the source geometry to a form convenient for calculations of dose rates. Several geometric forms and their possible applications are discussed below.

1. Tubular and Line Sources

The tubular source geometry is useful for estimating work area doses from internal surface contaminated pipes. This geometry has been previously discussed in Section 3 of this chapter, but will have a slightly different form for dose rates a distance from the pipe[32]:

$$\dot{D} = 0.0567\, E_0 \left(\frac{\mu_a}{\rho}\right)_{\text{tissue}} S_A\, (\theta_1 + \theta_2)\, I\,(h,R)\, Be^{-\mu t} \qquad (23)$$

Where:

$\dot{D}$ = dose rate at a perpendicular distance h from the axis of the tube source (mrem/hr)

E_0 = energy of decay gamma (MeV)

$\left(\frac{\mu_a}{\rho}\right)_{tissue}$ = mass absorption coefficient of tissue (cm/gr)

S_A = source strength per unit area of cylinder (gammas/cm^2 -sec)

$(\theta_1 + \theta_2)$ = angles subtended by source (radians)

R = radius of tubular source (cm)

h = perpendicular distance from detector to the axis of the tube source (cm)

I(h, R) = an integral function plotted in References 32 and 33 equals I(h/r)

B = exposure buildup factor from Equation 8

μt = thickness of the pipe wall and insulation in relaxation lengths

If (h/R) > 5, less than 5% error is made by assuming that all the emission is concentrated at the axis of the tube; that is, a line source.[32] The equation for calculating the gamma dose rates due to a line source as given by Rockwell[15] is:

$$\dot{D} = 0.0576\, E_0 \left(\frac{\mu_a}{\rho}\right)_{tissue} \frac{S_L B}{4\pi d}\; F(\theta_1, \mu t) + F(\theta_2, \mu t) \qquad (24)$$

Where:

S_L = source strength per unit distance of line (gamma/cm-sec)
θ_1, θ_2 = angles subtended by source (degrees)
$F(\theta, \mu t)$ = Sievert integral function plotted in Reference 27
d = distance from line source to detector (cm)

2. Unshielded Point Sources

The point source geometry is useful for estimating work area doses at a distance, from small volumetric sources. The dose rate a distance from the point source is:

$$\dot{D} = 0.0576\, E_0 \left(\frac{\mu a}{\rho}\right)_{\text{tissue}} \frac{SB}{4\pi r^2} \tag{25}$$

Where:
S = isotropic source strength (gammas/sec)
r = distance from source to detector (cm)

3. Distributed Volume Sources

The distributed volume source geometry has been previously discussed. The dose rates of many of the activated components may be calculated using the following equation:

$$\dot{D} = 0.0576\, E_0 \left(\frac{\mu a}{\rho}\right)_{\text{tissue}} \frac{S_V B}{2\mu_s} \{1 - E_2(\mu_s a)\} \tag{26}$$

Where:
S_V - constant distributed volume source (gammas/cm^3-sec)
μ_s = linear attenuation coefficient of source material (cm^{-1})
a = thickness of slab source (cm)

The above equations are some of those which may be used to define source geometries. References 25, 26, 27, 28, and 34 should be accessed for further information on source geometry.

4.4.5 Calculating the Dose Levels at a Time after Shutdown

The equations presented above will calculate the dose levels at the time when the curie content is determined. Since activity levels will decrease with time for each radionuclide, the calculated dose rates may be found at time (τ) after the activity measurement has been made. This is done simply by multiplying the calculated dose rate by $e^{-\lambda\tau}$ where λ is the radionuclide decay constant.

Sample Calculation

For our sample calculation, we shall consider a work area in which there are three radioactive sources, each containing the radioisotope ^{60}Co. The location and dimensions of these sources may be seen in Figure 4.6.

The 24 inch OD Schedule 80 pipe is internally contaminated with 1 μ C of ^{60}Co per square centimeter. The working location is 1 meter from the outside of the pipe and the length of the pipe run in the room is 3 meters. From geometry considerations:

$\theta_1 = \theta_2$ = 0.9828 radians

h = 100 cm

t = 3.096 cm

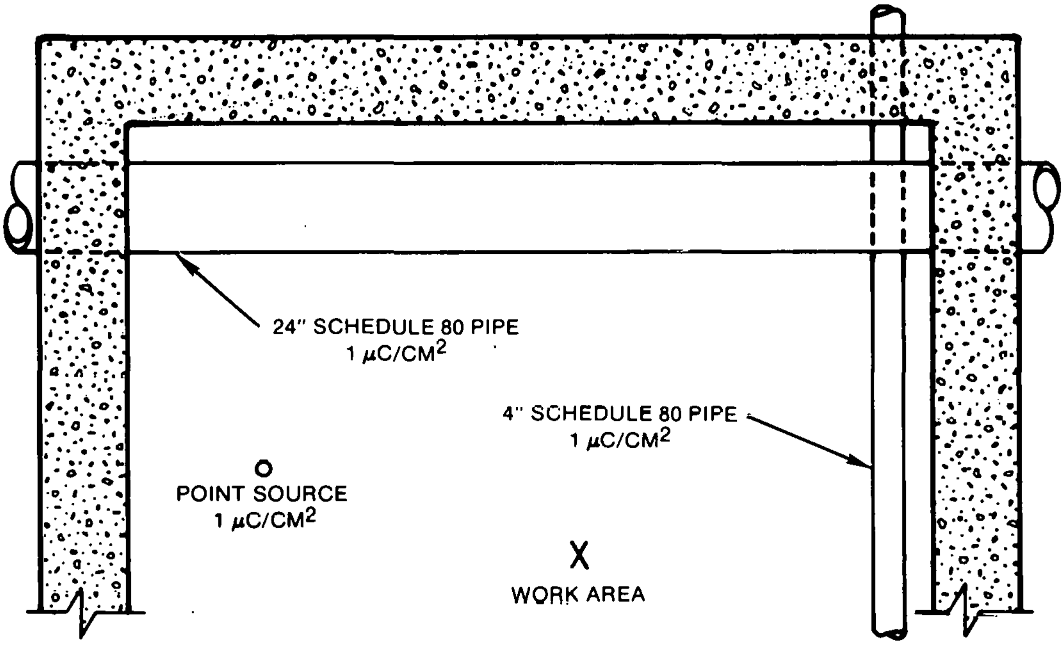
R = 27.384 cm

$E_{\gamma 1}$ = 1.173 MeV

$I(h/R)$ = 0.12

FIGURE 4.6

WORK AREA RADIOACTIVE SOURCES



$$E_{\gamma 2} = 1.332 \text{ MeV}$$

$$\left(\frac{\mu_a}{\rho}\right)\gamma 1 = 0.0292 \text{ cm}^2/\text{gr}$$

$$\left(\frac{\mu_a}{\rho}\right)\gamma 2 = 0.0284 \text{ cm}^2/\text{gr}$$

$$B_1 = 2.34$$

$$B_2 = 2.29$$

Inserting the above values into Equation 23, we find the gamma dose due to the internally contaminated piping:

$$\dot{D} = 773 \text{ mrem/hr}$$

The 4" ID Schedule 80 pipe is also contaminated with 1 μC per square centimeter of ^{60}Co. At 1 meter from this pipe, h/R is greater than 5, thus we can use the equation for a line source. The total ^{60}Co curie content in the 3 meter pipe is:

$$2\pi R\ell\ (1\ \mu C) = 2\pi\ (5.08)\ (300)\ (1\ \mu C) = 9576\ \mu C$$

and for the source term S_L in Equation 24:

$$S_L = 31.9\ \mu\text{Curies/cm}$$

From the geometry considerations:

$$\theta_1 = \theta_2 = 56.3^{\circ}$$

$$d = 100 \text{ cm}$$

$$t = 0.856 \text{ cm}$$

$$F_{\gamma 1}(\theta_1, \mu t) = F_{\gamma 2}(\theta_2, \mu t) = 0.56$$

$$F_{\gamma 2}(\theta_1, \mu t) = F_{\gamma 2}(\theta_2, \mu t) = 0.60$$

$$B_1 = 1.36$$

$$B_2 = 1.34$$

Inserting the values above into Equation 24 we obtain:

$$\dot{D} = 6 \text{ mrem/hr}$$

The 1 µC ^{60}Co point source in Figure 4.6 is also 1 meter from the work area. Having previously defined values for the variable in Equation 25, the dose contribution due to the point source is:

$$\dot{D} = 1.222 \times 10^{-3} \text{ mrem/hr}$$

The scalar sum of the three dose rates represents the total dose at the work location.

$$\dot{D}_t = 779 \text{ mrem/hr}$$

Other work area doses may be estimated in this manner.

4.5 REFERENCES

1. Basic Radiation Protection Criteria, National Council on Radiation Protection and Measurements, Report No. 39, Washington, D.C. (1971)

2. Peckner and Bernstein: "Handbook of Stainless Steel," McGraw-Hill Book Company, Inc., p. 14-2, New York (1977)

3. Stephens, J.J. and Pohl, R.D.: "Trace Elements in Reactor Steels: Implications for Decommissioning," North Holland Publishing Company (1977)

4. Honeck, H.D.: ENDF/B-IV Specification for an Evaluated Nuclear File for Reactor Applications, BNL-50066 (T-467), Brookhaven National Laboratory (May 1966, Revised July 1967) and Ozer, O. and Garber, D.: ENDF/B Summary Documentation, ENDF/B-201 (May 1973).

5.* Raymund, M.: ETOG-3, A Fortran IV Program to Process Data from the ENDF/B File to the MUFT, GAM, and ANISN Formats. WCAP-3845-1 (ENDF-114) Supplement, Westinghouse Electric Corporation (August 1973).

6. Green, N.M. et al.: AMPX - A Modular Code System for Generating Coupled Multigroup Neutron-Gamma Libraries from ENDF/B, ORNL-TM-3706 (to be published)

7.** Petrie, L.M. and Cross, N.F.: KENO IV - An Improved Monte Carlo Criticality Program, ORNL-R938 (November 1975)

8. Bell, G.I. and Glasstone, S.: "Nuclear Reactor Theory," Van N'ostrand Reinhold Co., New York, New York (1970)

9. Engle, W.W.: A User's Manual for ANISN, Union Carbide K-1693 (1967)

10. Lathrop, K.D.: DTF-IV, A Fortran IV Program for Solving the Multigroup Transport Equation with Anisotropic Scattering, LA-3373 (1965)

11. Rhoades, W.A.: A User's Manual for DOT, Union Carbide K-1694 (1973)

12. Lathrop, K.D., Brinkley, F.W.: Theory and Use of the General Geometry TWOTRAN-II Program, LA-4432 (1966)

13. Peterson, E.G.: MAC, A Bulk Shielding Code, HW-73381 (1962, with Supplements 9/1965)

14. Hjarne, L.: A User's Manual for the NRN Shield Design Method, AB Atomenergi AE-145 (1964)

* Available from Argonne National Laboratory Code Center.

** Available from Oak Ridge National Laboratory Radiation Shielding Information Center.

15. Straker, E.A. et. al.: The MORSE Code - A Multigroup Neutron and Gamma Ray Monte Carlo Transport Code, ORNL-4585 (1970)

16. Klopp, D.A.: NAP Neutron Activation Prediction Code, IITRI A6088-21, IIT Research Institute (prepared for NASA-MSFC) (1966)

17. Heiser, P.C., Ricks, L.O.: ACT-II: Activation Gamma-Ray Source Strength Code - Simple Geometry, Finite Dilution, WANL-TNR-063 and Addendum, Westinghouse Astronuclear Laboratory (1962)

18. Bell, M.J.: ORIGEN - The ORNL Isotope Generation and Depletion Code, ORNL-4682, Oak Ridge National Laboratory (May 1973)

19. Manion, W.J. and LaGuardia, T.S.: An Engineering Evaluation of Nuclear Power Reactor Decommissioning Alternatives, Atomic Industrial Forum AIF/NESP-009, Washington, D.C. (1976)

20. The General Electric Company: Chart of the Nuclides, Schenectady, N.Y. (April 1977)

21. Hughes, D.J. et. al.: BNL-325, 2nd Edition (1958), also Supplements 1 (1960) and 2 (1966)

22. Roy, J.C. and Hawton, J.J.: CRC-1003 (1960)

23. Chattergee, A.: Nucleonics 23:8 (August 1965)

24. Landolt-Bornstein: Energy Levels of Nuclei Tables, New Series, Volume 1, Springer-Verlag, Berlin (1961)

25. Rockwell, F.: U.S.A.E.C. Report TID7004 (1956)

26. Etherington, H.: "Nuclear Engineering Handbook," McGraw-Hill Book Company, New York (1958)

27. Lamarsh, J.R.: "Introduction to Nuclear Engineering," Addison-Wesley Publishing Company, Reading, MA. (1975)

28. Goldstein, H.: "Fundamental Aspects of Reactor Shielding," Addison-Wesley Publishing Company, Reading, MA. (1959)

29. CRC Handbook of Chemistry and Physics, 53rd Edition,

30. Balakrishan, P.V. and Allison, G.M.: Some In-Reactor Loop Experiments on Corrosion Product Transport and Water Chemistry, Nuclear Technology, Volume 39 (July 1978)

31. Puerto Rico Water Resources Authority and United Nuclear Corporation Report WRA-B-69-1: BONUS Decommissioning Plan, Volume 1 (April 1969)

32. Price, B.T., Horton, C.C., and Spimey, K.T.: "Radiation Shielding," Pergamon Press, New York (1957)

33. Andrews, D.G.: U.K.A.E.A. Report, Risley 5225 (1954)

34. Springer Verlag: "Engineering Compendium on Radiation Shielding," New York (1968)

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CHAPTER 5

DECONTAMINATION

5.1 INTRODUCTION

5.1.1 Use of Decontamination in Decommissioning

Decontamination can be defined as the removal, by chemical or physical methods, of the radioactive material deposited on the internal and external surfaces of components, systems, and structures in a nuclear facility.

In decommissioning programs, the primary objective of decontamination is likely to be the reduction of the total radiation exposure of the work force performing the decommissioning activities. Other objectives of decontamination may be established on economic or legal bases such as:

1. To salvage equipment and materials
2. To reduce the volume of equipment and materials requiring disposal in licensed burial facilities
3. To restore the site and facility, or parts thereof, to an unrestricted use condition
4. To remove loose radioactive contaminants and fix the remaining contamination in place in preparation for protective storage or permanent disposal work activities
5. To reduce the magnitude of the residual radioactive source in a protective storage mode for socio-politic or public health and safety reasons, or to reduce the protective storage period.

Alternatively, the antithesis of each of the above reasons may also dictate a course of action that would require little or no decontamination.

The determination of the need for and extent of decontamination should be evaluated against the cost of the process and radiation exposure associated with decontamination, versus the exposure received by the work force in performing subsequent work activities on non-decontaminated structures, systems and components.

Decontamination in some form will be required in any decommissioning program, regardless of end product form. Certainly the floor, walls and external structure surfaces within work areas would be cleaned of loose contamination and a simple water flush of contaminated systems would most likely be performed, as a minimum. The question will arise, however, as to whether to chemically decontaminate piping systems, tanks and components. A strong case can be made in favor of leaving adherent contamination within piping and components in a dispersed form on the internal metal surfaces rather than concentrating the radioactivity via decontamination. In most cases decontamination will not be sufficiently thorough to allow unrestricted release of the item being treated, therefore, there could be a savings both in occupational exposure and cost by simply removing the contaminated system and its components and only performing certain packaging activities such as welding end caps on pipe sections. A major decontamination program will require a facility capable of processing the chemical solutions by such means as neutralization and precipitation, filtration, evaporation and demineralization. The concentrated wastes, which now represent a more significant radiation source, must be solidified and shipped for burial in licensed burial facilities. Each of these additional activities can add to the occupational exposure of removal and could conceivably be greater than the dose received from removal, packaging and shipping of the contaminated system without extensive decontamination. Resolution of this question will depend on specific facts such as the strength of the gamma emitting contamination, magnitude of the contamination and the effectiveness of the containing component and piping (wall thickness) in reducing work area radiation fields.

5.1.2 Categories of Processes

There are four basic process types in decontamination: (1) chemical; (2) manual and mechanical; (3) electropolishing and; (4) ultrasonic/chemical. The applicability of each process to the specific system, component, structure or equipment to be decontaminated will be determined in the planning phase of a decontamination program. The potential application of each category is discussed below.

1. Chemical Decontamination

   This technique uses concentrated or dilute solvents in contact with the contaminated item to dissolve either the contamination film covering the base metal, or the base metal. Dissolution of the film is intended to be nondestructive to the base metal, and is generally used for operating facilities. Dissolution of the base metal should only be considered in a decommissioning program where reuse of the item will never occur.

   Chemical flushing is recommended for remote decontamination of intact piping systems. Chemical decontamination has also proven to be effective in reducing the radioactivity of large surface areas, such as floors and walls, as an alternative to partial or complete removal.

2. Manual and Mechanical Decontamination

   Manual and mechanical decontamination are physical techniques and include washing, swabbing, using foaming agents and latex peelable coatings. Mechanical techniques are generally wet or dry abrasive blasting, grinding of surfaces and removal of concrete by spalling as discussed in Chapter 7. These techniques are most applicable to decontamination of structural surfaces.

3. Electropolishing

Electropolishing is a new application of an electrochemical technique used in the steel making industry to clean finished products. Thin layers (2 mils thick) of contaminated metals are removed using an electrical potential difference between the workpiece and the cathode in a phosphoric acid electrolyte. Electropolishing can be performed in a vat of electrolyte for small tools and components; it can be used on in-place components using an electrolyte-fed brush electrode directed at "hot spots"; or inside electrolyte-filled piping with a traveling electrode (being developed at Battelle Pacific Northwest Laboratory).

4. Ultrasonic/Chemical Decontamination

This technique utilizes ultrasonic energy in a liquid couplant to agitate and remove corrosion films from contaminated items. The liquid couplant is contained in a tank sized and designed for optimum cleaning effectiveness. The ultrasonic generator(s) is located within the tank and is positioned near the contaminated item. Chemical solvents or solvents with an abrasive may be used as the liquid couplant to increase cleaning effectiveness. Ultrasonic cleaning is well suited to decontaminating small tools and equipment (valves, pump parts, etc.).

5.2 DECONTAMINATION PLANNING

As noted in paragraph 5.1.1, the inclusion of a major decontamination program in a decommissioning program must be determined on a case basis. For purposes of completeness in this section, it is assumed that a decision has been made to pursue a major chemical decontamination program of piping systems. The selection of the chemical process will involve an iterative evaluation of a number of variables. These variables are listed in Table 5.1. It is anticipated that candidate processes identified by evaluation of these variable characteristics will be tested in the laboratory on actual facility contamination specimens; thus, assuring that decontamination program goals can be achieved by the reference process(es). An excellent description of this type of preselection test program is contained in Reference 1. Further discussion of the more important variables follows.

TABLE 5.1

VARIABLES RELATED TO CHEMICAL DECONTAMINATION PROCESSES

Piping System Related

Base Metal Type
Contamination Physical and Nuclear Properties
Piping Geometry/Volume/Wall Thickness
Facility Operating History

Process Related

Decontamination Effectiveness
Waste Processing Requirements
Corrosion Effects
Application Temperature
Solvent Stability
Application Safety
Process Duration

\- Cost Impacts -
Application/Processing Facilities
Process Operation
Program Schedule

5.2.1 Decontamination Effectiveness

The efficiency of a decontamination process in a particular application is usually expressed by its decontamination factor (DF). DF is the ratio of the original level of radioactivity to the level that remains after decontamination. Experience has shown that the DF in a large scale decontamination program can vary widely from one part of the same piping system to another and over radial segments of the same pipe section.[2] Therefore, a DF obtained by laboratory testing can only be considered an indicator and not an absolute measure of expected program performance.

A field program will also introduce system geometry factors such as crevices, dead legs, low points and regions of low velocity. These system characteristics introduce the possibility for redistribution as well as adversely influencing any redeposition potential of the process. Care must be taken in process selection to avoid this condition or to physically eliminate the component or piping run from the program. As an example, the AP-AC process used on the Shippingport Reactor Primary System caused increases in radiation levels of about a factor of 10 at certain system locations (e.g., pump casings) although overall effectiveness was about a DF of 7.[3]

The method of process application will strongly effect the efficiency of the process. The preferred method consists of filling the system with a mixture of water and chemicals, or adding the chemicals directly to the filled system and recirculating the mixture vigorously for the prescribed time. This method has proved most effective because the rapid flow maintains the chemical concentration fairly uniformly throughout the process, replacing locally saturated or depleted solvent with fresher solvent. The solvent solution is usually passed through a filter in the decontamination system to remove particulates that have sloughed from the system interior surfaces.

An alternate method consists of filling the system with the solvent mixture as before and allowing the system to soak without recirculation. This process may be repeated several times to allow for some agitation of the surface and to provide for solvent mixing to maintain concentration uniformity. This method is useful when system recirculation pumps are not available, when portions of the loop are not contaminated and must be isolated from the contaminated solvent, or if portions of the system must be isolated from a particular corrosive solvent. It is generally not as effective as recirculation decontamination but may be the only available option.

5.2.2 Liquid Waste Processing Requirements

An ideal decontamination program would be one that is both highly effective and results in wastes that can be economically processed by the existing liquid waste system of the facility. The CAN-DECON process has been developed with this in mind; however, the DF achieveable with the current state-of-the-art process may be too low for decommissioning application.[4]

The NS-1 process developed by Dow Chemical, and presently in application at Dresden Unit 1, required the addition of a liquid waste facility capable of storing and processing approximately 500,000 gallons of solvent and rinse solutions.[5] Certainly the original liquid waste system furnished with that plant is not representative of the current large reactor design philosophy, however, the example clearly illustrates the potential increase in complexity and total cost that any process may have on the program simply due to the volume of liquid wastes generated.

One last example of a somewhat different approach to decontamination solution processing involves the Shippingport program. In this case the solvent solution from each step of the two step process was demineralized resulting in complete recovery of the fluid as deionized water and disposal of the contamination with the spent resins. The drawback with this approach is the battery of demineralizers required. The 1840 ft^3 of resin used in the process represented about 80% of the total volume of the reactor's primary system.[6]

5.2.3 Solvent/System Interface Consideration

The nature of the contamination (i.e., whether loosely or tightly adherent, and the fission product or material of construction in content) will be a major influence on the process, as will the base metal composition. Note: tightly adherent crud is usually found in systems that have operated at elevated temperatures.

There will be greater flexibility in solvent selection due to minimal concern for bare metal attack in most decommissioning programs. A more significant concern is the protection of system parts such as seals and gaskets against local corrosive attack in order to avoid leakage of contaminated liquids. Also, excessive corrosion could lead to excessive redeposition. It should be noted that corrosive attack of the base metal does not ensure a high DF and, conversely, that high DF can be achieved without significant corrosion of the base metal. The strong solutions of nitric and phosphoric acid used in the BONUS program resulted in removal of up to 0.009 inches of piping inner wall. However, the average DF achieved was approximately $10.^2$ Results to date for the NS-1 process indicate DF's as high as 2000 without significant corrosion of base metal.

Optimum results are usually obtained with the solvents at an elevated temperature, e.g., 120°C. This may be difficult to maintain in uninsulated pipe runs, long pipe runs or runs in unheated areas. Certain solvents will decompose at excessively high temperatures resulting in undesirable effects such as toxic fumes or highly corrosive solutions. Certain solvents exhibit a time dependency in the mixing, heating, recirculation and draining cycle that affects both chemical solution stability and the solubility of contained contamination. Each process considered would have to be evaluated for the effect of a loss-of-flow accident and associated solvent cool down. Factors considered would include toxic or explosive gas generation, excessive plateout and excessive corrosion. The selected process must include appropriate emergency procedures, e.g. emergency draining, gas detection, and emergency ventilation.

5.2.4 Cost Impact Considerations

The cost elements of a major chemical decontamination program include:

1. Facility preparation
2. Decontamination equipment
3. Waste disposal facility
4. Decontamination/waste disposal operation
5. Schedule extension.

Facility preparation could entail penetration modifications to the piping systems in order to provide inlet and outlet points for the solvent solution. Other possible requirements in this category could include a building or service area for preparation of the solvent solutions. Equipment costs could include a solvent injection and drain system, mixing tanks, circulation pump, toxic gas scrubber, ventilation system and associated monitoring and control system. The waste disposal facility could include modification or extension of liquid waste storage, neutralization or demineralization systems, evaporation system, solidification system and solid waste processing equipment.

The operating costs for decontamination include the crew cost, chemicals, electrical power and waste disposal. The crew cost includes the labor for equipment set-up, decontamination, radwaste treatment and waste packaging. Unless plant personnel have experience with the use of decontamination chemicals, it is probably advantageous to contract for experienced personnel.

Chemicals may be purchased in their generic form (e.g., as oxalic acid), or as proprietary commercial formulations with additives designed for specific applications. The costs for electrical power required for pumping and heating the solvent, evaporating wastes and mixing or solidifying wastes may be a substantial part of the total power requirements for decommissioning.

A large scale decontamination will impact the overall schedule of a decommissioning program. Since the decontamination is a prerequisite to all activities involving the residual radioactive inventory, very little decommissioning work can be accomplished prior to it in any type of decommissioning program. For example, it would be possible to remove non-essential systems in a complete removal program, but this activity is usually not on the critical path and would probably only serve to keep a staff occupied early in the program. If major facility modification or construction of a new waste processing facility is required, the resulting extension of the critical path schedule will proportionally increase period-dependent costs (see Chapter 11). The time consumed in actual decontamination of the piping systems should only impact the critical path by one to two weeks. The processing of the liquid and solid wastes should not be a critical path activity in a complete removal program, but it could be in a protective storage program.

5.3 PROCESS SELECTION

The selection of a candidate process for decontamination of piping, structures, tools and portable equipment can be simplified by reference to the following tables. Table 5.2 presents a tabulation of chemical solvents for use on piping materials including stainless steel, aluminum, inconel, and copper and its alloys. Table 5.3 presents a tabulation of decontaminating solvents for use on portable tools, equipment and structures. Note: concrete surface removal techniques are presented in Chapter 7. Electropolishing and ultrasonic techniques do not lend themselves to tabular presentation of data. These methods will be discussed in the Detailed Description of Process, Section 4. A list of commercial chemical solvents and their typical applications is included in Appendix A for information.

5.4 DETAILED DESCRIPTION OF PROCESS

This section includes a summary description of chemical decontamination processes for piping systems, the water lance in that application, electropolishing and ultrasonic methods for tools and equipment.

5.4.1 Piping Decontamination by Chemical Process

There are many possible solvents and combinations of processes applicable to the decontamination of various piping system material and contaminant pairs. This section presents some of the better known processes, provides guidance as to their applications, and defines their major limitations. As discussed earlier, candidate solvents should be laboratory tested to verify their effectiveness in each specific application.

TABLE 5.2

CHEMICAL DECONTAMINATION APPLICATIONS FOR PIPING SYSTEMS

Reagent		Piping System Base Metal					
Name	**Formula**	**Stainless Steel**	**Carbon Steel**	**Aluminum**	**Inconel**	**Copper/its Alloys**	**Remarks**
Alkaline Permanganate (AP)	NaOH $KMnO_4$	Pretreatment to remove Cr_2O_3 and make corrosion film porous					Non-corrosive to SS; mildly corrosive to CS
Ammonium Citrate (Dibasic) (AC)	$(NH_4)_2HC_6H_5O_7$	Removes remaining corrosion film after AP treatment.	Attacks base metal				Formed from citric acid in solution with ammonium hydroxide. Corrosive to CS unless inhibited
Ethylene-Diamine-Tetra-Acetic Acid (EDTA)		Complexing agent to prevent reprecipitation of iron oxide. Added to AC in APAC process (APACE)					Non-corrosive to stainless steel
Oxalic Acid (OX)	$H_2C_2O_4$	Used after AP treatment to remove remaining MnO_2 corrosion film (APOX)	Attacks base metal				Forms insoluble precipitate which redeposits and reduces effectiveness.
Citrox	$H_2C_2O_4$ $(NH_4)_2HC_6H_5O_7$ $Fe(NO_3)_3.9H_2O$ $(C_2H_5NH)_2CS$	Used after AP treatment to remove residual MnO_2 and neutralize residual OH^-. Inhibits formation of precipitate (APCitrox)			Will remove corrosion film		

TABLE 5.2
(Continued)

Reagent		Piping System Base Metal					
Name	**Formula**	**Stainless Steel**	**Carbon Steel**	**Aluminum**	**Inconel**	**Copper/its Alloys**	**Remarks**
Sulfamic Acid	NH_2SO_3H	Used after AP treatment (APSul)	Effective decontaminating agent for carbon steel. Low corrosion rate	Effective decontaminating agent for aluminum		Will remove corrosion film	
Hydrochloric Acid	HCl	Attacks base metal	Attacks base metal			Will remove corrosion film	Corrosive to stainless and carbon steels
Nitric Acid	HNO_3	Used on austenitic SS to remove uranium and plutonium materials	Attacks base metal			In dilute form removes corrosion film	Corrosive to carbon steel
Sulfuric Acid	H_2SO_4	Used for removing organic deposits					Highly corrosive to CS and SS
Phosphoric Acid	H_3PO_4		Effective decontaminating agent. Attacks base metal			Removes corrosion film	May cause redeposition if left in system too long

TABLE 5.2
(Continued)

Reagent		Piping System Base Metal					
Name	**Formula**	**Stainless Steel**	**Carbon Steel**	**Aluminum**	**Inconel**	**Copper/its Alloys**	**Remarks**
Oxalic Peroxide (OPP)	$Na_2C_2O_4$ $H_2C_2O_4$ H_2O_2 Peracetic acid Oxine	Used to remove uranium and plutonium films after fuel failure	Used to remove uranium and plutonium films after fuel failure	Used to remove uranium and plutonium films after fuel failure	Used to remove plutonium and uranium films after fuel failure	Attacks base metal	Non-corrosive to CS, SS, inconel, zirconium, aluminum
Sulfox	H_2SO_4 $H_2C_2O_4$ $C_6H_5NHCSNH_2$		Removes corrosion film	Effective decontaminating agent			Mildly corrosive to carbon steel
CAN-DECON	Proprietary	Removes corrosion film	Removes corrosion film				Non-corrosive to SS; mildly corrosive to CS
NS-1	Proprietary	Removes corrosion film	Removes corrosion film				Very low corrosion rate on SS and CS

TABLE 5.3

CHEMICAL DECONTAMINANTS FOR TOOLS, EQUIPMENT AND STRUCTURES

Material	Reagent
Concrete (bare)	Hydrochloric acid
Stainless Steel	Nitric acid and sodium fluoride Sulfuric acid and hydrogen peroxide
Carbon Steel	Phosphoric acid
Aluminum	Dilute sodium hydroxide Citric acid and detergent
Lead	Dilute nitric acid Concentrated hydrochloric acid
Copper	Dilute nitric acid

Decontamination chemicals perform specific functions in a decontamination process. A brief discussion of these functions and an explanation of the terminology will aid in understanding chemical decontamination and in selecting candidate solvents.

1. Oxidizing Agents

These agents are used to provide a source of oxygen for the oxidizing of another substance. For example, PWR stainless steel corrosion films contain chromium that must be oxidized to the +6 valence state to be dissolved. Alkaline permanganate is used to oxidize the chromium.

2. Reducing Agents

Reducing agents are used to remove oxygen from a compound by bonding with the oxygen. For example, BWR system corrosion films contain nickel ferrite as the predominant compound; alkaline hypophosphite acts as a reducing agent when heated, and reduces the nickel ferrite to the +3 valence state so it will dissolve.

3. Sequestrants

Sequestrants (also called complexing agents and chelating agents) are used to prevent dissolved salts in the solution from forming a sludge (precipitation) when the acids are neutralized. For example, ethylenediaminetetraacetic acid (EDTA) ionizes and forms very stable complexes with the hardness ions of calcium, magnesium, iron and chromium.

4. Inhibitors

Inhibitors are used to inhibit the corrosive reaction and loss of base metal. Inhibitors are organic polar compounds having a carbon chain or ring with H atoms attached, and a polar group such as amino (NH_2^-), sulfonic (SO_3^-), or carboxy (CO_2^-). The polar group is electrically unsymmetrical and tends to be strongly adsorbed on the metal surface available for corrosion. Phenylthiourea inhibitor is often used in high temperature flushes but tends to recrystallize at room temperature.

5. Surfactants

Surfactants are used as wetting agents, detergents and emulsifiers. They typically consist of long carbon-to-carbon skeletons plus a polar group containing atoms of nitrogen, oxygen or sulfur. The polar group is hydrophilic (water-loving) and the hydrocarbon part is hydrophobic (water-hating). These molecules (or ions) tend to migrate to water-oil interfaces where the polar group will be attracted to the water phase and the hydrocarbon residue will remain in the oil phase.

These basic chemical types and functions may be incorporated into a decontamination program as one-step or multi-step processes to remove the contamination film. One-step processes can be fast and effective if the primary contaminant can be dissolved with a single treatment. However, in some cases, the corrosion film must first be treated to expose the contaminant to the solvent before dissolution can take place. Furthermore, chelating agents must be added to ensure the contaminant does not precipitate out of solution and redeposit within the system. In these latter cases, multi-step decontamination processes are more effective, although the treatment is more time consuming and generates greater quantities of liquid waste. This is because each chemical flush is generally followed by one or more complete system volume water rinses which must also be treated as radioactive liquid waste.

5.4.1.1 Detailed Description of Chemicals

A brief discussion will be provided for each chemical and the decontamination characteristics will be presented in tabular form. Where reported characteristics vary widely, such as decontamination factors, the range of values is given.

1. Alkaline Permanganate (AP)

AP is an oxidizing agent used to oxidize chromium in the corrosion film to Cr_2O_3, which can subsequently be dissolved in an alkaline solution. It is used as a pretreatment process in multi-step decontamination programs to expose the remaining corrosion film matrix to subsequent chemical dissolution.[7]

AP Solvent Data:

Formula - Chemical: (grams/liter)	NaOH (100g/l); $KMnO_4$ (30g/l); H_2O (870g/l)
Primary Application:	Stainless steel
Decontamination Factor:	Not applicable
Corrosivity:	Not corrosive to stainless steel; 0.2mg/cm^2-hr for carbon steel
Stability:	Stable at recommended temperature

Decontamination Temp.:	105°C
Decontamination Time:	24 hours
Number of System Volumes:	1 flush; used with acids in subsequent steps.
Waste Processing:	Demineralization
Remarks:	Attacks corrosion film to dissolve Cr_2O_3 and leave the film porous.

2. Ammonium Citrate - Dibasic (AC)

AC has been successfully used with an AP pretreatment to achieve DF's as high as 1000. In dilute form, ammonium citrate removes the residual MnO_2 from the $KMnO_4$ AP flush and neutralizes the OH^- from the NaOH. Concentrated AC attacks the remaining corrosion film. Refer to the multi-step APAC process for more information.[7]

AC Solvent Data

Formula - Chemical: (grams/liter)	$(NH_4)_2HC_6H_5O_7$ (100g/l)
Primary Application:	Stainless steel, carbon steel
Decontamination Factor:	2-12
Corrosivity:	Corrosive to carbon steel unless inhibited
Stability:	Stable at recommended temperature
Decontamination Temp.:	85-95°C
Decontamination Time:	24 hours
Number of System Volumes:	Used with AP; 1 flush, 1 rinse
Waste Processing:	Demineralization
Remarks:	Not effective for removing aged films from some stainless steel surfaces; susceptible to redeposition.

3. Alkaline Permanganate - Ammonium Citrate (APAC)

The APAC multi-step process was used extensively at Shippingport. The procedure consisted of the following steps:

1. Circulate the AP solution at 120°C for 24 hours
2. Discharge diluted AP solution through heat exchangers to holdup tank

3. Process diluted AP waste solution through mixed bed demineralizers
4. Use effluent water to refill reactor
5. Circulate the AC solution at 120°C for 24 hours
6. Discharge diluted AC solutions through heat exchangers to holdup tank
7. Process diluted AC waste solution through mixed bed demineralizers
8. Use effluent as deionized process water.

The process used 15 demineralizers of 100 ft^3 each to treat the spent solutions. Deionization of the dilute AP solution required 850 ft^3 of resin, and 990 ft^3 of resin for the AC solution. The AC solution was not effective in removing contamination from dead-leg areas and crevices. High velocity flow is recommended for these crud trap regions. EDTA may be added to AC (ACE) to complex the iron oxides and keep the radionuclides in solution so they can be removed by demineralization. This improves the DF markedly.

APAC and APACE Solvent Data

Formula - Chemical: (grams/liter)	NaOH (100g/l); $KMnO_4$ (13g/l); $(NH_4)_2HC_6H_5O_7$ (13g/l)
Primary Application:	Stainless steel
Decontamination Factor:	2 (with redeposition); 50 (without redeposition)
Corrosivity:	Not corrosive to stainless steel; corrosive to carbon steel unless inhibited
Stability:	Stable at recommended temperatures
Decontamination Temp.:	120°C
Decontamination Time:	48 hours
Number of System Volumes:	1 AP flush, 1 AC flush, 1 or more rinses
Waste Processing:	Demineralization
Remarks:	Ineffective in removing aged films from some stainless steel surfaces. EDTA chelating agent may be added to APA (APACE) to complex the iron oxides and keep the radionuclides in solution.

4. Oxalic Acid (OX)

Oxalic acid is effective in removing rust from iron. In decontamination of reactor systems it is an excellent complexer for niobium (when present) and fission products.

Oxalic acid was used at the Savannah River Plant in stainless steel heat exchangers. The process consisted of filling the system with water, adding a corrosion inhibitor (ferric sulfate 2.6 g/l), steam heating to 70°C, adding oxalic acid to 2 wt% and recirculating the mixture. The system was then drained, water-rinsed and neutralized with 50% KOH. The system was drained and rinsed again with water. Decontamination factors of 3 to 20 were achieved. At temperatures of about 90°C the oxalic acid reacted with the stainless steel to form a highly insoluble ferrous oxalate tenacious film. Subsequent treatment with sulfuric and nitric acid was necessary to remove the precipitate.[8]

It is used as the second step with AP preconditioning but because of the precipitate it is not of significant interest.

OX Solvent Data

Formula - Chemical: (grams/liter)	$H_2C_2O_4$ (100g/l)
Primary Application:	Stainless steel, not effective for aluminum
Decontamination Factor:	SS = 3-20
Corrosivity:	Corrosive to carbon steel unless inhibited
Stability:	Stable at recommended temperature. Forms precipitate at 90°C
Decontamination Temp.:	70-80°C
Decontamination Time:	1-4 hours
Number of System Volumes:	1 AP flush, 1 acid flush, 1 neutralizing rinse, 1 water rinse
Waste Processing:	Deionization
Remarks:	Forms an insoluable precipitate at elevated temperatures that films the surface and reduces effectiveness of the reagent. Usually used with AP.

5. Citrox (AP Citrox)

Citrox is a reducing agent consisting of a mixture of citric (0.2M) and oxalic (0.3M) acids with a corrosion inhibitor. It is very corrosive to carbon steel and 400 series stainless steel and should be isolated from these portions of systems. The Citrox process is very effective for decontaminating stainless steel in a two-step process of alkaline permanganate (AP) followed by Citrox. A typical procedure consists of the following steps:

1. AP circulation for two hours at 105°C
2. Water rinse until removal of MnO_4^- is complete and until pH is less than 10
3. Dilute (10%) Citrox circulation for two hours at room temperature
4. Citrox circulation for two hours at 60°C
5. Water rinse until the conductivity of the rinse water is less than 50 µmho.

The citrate ions are added to complex the iron ions and inhibit the formation of any precipitate. The dilute Citrox rinse neutralizes traces of residual NaOH (from AP) and dissolves any MnO_2 (by reduction to Mn^{2+}). This dilute rinse may be eliminated for simple systems without dead-legs or crud traps. The process is not very effective unless preceeded by the AP flush.[9] The AP Citrox process was evaluated for inservice decontamination on the Douglas Point 200 MWe CANDU-PHWR. The decision was made not to use the process, because:

1. About 2 months of reactor down time would be required
2. About 25% of the mechanical seals in the system would have to be replaced after decontamination due to corrosion during decontamination

3. Copper from the Monel-400 boiler tubes would plate-out on the carbon steel tubes
4. Large storage tanks would be required
5. About 400,000 gals of radioactive liquid waste would be generated
6. It would be necessary to replace the D_2O with H_2O for the process with an accompanying loss of D_2O
7. About 100 man-rem would be consumed in decontamination and liquid waste disposal.

Ontario Hydro (owners of Douglas Point) decided to use the CAN-DECON and NUTEK L-106 processes. (See CAN-DECON herein[4]).

Citrox Solvent Data

Formula - Chemical: (grams/liter)	$H_2C_2O_4$ (25g/l); $(NH_4)_2HC_6H_5O_7$ (50g/l); $Fe(NO_3)_3.9H_2O$ (2g/l); $(C_2H_5NH)_2Cs$ (1g/l)
Primary Application:	Stainless steel
Decontamination Factor:	3-56
Corrosivity:	Non-corrosive to 300 series SS or carbon steel
Stability:	Forms a precipitate with CS and 400 series SS that is absorbed on piping surfaces if exposed to these materials too long.
Decontamination Temp.:	85°C
Decontamination Time:	1-4 hours
Number of System Volumes:	1 AP flush, 1 water rinse, 1 dilute Citrox flush, 1 full strength Citrox flush, 1 water rinse.
Waste Processing:	Demineralization
Remarks:	Usually used with AP and an inhibitor.

6. Sulfamic Acid

Sulfamic acid with an inhibitor is an effective decontaminant for carbon steel components. It provides good DF's with low corrosion rates. Redeposition or film formation does not occur.

Because it is a less reactive reagent, longer contact times may be necessary than with other reagents. Sulfamic acid has not been used extensively in decontaminating reactor carbon steel systems but is acknowledged to be an effective decontaminant.

Sulfamic Solvent Data

Formula - Chemical: (grams/liter)	NH_2SO_3H (90g/l)
Primary Application:	Carbon steel, aluminum
Decontamination Factor:	3-20
Corrosivity:	4-6 mg/cm^2-hr for carbon steel
Stability:	Hydrolyzes to ammonium acid sulfate (NH_4HSO_4) at 8% per hour at 80°C.
Decontamination Temp.:	45-80°C
Decontamination Time:	1-4 hours
Number of System Volumes:	1 acid flush, 1 inhibitor flush, 1 rinse
Waste Processing:	Neutralization, filtration, and evaporation
Remarks:	Used with an inhibitor to decontaminate Cs and Al. If fluorides are added as a booster, it becomes excessively corrosive to Al and Zr.

7. Hydrochloric Acid

Hydrochloric acid is a reducing agent and one of the first chemical cleaning agents used for utility boilers. However, the chloride content is highly corrosive to stainless steel and should not be used for nondestructive decontamination of primary systems. When used on carbon steel systems a corrosive inhibitor should be added if the system is to be returned to service.

Hydrochloric acid was used in decontaminating the BONUS reactor Cr-Mo steel main steam system and stainless steel purification system in preparation for entombment.[10] A 10 volume percent reagent grade solution was found to be effective at an operating temperature of 70°C. One-inch square samples for testing in the United Nuclear Corporation (UNC) laboratory were cut from sections of piping contaminated with ^{60}Co, ^{58}Co and ^{65}Zn and small quantities of fission products including ^{137}Cs. Laboratory testing consisted of 30-minute cycles in static tests (soaking) of candidate solutions and then 30-minute cycles in dynamic tests (stirred) of solutions. The most effective solutions were given a final dynamic test on larger samples from the reactor systems. Laboratory data indicated hydrochloric acid decontamination of stainless steel gave repeatable DF's of approximately 10. No inhibitor was used because the systems were not going to be returned to service, and the expected corrosion would not affect the residual radioactivity containment integrity of the systems.

Actual system decontamination at BONUS confirmed the laboratory results. Stainless steel and Cr-Mo systems were decontaminated by a factor of approximately 10 overall. A brief description of the acid flushing system is included in Section 5.4.1(2).

Hydrochloric Acid Solvent Data

Formula - Chemical: (grams/liter)	HCl (42.5g/l)
Primary Application:	Stainless steel, carbon steel, chrom-moly steel, copper and its alloys
Decontamination Factor:	SS=5-22; CS=7; CrMo=15; Brass=2.
Corrosivity: (5% HCl containing 0.1% inhibitor)	CS = 0.08 mg/cm^2-hr; 300 series SS = 0.122; 400 series SS = 0.020; Monel 75 Ni 25 Cu = 0.020
Decontamination Temp.:	70°C
Decontamination Time:	1-6 hours
Number of System Volumes:	1 acid flush, two water rinses
Waste Processing:	Neutralization by addition of sodium hydroxide and sodium citrate; filtration and evaporation
Remarks:	Corrosive to carbon and stainless steel unless inhibited. Used to remove surface layer of base metal.

8. Nitric Acid

Nitric acid is an oxidizing agent used for dissolving uranium and its oxides in stainless steel and Inconel systems. A typical solution is 10 vol.% HNO_3 at $75^{\circ}C$. However, it cannot be used on carbon steel because of high corrosion rate. Nitric acid is also used at reprocessing plants to dissolve plutonium dioxide, fission products, sludge deposits and residual contamination from system piping and components. At the Eurochemic reprocessing facility, potassium permanganate ($KMnO_4$) was added to the nitric acid resulting in the most effective decontaminant of that major decontamination program.[11]

Nitric Acid Solvent Data

Formula - Chemical: (grams/liter)	HNO_3 (190g/l) (3MHNO_3)
Primary Application:	Stainless steel, carbon steel, Inconel
Decontamination Factor:	10
Corrosivity:	Highly corrosive to carbon steel
Stability:	Stable at recommended temperature
Decontamination Temp.:	$20\text{-}70^{\circ}C$
Decontamination Time:	1 hour to several days
Number of System Volumes:	2 or more acid flushes, 2 or more rinses
Waste Processing:	Neutralization, filtration, and evaporation
Remarks:	Used for the removal of uranium, plutonium and their oxides.

9. Sulfuric Acid

Sulfuric acid is an oxidizing agent used to a limited extent for removing deposits that do not contain calcium compounds. The highly corrosive acid is used in dilute form with an inhibitor. The concentrated form has been used for removing organic deposits. Sulfuric acid has not been used extensively as a decontaminating solvent because the DF's are relatively low.[12]

Sulfuric Acid Solvent Data

Formula - Chemical: (grams/liter)	H_2SO_4
Primary Application:	Stainless steel, carbon steel (with inhibitor)
Decontamination Factor:	2
Corrosivity:	Highly corrosive to carbon and stainless steel
Stability:	Stable at recommended temperatures
Decontamination Temp.:	45-70°C
Decontamination Time:	0.5-1.0 hours
Number of System Volumes:	1 acid flush, 1 inhibitor rinse, 1 water rinse
Waste Processing:	Neutralization, filtration, and evaporation
Remarks:	Not suitable for removing deposits containing calcium.

10. Phosphoric Acid

Phosphoric acid rapidly defilms and decontaminates carbon steel surfaces. At 60-70°C inhibited dilute (10%) phosphoric acid solutions will remove 95-99% of the contamination and all visible film in approximately 20 minutes. If the acid remains in contact with the carbon steel surface longer than 20 minutes, a ferrous phosphate film forms and deposits on the pipe walls along with the contamination. Phosphoric acid is too corrosive to use on operating reactor systems without a suitable inhibitor.[7]

Dilute (15 v/o) phosphoric acid was used in decontaminating the BONUS reactor carbon steel and brass piping and components in preparation for entombment. The selection was based on a test program similar to that described for HCl. Decontamination factors of between 5 and 37 experienced in laboratory tests were generally achieved during actual decontamination flushes. The carbon steel condensate system was passivated using 2 liters of ammonium hydroxide per 150 gallons of water, and followed by a rust inhibiting rinse of 2 lb of Turco-4517 per 150 gallons of water.[13]

Phosphoric Acid Solvent Data

Formula - Chemical: (grams/liter)	H_3PO_4 (130g/l)
Primary Application:	Steel, copper alloys
Decontamination Factor:	SS=2-10 CS=5-37
Corrosivity:	4-6 mg/cm^2-hr for carbon steel; 0.014 mg/cm^2-hr for SS
Stability:	Phosphoric acid reacts with carbon steel to form ferrous phosphate. This film deposits on piping walls carrying with it contamination.
Decontamination Temp.:	85°C
Decontamination Time:	0.3 hours if solution is recirculated. Longer if once-through flush is used.
Number of System Volumes:	1 acid flush, 2 water rinses, 1 passivating rinse, 1 inhibitor rinse maybe in order for protective considerations
Waste Processing:	Neutralization, filtration, and evaporation
Remarks:	Corrosive to carbon steel. Used to remove surface layer of base metal.

11. Oxalate Peroxide (OPP)

Oxalate perxoide is an oxidizing agent consisting of a mixture of oxalic acid and hydrogen peroxide. It is used for the simultaneous dissolution of UO_2, and the defilming and decontamination of metals. The oxalic acid decontaminates the surface, and the hydrogen peroxide enhances the decontamination and passivates the steel by its oxidative action. However, the peroxide destroys the oxalic acid preventing reuse of the solvent. The decontamination is fast enough to be effective before the oxalic acid is destroyed.

Hydrogen peroxide acts as a carbon steel cleaner in concentrations up to $0.2MH_2O_2$ and then as a passivator at concentrations above 1.0 MH_2O_2.[14] In tests at ORNL, carbon and stainless steels heated to about 200°C and treated with oxalate-peroxide (pH-4) exhibited DF's of 100 to 1000 or more.

Oxalate Peroxide (OPP) Solvent Data

Formula - Chemical: (grams/liter)	$Na_2C_2O_4$ (32g/l); $H_2C_2O_4$ (2.3g/l); H_2O_2 (50g/l); Peracetic Acid (5g/l); Oxine (1g/l)
Primary Application:	Uranium and uranium oxide cleanup
Decontamination Factor:	20
Corrosivity:	Non-corrosive to 300 series SS and Inconel (0.02mg/cm^2-hr, max). Corrosive to 400 series SS (2mg/cm^2-hr, min). Highly corrosive to copper alloys (15-90 mg/cm^2-hr)
Stability:	Stable at recommended temperatures
Decontamination Temp.:	80°C
Decontamination Time:	1-4 hours
Number of System Volumes:	At PRTR the process included: OPP flush, rinse, OPP flush, rinse, APOX flush, rinse, APACE flush, rinse
Waste Processing:	Neutralization, filtration, demineralization, evaporation.

12. CAN-DECON

CAN-DECON is a proprietary chemical decontamination process developed in Canada to decontaminate CANDU-PHW reactors. It is marketed by London Nuclear Decontamination Limited, of Niagara Falls, Ontario.

The CAN-DECON process involves the addition of chemical reagents (typically to give 0.1 wt% concentration) directly to the coolant of a shutdown reactor. The reagent consists of a mixture of weak acids and chelating agents, such as citric acid, oxalic acid and EDTA, that attack the surface oxide layer and release both particulate and dissolved material to the coolant. A continuous high flow of coolant is passed through filters and cation exchange resins in the reactor purification system. The filters remove the insoluable matter while the cation resin removes dissolved metal ions and at the same time regenerates the reagents. The regenerated reagents are recirculated back to the primary system where they again attack the contaminated surfaces. The process is continued as long as contaminants are being removed, until the ion-exchange resin is spent, or until the allotted time has expired. The reagents and dissolved corrosion products remaining are then removed by the mixed-bed resin.[15]

The process is applicable to CANDU-PHW reactors where the principal contaminant is ^{60}Co imbedded in the magnetite oxide (Fe_3O_4) film. Similarly, CANDU-BLW reactors and BWR's may use CAN-DECON to remove the magnetite and hematite (Fe_2O_3) film. Pressurized water reactor (PWR) oxide films are of two layers, a loose outer deposit and an adherent base metal oxide. CAN-DECON can remove the outer deposit but cannot attack the loose metal oxide. A development program is underway in Canada to solve this problem.[16]

Compared to conventional decontamination processes using strong reagents, this process requires very little equipment and no special liquid waste handling facility.

The regeneration principle economizes on reagents while at the same time concentrates wastes on the resin and filters. This simplifies disposal, since there are essentially no liquid wastes to deal with.

According to J.L. Smee of London Nuclear[17], it may be possible to increase the process decontamination effectiveness with:

1. Higher reagent concentrations (0.5 wt% instead of 0.1 wt%)
2. Increased process temperatures (150°C instead of 90°C)
3. Different reagents (more corrosive)

CAN-DECON Solvent Data

Formula - Chemical: (grams/liter)	Proprietary (0.1 wt% concentration)
Primary Application:	Stainless steel and carbon steel
Decontamination Factor:	CANDU Reactors = 3-6 BWR Specimens = 10-20
Corrosivity:	Can be corrosive to mechanical seals CS = 0.28 µm/hr 410 SS = 0.08 316 SS = 0.02 Monel-400 = 0.03 Nickel = 0.02
Decontamination Temp.:	90°C
Decontamination Time:	At Douglas Point: Regeneration 9 hrs Removal 10 hrs Total 72 hrs
Number of System Volumes:	Not applicable
Waste Processing:	Spent resin disposal

13. NS-1 (Dow Chemical Co)

NS-1 is a Dow Chemical Co. proprietary high concentration chemical decontamination process. The process consists of circulating the reagent mixture through the system at 120°C for 100 to 200 hours under a nitrogen blanket to dissolve the contamination oxide film.

The process was used at Peach Bottom 2 and 3 to decontaminate the regenerative heat exchangers. The decontamination factor obtained ranged from 2 to 10. An extensive test program was carried out by Dow in preparation for the Dresden-1 decontamination. A considerable protion of the program consisted of design and development of an on-site liquid waste treatment facility, because the Dresden-1 existing facility was inadequate to dispose of the waste volumes to be generated. The test program included a thorough literary search of existing decontaminants, laboratory tests of Dresden-1 material specimens, a pilot test loop demonstration and metallographic analysis of decontaminated test coupons.

Decontamination factors of 500 to 2000 have been observed in these tests without sloughing of undissolved deposits or sludging of solvent components. Corrosion rates on carbon and stainless steel materials is not excessive (less than 5 mils/year).

The in-situ decontamination of Dresden-1 is scheduled to be performed in 1980.[18]

NS-1 Solvent Data

Formula - Chemical: (grams/liter)	Proprietary
Primary Application:	Stainless steel, chrom-moly steel, carbon steel
Decontamination Factor:	500-2000
Corrosivity:	300 Series SS = 5 mils/year, max. 400 Series SS = 1-5 mils/year 2-1/4 Cr - 1 Mo = 1-5 mils/year 1020 Carbon Steel = 1-5 mils/year Copper, nickel, chromium = 0.1 mils/year, max.
Stability:	No thermal decomposition
Decontamination Temp.:	120°C
Decontamination Time:	100-200 hours
Number of System Volumes:	1 NS-1 flush, 3 rinses to remove copper and residual NS-1
Waste Processing:	Filtration, evaporation

5.4.1.2 Chemical Flushing Equipment

For most reactor facilities decontamination of the reactor coolant system and associated contaminated systems may be accomplished by filling the system with the solvent and circulating it with existing reactor or system pumps. These pumps are usually of high capacity and can maintain high solvent velocities in piping and components to assure adequate exposure of the corrosion film to the recirculating solvent.

In some cases, it may be necessary to isolate these pumps to protect mechanical seals or susceptible materials from solvent corrosion. In the case of decontamination of auxiliary systems, portability may be a necessity to eliminate long runs of solvent hose.

For the BONUS decontamination program a specially designed portable decontamination system was developed consisting of the acid (hydrochloric or phosphoric acid) mixing tank, circulating pump, filters, heater and fume scrubber. Associated equipment consisted of the acid flush hoses with quick connect couplings, neutralizing tank and mixer.[19] General specifications for this flushing equipment are as follows:

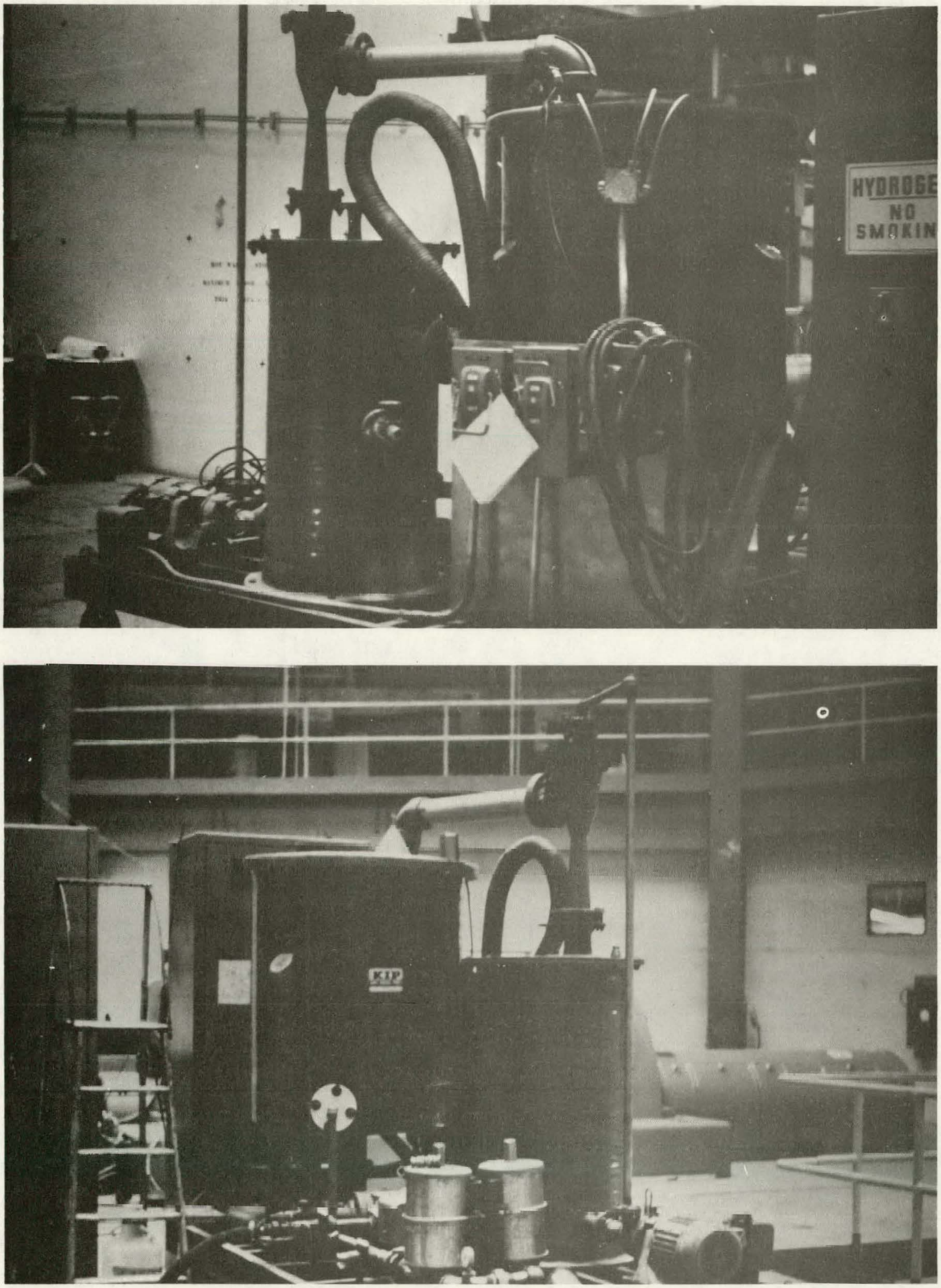
Acid Tank	150 gal capacity fiberglass tank made with Dow Derakane vinyl ester resin
Circulating Pump and Motor	110 ft of head at 50 gpm; 5HP, 3600 rpm, 220 volts. 3-Phase; fiberglass impellor and casing
Filters	Two in-line stainless steel housings with cartridge filters
Heaters	Three immersion heaters: 3KW, Single Phase, 230 Volt
Fume Scrubber	Ejector scrubber with a recirculating-type separator and fiberglass tank. 150 scfm draw with scrubber recirculation pump supplying 30 gpm at 90 ft of head
Neutralizing Tank	800 gal capacity fiberglass tank made with Dow Derakane vinyl ester resin
Mixer	Portable gear drive with 3 ft long shaft, 1/3 HP, 220 volt, single phase

Figure 5.1 shows the portable decontamination system (exclusive of neutralizing tank) used at BONUS.

There are several commercial chemical cleaning service companies available with larger capacity equipment designed to handle corrosive solvents and provide pumping capacity for recirculation. A brief summary of the pumping capacity available is provided herein.

FIGURE 5.1

PORTABLE DECONTAMINATION SYSTEM



1. Heavy Duty High Volume Equipment

These pumps are skid-mounted so they can be moved into the nuclear facility to minimize long runs of piping carrying hazardous solvents. Dual units may be used when higher capacities are needed. Pumping characteristics of these units are as follows:

Power Unit:	635 horsepower diesel engine
Flow Rate:	5,000 gpm
Discharge Pressure:	270 psi max
Suction Connection:	10 in
Discharge Connection:	8 in

2. Heavy Duty Moderate Volume

These pumps are mounted on skids or on semi-trailers for portability. Dual pumps are provided to insure reliability and are normally used in parallel with the discharge from each pump feeding a common 8-inch discharge connection. Each unit has a hydraulic jet mixer to mix powdered or flake chemicals on-site plus all necessary temperature and flow rate instruments. Pump characteristics of these units are as follows:

Power Unit:	265 horsepower diesel engine
Flow Rate:	1680 gpm per unit; 3200 gpm total
Discharge Pressure:	180 psi max
Suction Connections:	8 in x 150 psi flanged; 4 in threaded; 2 in threaded
Discharge Connections:	8 in x 150 psi flanged; 2 in threaded; 4 in threaded

3. Low Volume Pumping Units

These are truck mounted units designed for portability. The maximum flow is about 1000 gpm, which is adequate for most auxiliary systems with small diameter piping. However, the contamination carryover into the mobile pumping unit will necessitate decontamination or controlled burial of the unit upon completion of the decontamination program.

4. Positive Displacement Pumps

These pumps are used where pressures higher than those obtainable with centrifugal pumps are necessary. They are used in the cleaning of pipelines to propel large quantities of fluid along with scrapers, sand, brushes, etc. A twin pump unit is capable of delivering over 1700 gpm at pressures up to 20,000 psi. These units would similarly have to be decontaminated or buried upon completion of decontamination.

5.4.2 High Pressure Water Lance

The high pressure water lance (also called "hydrolaser") consists of a permanent or portable high pressure pumping unit driven by a gasoline or diesel engine, electric motor or steam turbine. The high pressure (1,000 to 10,000 psi) fluid is directed through high pressure hose to an operator-controlled gun. The gun tip is fitted with nozzles designed for either straight flow or flat fan discharge to decontaminate surface.

Water lances have successfully decontaminated pump internals, valves, cavity walls, spent fuel pool racks, reactor vessel walls and head, fuel handling equipment, feedwater spargers, floor drains, sumps, interior surfaces of pipes and storage tanks. Decontamination factors of up to several hundred have been obtained. Experience at one site indicated DF's of 2 to 50 with water as the agent, and DF's of 40-50 if a cleaning agent such as Radiac-Wash was added. Plant personnel recommend an initial treatment at lower pressures (500 psi) since the lower pressures perform just as well as higher pressures (3,000 - 5,000 psi).[20]

A variation on the water lance is the "pipe mole" whereby a high pressure nozzle head is attached to a high pressure flexible hose and inserted in contaminated pipe runs. The nozzle orifices are angled to provide forward thrust of the nozzle during cleaning to drag the hose through the pipe.

Operating characteristics for several size water lances are presented below:

Discharge Pressure, psi	2,000	6,000	10,000
Flow Rate, gpm	8.4	16	22
Horsepower	10	60	143

The approximate cost for an electric motor drive, skid mounted unit of 6,000 psi discharge pressure is $16,000.00.

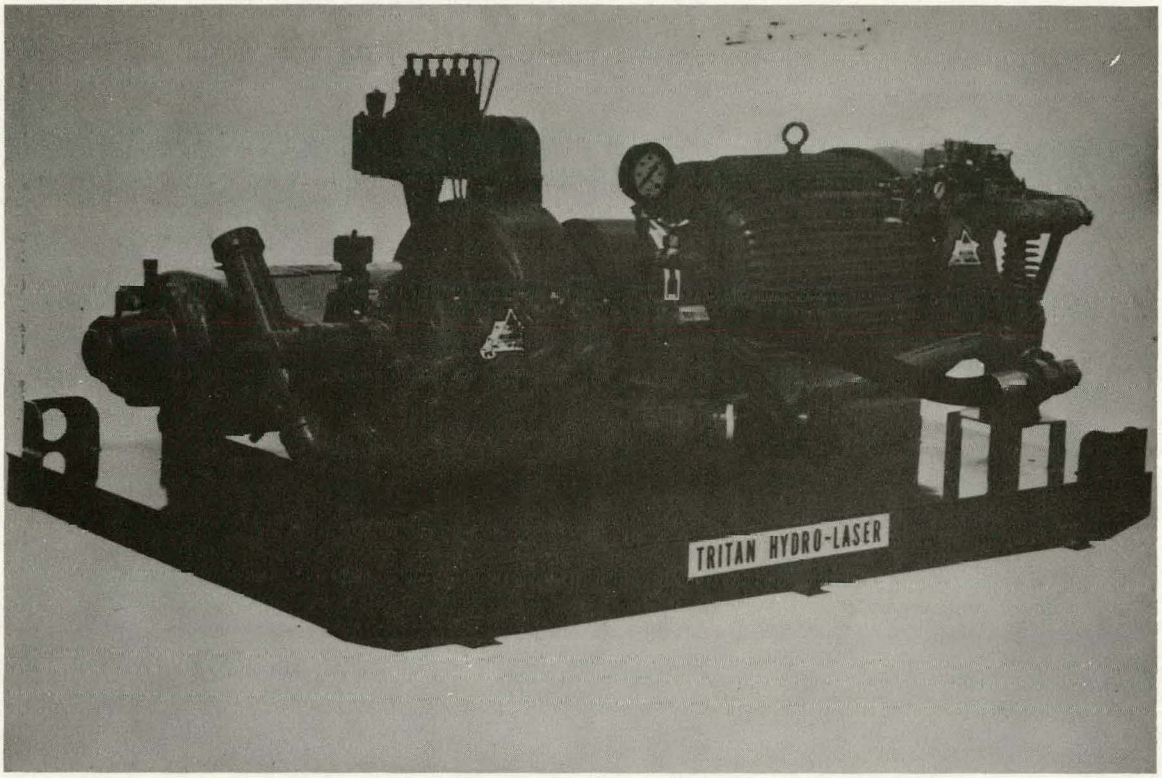
Figure 5.2 shows a typical skid-mounted electric motor driven water lance unit and a smaller portable unit.

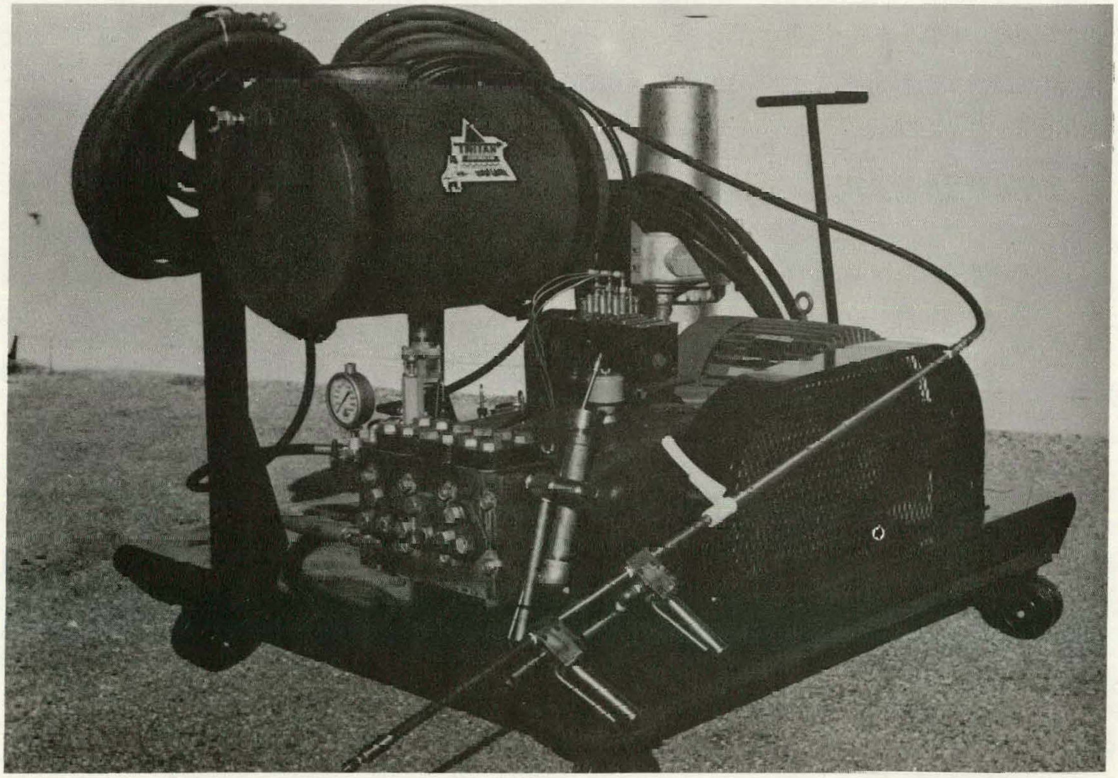
5.4.3 Electropolishing

Electropolishing is an electrochemical process used in both laboratory and industrial applications to produce a smooth, polished surface on a variety of metals and alloys. The object to be decontaminated serves as the anode in an electrolytic cell. The passage of electric current results in the anodic dissolution of the surface material and, with proper operating conditions, a progressive smoothing of the surface. Any radioactive contamination on the surface or entrapped within surface imperfections is removed and released into the electrolyte by this surface dissolution process. The production of a polished surface also facilitates the removal of residual electrolyte by rinsing.

FIGURE 5.2

WATER LANCE UNITS





1. Electropolishing Tank Cleaning

Studies performed at Battelle Pacific Northwest Laboratories (PNL) in cooperation with Rockwell Hanford Operations and United Nuclear Industries show that components heavily contaminated with PuO were decontaminated from 1 million dpm per 100 cm^2 to background in less than 10 minutes.[21]

Representative operating conditions for electropolishing decontamination are as follows:

Electrolyte	Phosphoric Acid 40 to 80% concentrations
Operating Temperature	40 - 80°C
Electrode Potential	8 - 12 V(de)
Current Densities	50 - 250 A/ft^2

Figure 5.3 shows a schematic of an electropolishing cell.

Typical decontamination times range from 5 to 30 minutes, corresponding to the removal of 0.3 to 2 mils of surface material at a current density of 150 A/ft^2. It is usually necessary to move the anode contacts once during a cycle to decontaminate the area under the contacts.

Other components of an electropolishing decontamination system are a DC power supply, one or more rinse tanks, a ventilation system, and provision for heating and agitating the electrolyte and rinse tanks.

A 400 gallon system was designed, built and used for decontamination studies at PNL. It consists of the 400-gal electropolishing tank, two 400-gal rinse tanks, a 5600 A(DC) power supply, and an overhead hoist system for material handling.

A large tank system capable of providing up to 10,000 A at about 10V(DC) and current densities of 500 to 1500 A/m^2 is expected to

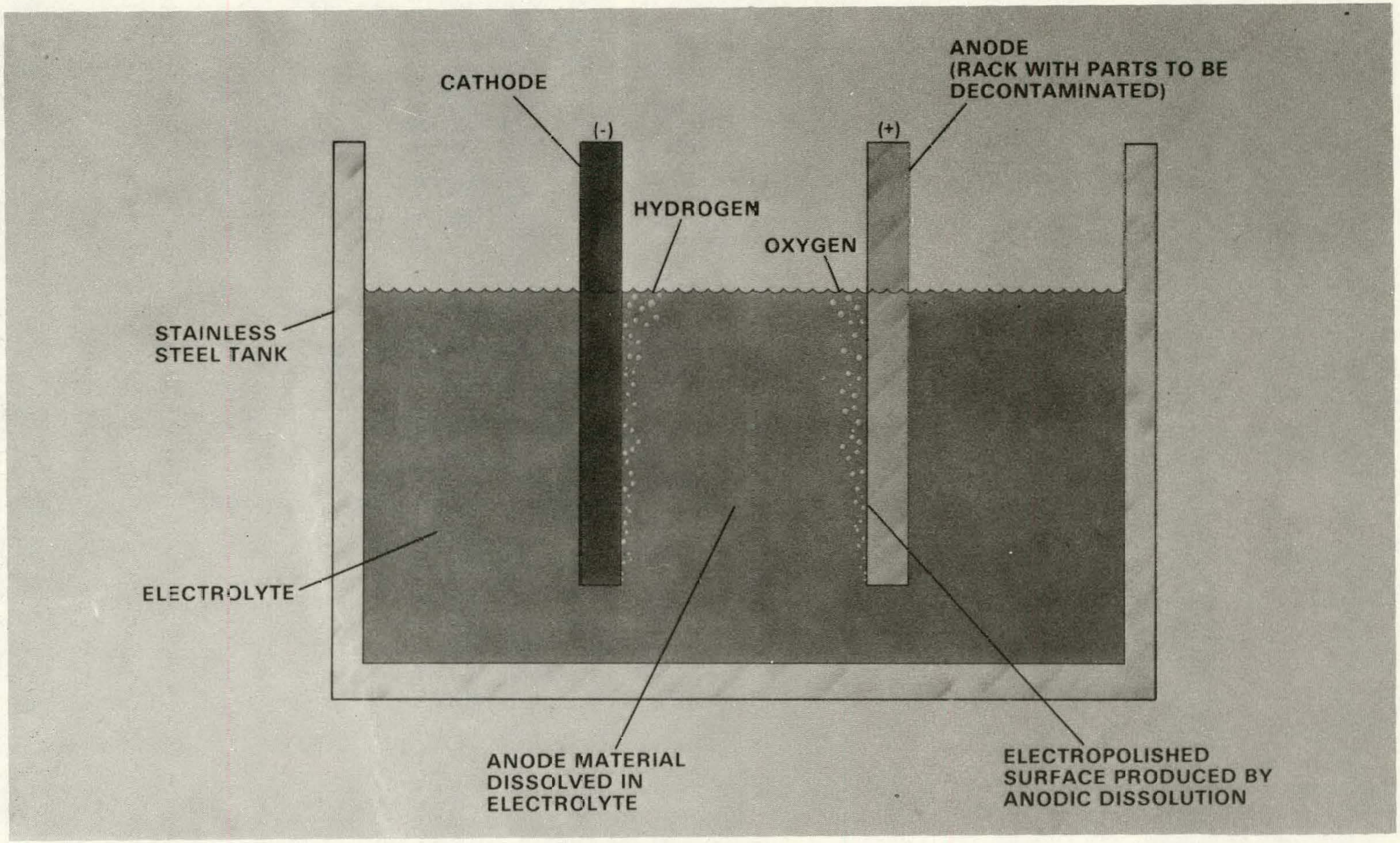


FIGURE 5.3

ELECTROPOLISHING CELL

cost approximately \$100,000.[22] Mobile electropolishing decontaminating services are available from Chem-Nuclear which include power supplies, chemicals (phosphoric acid) and recirculation pumps. Spent acid solidification facilities are also mobile mounted and would be required to dispose of the spent contaminated phosphoric acid. Figure 5.4 shows an electropolishing decontamination of a mild steel valve body.

2. In-Situ Electropolishing

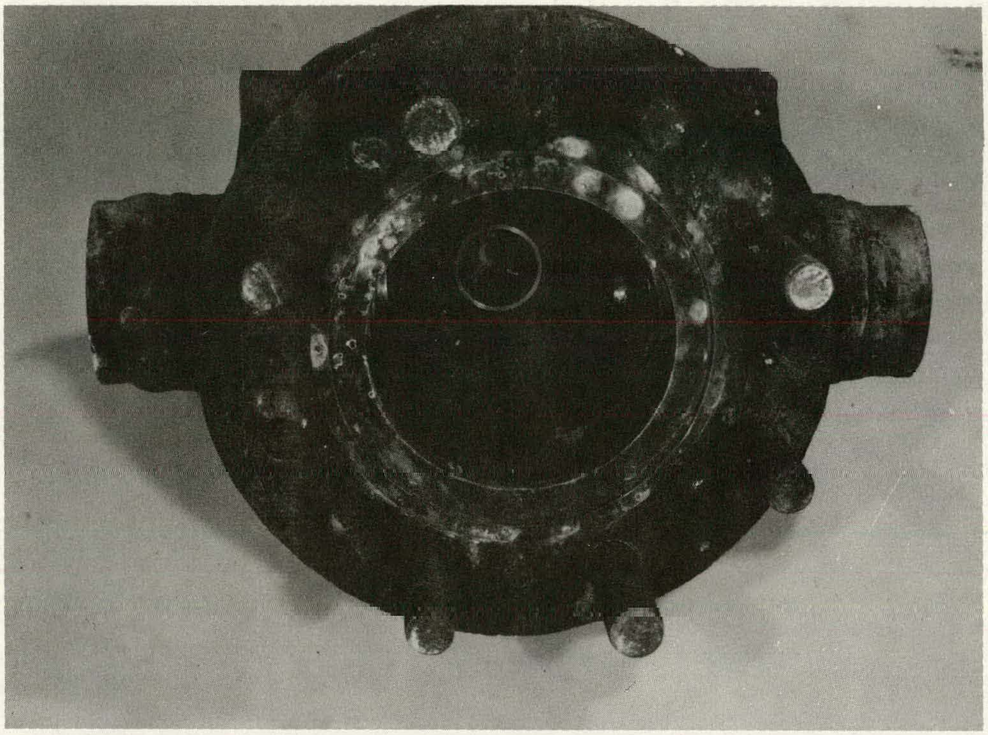
Studies are underway at PNL to demonstrate in-situ techniques such as pumped stream cleaning and contact cleaning.[21] For example, a $0.31 m^2$ area of stainless steel surface can be electropolished by a 0.75 in. long stream of phosphoric acid. The current densities are about the same as in-tank cleaning ($280\ A/ft^2$) but the voltages are significantly higher (24 versus 12 VDC). Figure 5.5 is a photograph of pumped stream cleaning.

A second type of in-situ cleaning device was developed using high current densities but normal electropolishing voltages. This contact type device is shown in Figure 5.6 and consists of an insulated fixture that holds the cathode at a fixed distance from the anode (component being decontaminated) surfaces. Electrolyte is pumped through the unit while maintaining a slightly negative pressure to contain the electrolyte. Testing demonstrated the ability to electropolish a $3\ in^2$ area on a stainless steel surface in 5 minutes using a phosphoric-sulfuric electrolyte, a current density of $550\ A/ft^2$ and an electrode potential of approximately 12 VDC.

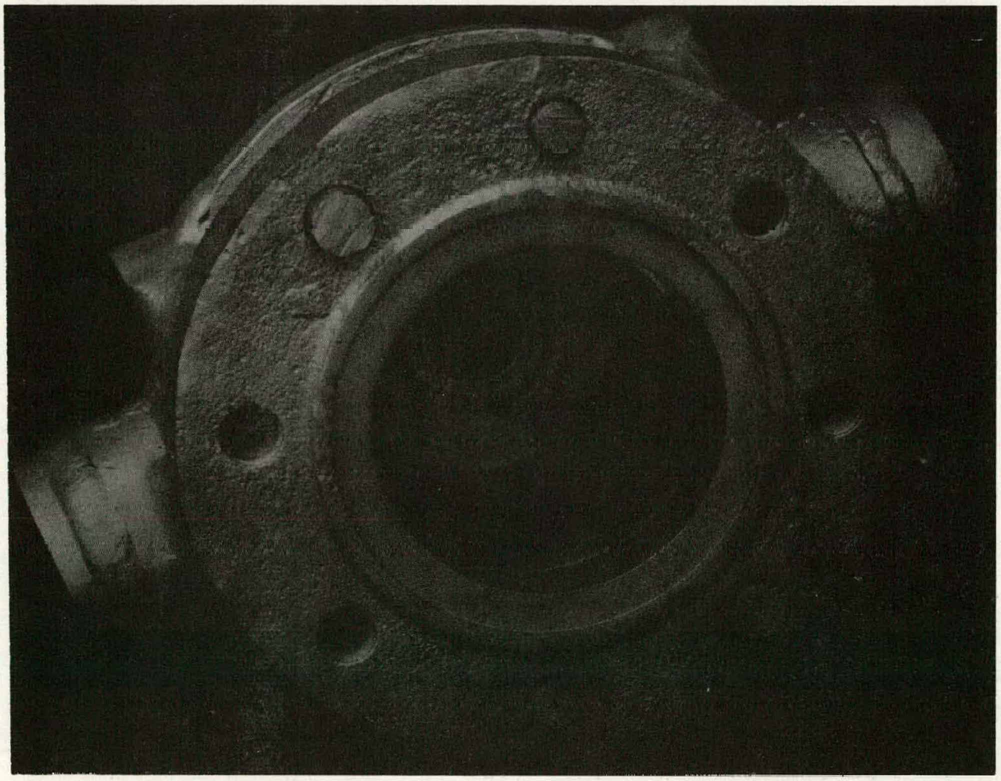
A third in-situ technique was demonstrated in the corrosion test loop at the Hanford N-Reactor in tests sponsored by United Nuclear Industries, Inc.[21] The test loop consisted of a 20 ft long section of 2.7 in. ID steel pipe. The inside of the pipe was electropolished 2 ft at a time using a movable cathode consisting of a 2 ft long, 1-7/8 in.

FIGURE 5.4

ELECTROPOLISHING OF A MILD STEEL VALVE BODY



VALVE HEAVILY CORRODED AND CONTAMINATED BEFORE ELECTROPOLISHING



VALVE COMPLETELY DECONTAMINATED AFTER ELECTROPOLISHING

FIGURE 5.5

IN-SITU ELECTROPOLISHING PUMPED STREAM

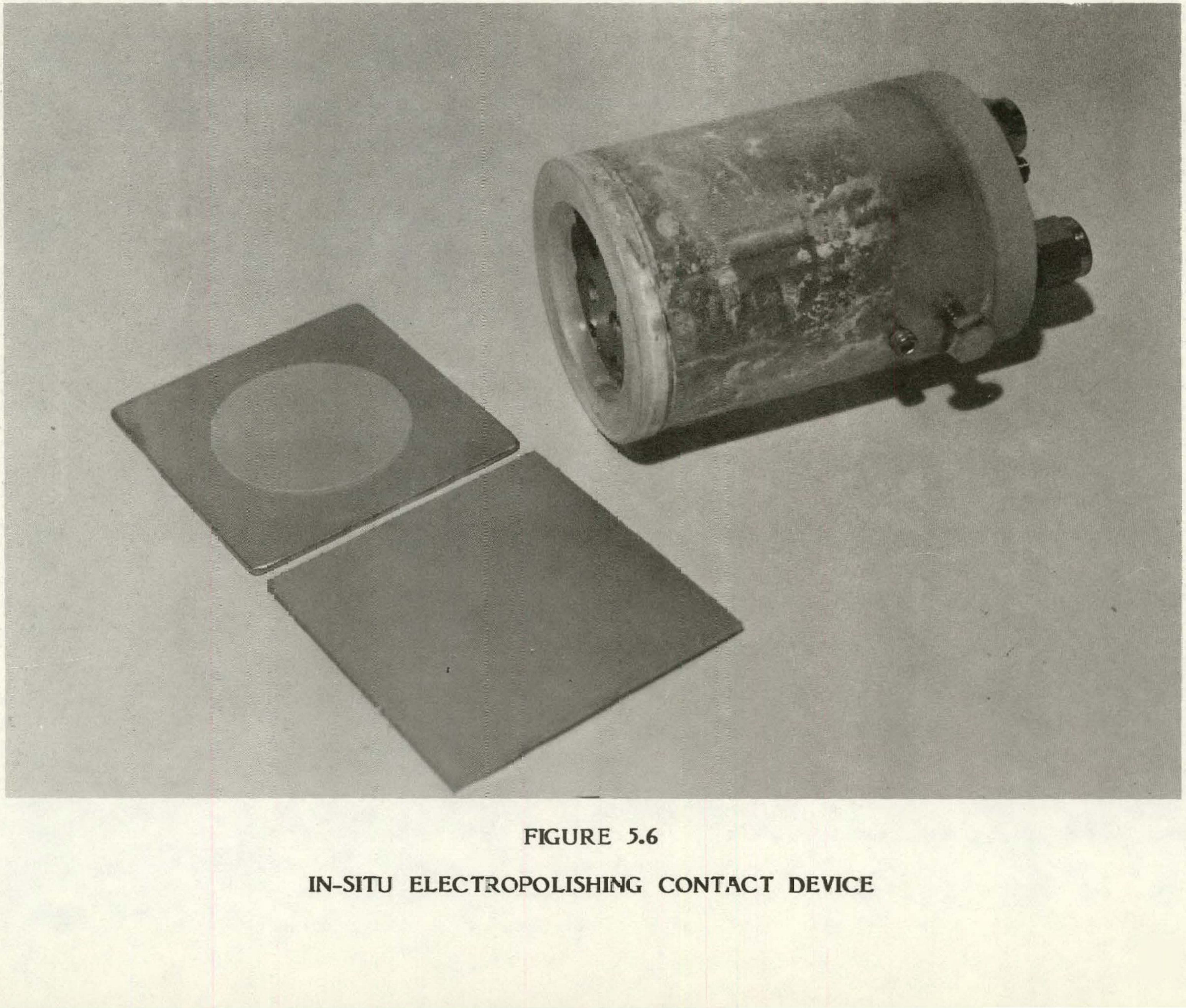


FIGURE 5.6

IN-SITU ELECTROPOLISHING CONTACT DEVICE

OD stainless steel pipe with nylon insulators at each end. Electrolyte was pumped through the cathode into the pipe and returned to the external electrolyte reservoir. The electrolyte was supplied to the cathode through a 20 ft long PVC pipe that moved the cathode and in addition contained the electrical cable to the cathode. Each 2 ft section was electropolished for 20 minutes at 100 A/ft^2. Radiation levels in the less contaminated portions of the pipe were reduced by about 4 R/hr, and in higher contamination areas by about 40 R/hr. Figure 5.7 shows a schematic of this system.

5.4.4 Ultrasonic Decontamination

An ultrasonic cleaning system consists of an ultrasonic generator, a transducer, a cleaning tank, a liquid couplant/solvent and a heater. The generator converts line power from 60 Hz to a higher frequency of from 18 to 90 kHz. The transducer converts these high frequency impulses to low amplitude mechanical energy of the same frequency. The warm liquid couplant (150 - 170°F) serves to transmit this energy to the object to be cleaned.

The compression-rarefaction-compression wave cycle transmitted by the generator causes the liquid to cavitate and implode creating minute quantities of energy with tremendous localized force. Pressures and temperatures are approximately 1×10^4 psi and $1\times10^{4\circ}$C. These imploding cavities serve to scrub the surface being decontaminated causing spalling and descaling.[23]

Ultrasonic tank size, and contaminated component geometry relative to transducer placement must be evaluated for application of ultrasonics. Commercial ultrasonic tanks measuring 10ft x 3ft x 3ft with an ultrasonic power rating of 18KW are available at an approximate cost of $60,000. A unit of this size has been in service for about 8 years at Bettis Atomic Power Laboratory.[24]

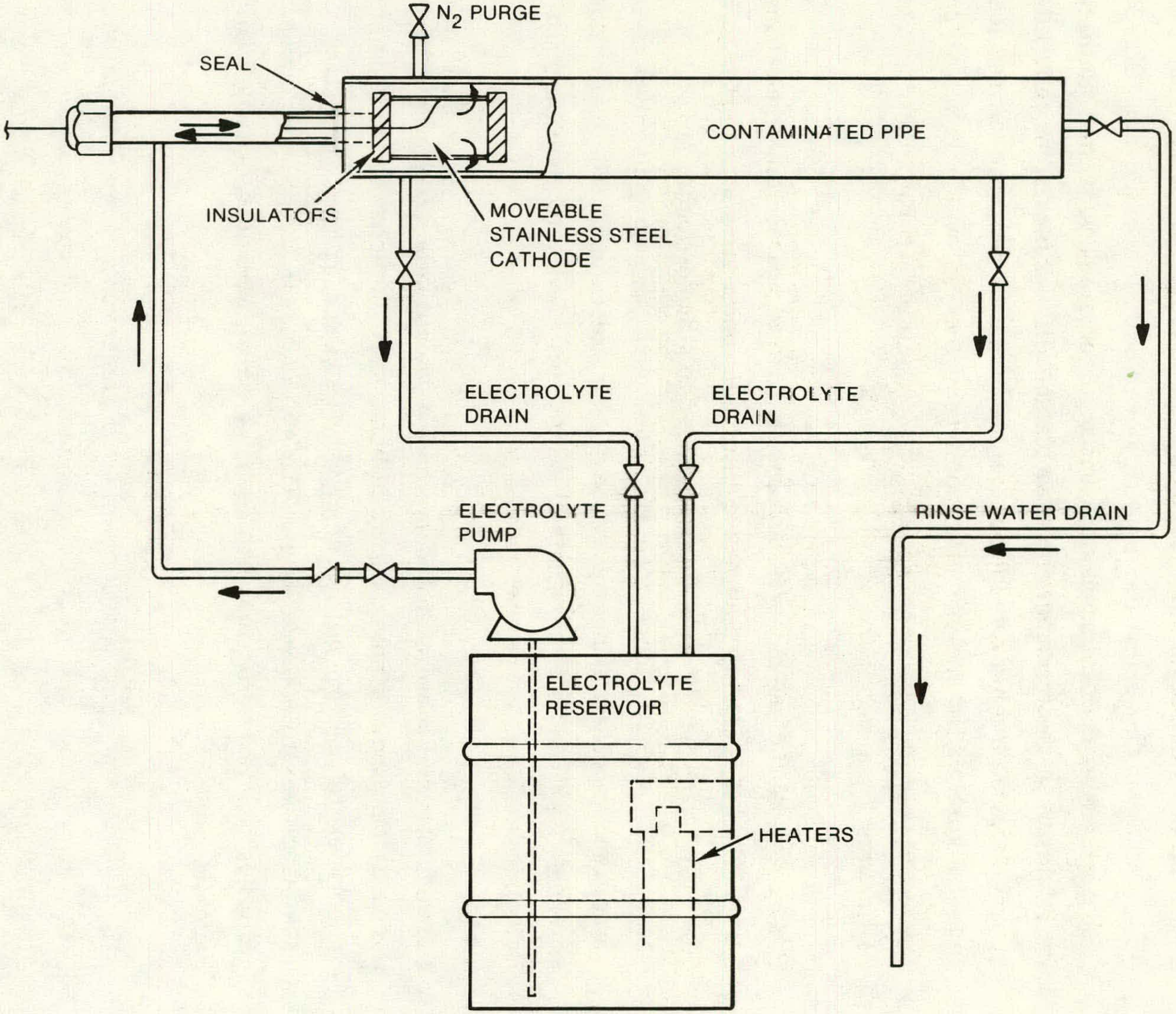


FIGURE 5.7

SCHEMATIC DIAGRAM OF MOVABLE ELECTROPOLISHING IN CORROSION TEST LOOP

A specially designed ultrasonic hand-held wall cleaner and a floor cleaner has been designed for Argonne National Laboratory to decontaminate flame-sprayed zinc on hot cell liners. No decontamination data is available at this time. The approximate cost of these two units was $3,000.[25]

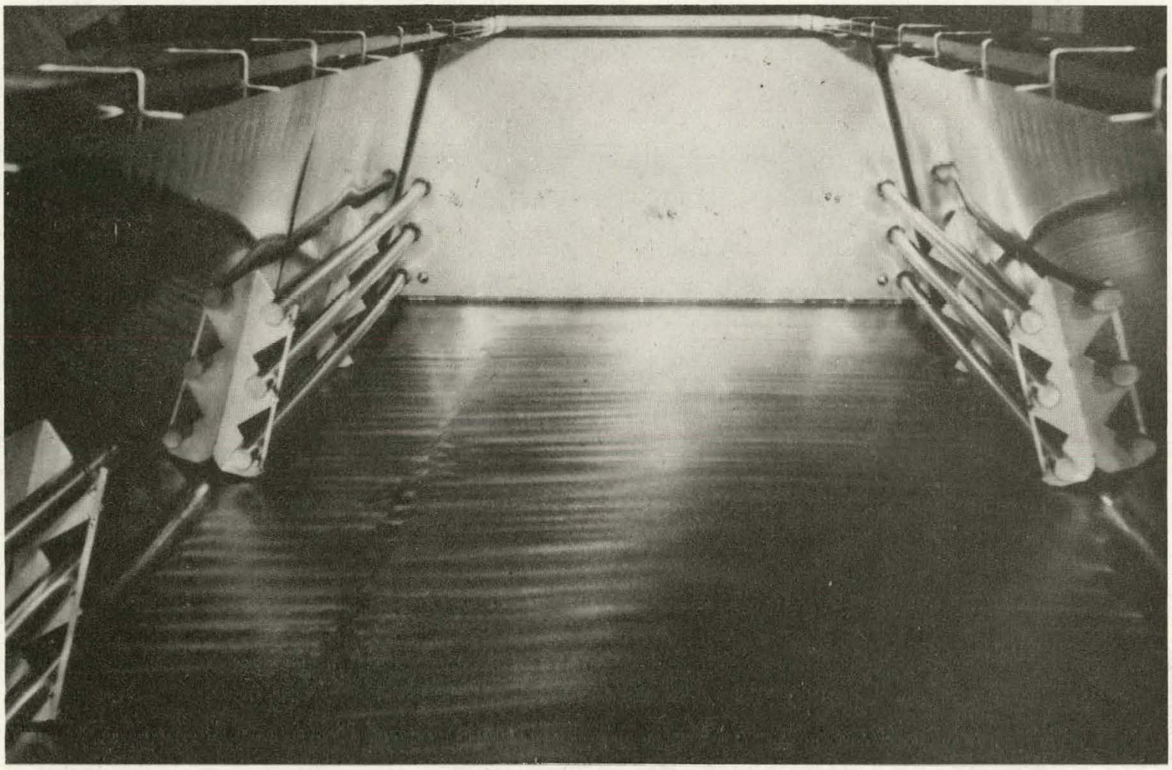
A specially designed ultrasonic tank was built for the New-Waste Calcining Facility (NWCF) under construction at Idaho Falls. This unit measured 26 in^3 and included a removable/disposable plastic tank liner. The transducers were mounted inside the tank but outside of the removable liner, which therefore required a high power density 6KW power unit. Approximate cost of this unit is $35,000.[26]

During the BONUS decontamination program an ultrasonic tank measuring 54in x 30in x 30in was used with five transducer units rated at 21 kHz each. Phosphoric acid at $120^{o}F$ was used for 30 minute cycles with decontamination factors of approximately 9.[27] Operators at the San Onofre Nuclear Generating Station have added citric acid to the couplant in their tank and have achieved a decontamination factor of 30. Decontamination at other sites ranged from 2-100.[20]

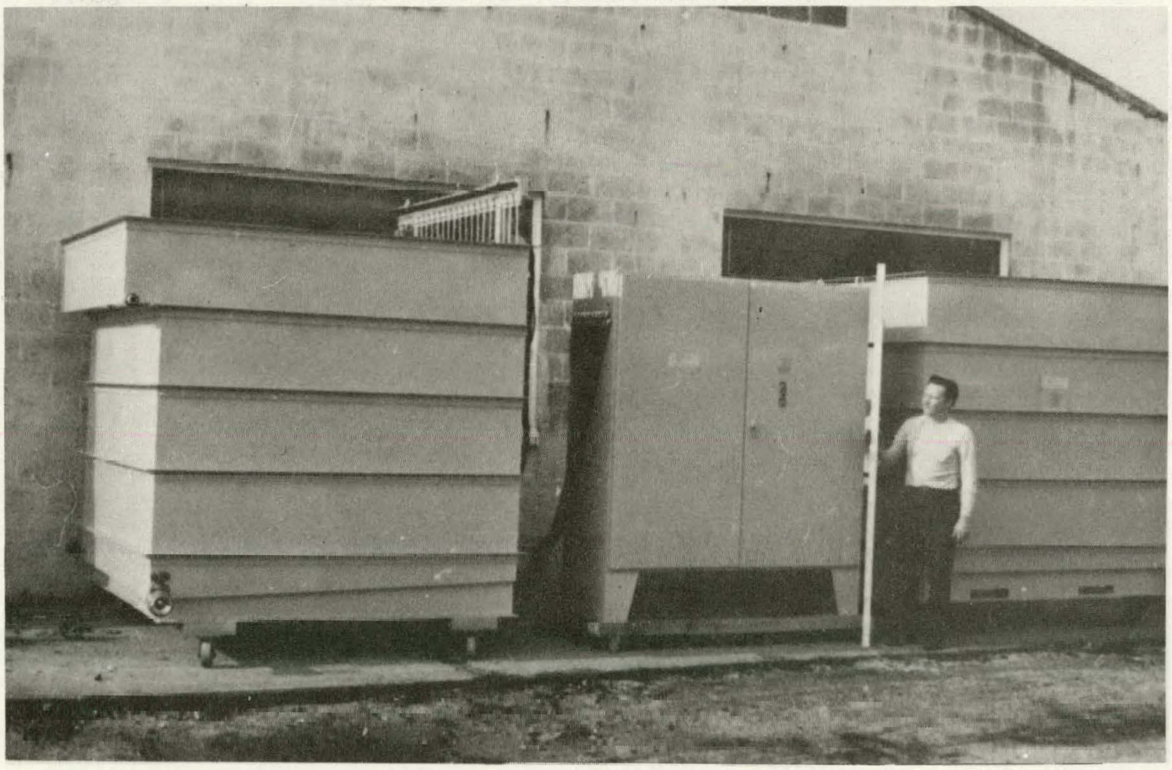
Figure 5.8 shows photographs of typical ultrasonic decontamination tanks and Figure 5.9 shows a photograph of a hand-held wall scrubber unit.

FIGURE 5.8

ULTRASONIC DECONTAMINATION TANKS



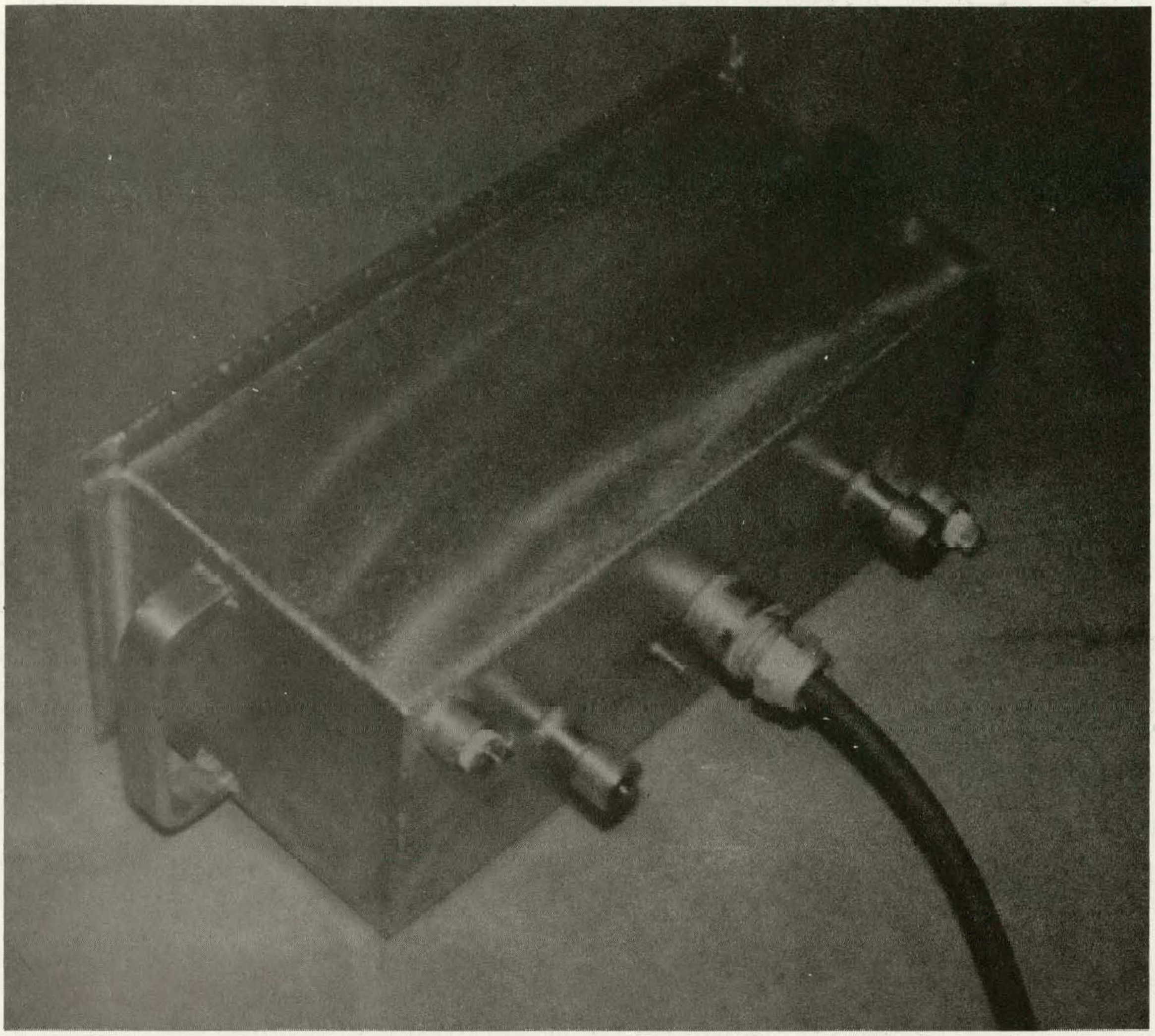
INTERIOR VIEW OF A DECONTAMINATION TANK



EXTERIOR VIEW OF DECONTAMINATION TANKS

FIGURE 5.9

HAND-HELD ULTRASONIC WALL SCRUBBER UNIT



5.5 REFERENCES

1. The Dow Chemical Company: Technical Study for the Chemical Cleaning of Dresden-1, DNS-D1-016, Volume III, Sections 4,5,6,7 and 8, Midland, Michigan (June 15, 1977)

2. The Puerto Rico Water Resources Authority and United Nuclear Corporation: Boiling Nuclear Superheater Power Station Decommissioning Final Report, WRA-B-70-500 (September 1, 1970)

3. Abrams, C.S., and Salterelli, E.A.: Decontamination of the Shippingport Atomic Power Station, WAPD-299, Bettis Atomic Power Laboratory (January 1966)

4. Pettit, P.J., et al.: Decontamination of the Douglas Point Reactor by the CAN-DECON Process, presented at the International Corrosion Forum, Houston, Texas (March 6-10, 1978)

5. The Dow Chemical Company: Technical Study for the Chemical Cleaning of Dresden-1, DNS-D1-016, Volume VI, Appendix VIII, Midland, Michigan (June 15, 1977)

6. The Dow Chemical Company: Technical Study for the Chemical Cleaning of Dresden-1, DNS-D1-016, Volume I, Sections 1 and 2, Midland, Michigan (June 15, 1977)

7. Weed, R.D.: Decontamination - Historical Survey in "Decontamination of Nuclear Reactors and Equipment," J.A. Ayres (Ed.), The Ronald Press Company, New York, N.Y. (1970)

8. Carlson, A.B., et al.: Low-Temperature Water Cooled Reactors in "Decontamination of Nuclear Reactors and Equipment," J.A. Ayres (Ed.), The Ronald Press Company, New York, N.Y. (1970)

9. Ayres, J.A.: Decontamination of Pressurized Water Reactors in "Decontamination of Nuclear Reactors and Equipment," J.A. Ayres (Ed.), The Ronald Press Company, New York, N.Y. (1970)

10. United Nuclear Corporation: Decontamination Process Study, ES-1 of UNC BONUS Specification 18248, p. 5 (November 25, 1968)

11. Detilleux, E., et al.: Experience Gained with the Decontamination of a Shut-down Reprocessing Plant, presented at the International Symposium on the Decommissioning of Nuclear Facilities, Vienna (November 13-17, 1978)

12. Loucks, Charles, M.: Cleaning and Defilming Arts in Industry in "Decontamination of Nuclear Reactors and Equipment," J.A. Ayres (Ed.), The Ronald Press Company, New York, N.Y. (1970)

13. United Nuclear Corporation: Decontamination Process Study, ES-1 of UNC BONUS Specification 18248, P. 12 (November 25, 1968)

14. Meservey, A.B.: Decontamination and Film Removal in "Decontamination of Nuclear Reactors and Equipment," J.A. Ayres (Ed.), The Ronald Press Company, New York, N.Y. (1970)

15. Smee, J.L.: Dissolution Characteristics of Metal Oxides in Water Cooled Reactors, London Nuclear Decontamination Limited, Niagara Falls, Ontario, Canada.

16. London Nuclear Decontamination Limited: CAN-DECON, A Nuclear Reactor Decontamination Process, unnumbered.

17. Private communications of J.L. Smee, Senior Chemist, London Nuclear Decontamination Limited, Niagara Falls, Ontario, Canada, with W.J. Manion, NES (January 11, 1980)

18. Harmer, D.E., Dow Chemical Company and White, J.L., Commonwealth Edison Company: Results to Date of the Dresden-1 Chemical Cleaning, presented to the American Nuclear Society, Sun Valley, Idaho (September 17-19, 1979)

19. Kettler, T.: BONUS Decontamination Equipment Specification, United Nuclear Corporation, S-18248 (November 25, 1968)

20. Remark, J.F., of Babcock and Wilcox, and Miller, A.D., of Electric Power Research Institute: Review of Plant Decontamination Methods, RDTPL 79-35, presented to the American Nuclear Society, Sun Valley, Idaho (September 17-19, 1979)

21. Allen, R.P., et al.: Electropolishing as a Decontamination Process: Progress and Applications, PNL-SA-6858, Battelle Pacific Northwest Laboratories (April 1978)

22. Smith, R.J., et al.: Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station, Battelle Pacific Northwest Laboratories, NUREG/CR-0130, Vol. 2, p. F-34 (June, 1978)

23. Muhala, T.F.: Ultrasonic Cleaning, in Decontamination of Nuclear Reactors and Equipment, J.A. Ayres (Ed.), The Ronald Press Company, New York, N.Y. (1970)

24. Personal communication with J. Logan, Lewis Corporation, Oxford, Connecticut, with T. S. LaGuardia, NES (January, 1979)

25. Personal communication with M. Hubner, Argonne National Laboratory, with T. S. LaGuardia, NES (March 1979)

26. Personal communication with J. Logan, Lewis Corporation, Oxford, Connecticut, with T. S. LaGuardia, NES (March, 1979)

27. United Nuclear Corporation: Decontamination and Liquid Waste Disposal, Activity Specification No. 1, Rev. 1, UNC-SS-223 (March 18, 1969)

APPENDIX A

SELECTED COMMERCIALLY AVAILABLE DECONTAMINATION COMPOUNDS

COMPOUND	USE
	Turco Products
Turco DECON 4501-A	Pre-conditioner for high temperature alloys and stainless steel
Turco DECON 4502	Pre-conditioner for high temperature alloys and stainless steel
Turco DECON 4512-A	Decontaminant for carbon steel
Turco DECON 4518	Decontaminant for high temperature alloys and stainless steel
Turco DECON 4521	General purpose decontaminant
	Nuclear Technology Corporation
NUTEK-246	Pre-conditioner for high temperature alloys and stainless steel
NUTEK-686	Decontaminant for high temperature alloys and stainless steel
NUTEK L-106 (CAN-DECON)	Primary system decontaminant with fuel in-place; no liquid process waste (demineralization removal)
	Atomic Products Corporation
Radiacwash	General decontaminant
	Dow Chemical USA
NS-1	Decontaminant for primary systems
	London Nuclear Decontamination Limited
CAN-DECON	Primary system decontaminant with fuel in-place; no liquid waste (demineralization removal)

CHAPTER 6

SEGMENTING PROCESSES FOR ACTIVATED METALLIC COMPONENTS

6.1 INTRODUCTION

Highly activated components and structures are unique to operating nuclear reactor plants. Certain components such as reactor vessels, vessel internals, thermal shields, and structures and supports in the vicinity of the reactor vessel will become activated due to the neutron flux emanating from the reactor core. Certain of the activated nuclides are highly energetic and present in large quantities. Therefore, the dismantling and removal of these components and structures while the radioactive inventory is still of significant magnitude must be done remotely and with adequate radiation shielding for personnel protection.

Typically, the vessel walls of 1100 MWe light water reactors consist of carbon steel, 10 to 13 inches in thickness, with stainless steel cladding approximately 1/4 inch in thickness. The vessel internals are made of stainless steel and usually range in thickness up to three inches, although certain structural sections of some pressurized water reactors are greater in thickness. In addition to steels, aluminum is a typical material of construction for low power test reactor vessels and internals.

This chapter deals with the segmenting processes appropriate for the activated metallic components. Specifically, the chapter includes information pertinent to the selection of a cutting method or methods for various metals and presents detailed descriptions of each cutting method. The data is presented in a manner to be of general use in the area of metal cutting since the data is keyed to metal type and section thickness.

6.2 PROCESS SELECTION

It is expected that a user of this handbook who has need for information concerning the segmenting of thick metallic components or structures will have a specific item and application in mind. Therefore, Table 6.1 presents a tabulation of useful processes as a function of material, material thickness, and cutting environment (in-air or underwater). This permits the user to make a preliminary selection of a process or processes. The detailed information pertinent to each process would then be referred to and an optimum process chosen.

6.3 DETAILED DESCRIPTION OF PROCESSES

The cutting processes presented for detailed description in this chapter include:

1. Arc Saw
2. Plasma Arc
3. Oxygen Burner
4. Thermic Lance
5. Explosive Cutting
6. Laser
7. Mechanical Nibbler

A summary of application characteristics of each process is included as Table 6.2.

6.3.1 Arc Saw Cutting

1. Description of Process

The arc saw, an extension of nonconsumable melting electrode technology, is a development of Retech, Inc.* The arc saw is a circular, toothless saw blade that cuts any conducting metal without physical contact with the workpiece. The cutting action is obtained by maintenance of a high current electric arc between the blade and the material being cut. The blade can be made of any electrical conducting material such as tool steel, mild steel or copper with equal success. Table 6.3 summarizes the important operational characteristics of the arc saw system. Figure 6.1 illustrates the cutting head of an arc saw.

---

* Retech, Inc., P.O. Box 997, 100 Henry Station Road, Ukiah, California 95482

TABLE 6.1

METAL SEGMENTING - SUMMARY OF APPLICATIONS

Material: All Metals				**Material:** Carbon Steel		
E	**F**	**R**		**E**	**F**	**R**
			Material Thickness Very Large Sections (not process limited)			
			Arc Saw		No	
			Plasma Arc		No	
			Oxygen Burner	Either	Yes	Yes
Either	Yes		Thermic Lance	Either	Yes	
			Explosive Cutting		No	
			Laser		No	
			Mechanical Nibbler		No	
			Material Thickness ≤ 36"			
Either	Yes	Yes	Arc Saw	Either	Yes	Yes
	No		Plasma Arc		No	
	No		Oxygen Burner	Either	Yes	Yes
	Yes		Thermic Lance	Either	Yes	
	No		Explosive Cutting		No	
	No		Laser		No	
	No		Mechanical Nibbler		No	
			Material Thickness ≤ 6"			
Either	Yes	Yes	Arc Saw	Either	Yes	Yes
In-Air	Yes	Yes	Plasma Arc	In-Air	Yes	Yes
	No		Oxygen Burner	Either	Yes	Yes
Either	Yes		Thermic Lance	Either	Yes	
Either	Yes	2	Explosive Cutting	Either	Yes	2
	No		Laser		No	
	No		Mechanical Nibbler		No	

Legend:
E = Environment[1]
F = Feasible
R = Recommended[2,3]

NOTES:

1. "Either" indicates the process can be used in-air or underwater for this metal thickness.
2. Explosive cutting can, in theory, segment metals of this thickness or greater. However, the practical consideration of adequate protection against the explosive shockwave will determine feasibility for use.
3. Due to the relatively high tooling costs, this method would not be preferred for this single application.

TABLE 6.1
(Continued)

Material: All Metals				**Material:** Carbon Steel		
E	**F**	**R**		**E**	**F**	**R**
			Material Thickness ≤ 4"			
Either	Yes	Yes	Arc Saw	Either	Yes	Yes
Either	Yes	Yes	Plasma Arc	Either	Yes	Yes
	No		Oxygen Burner	Either	Yes	Yes
Either	Yes		Thermic Lance	Either	Yes	
Either	Yes	2	Explosive Cutting	Either	Yes	2
	No		Laser		No	
	No		Mechanical Nibbler		No	
			Material Thickness ≤ 2"			
Either	Yes	Yes	Arc Saw	Either	Yes	Yes
Either	Yes	Yes	Plasma Arc	Either	Yes	Yes
	No		Oxygen Burner	Either	Yes	Yes
Either	Yes		Thermic Lance	Either	Yes	
Either	Yes	2	Explosive Cutting	Either	Yes	2
In-Air	Yes		Laser	In-Air	Yes	
	No		Mechanical Nibbler		No	
			Material Thickness ≤ 1/4"			
Either	Yes	3	Arc Saw	Either	Yes	3
Either	Yes	3	Plasma Arc	Either	Yes	3
	No		Oxygen Burner	Either	Yes	
Either	Yes		Thermic Lance	Either	Yes	
Either	Yes		Explosive Cutting	Either	Yes	
In-Air	Yes		Laser	In-Air	Yes	
Either	Yes	Yes	Mechanical Nibbler	Either	Yes	Yes

Material: Stainless Steel				**Material:** Aluminum		
			Material Thickness ≤ 36"			
Either	Yes	Yes	Arc Saw	Either	Yes	Yes
	No		Plasma Arc		No	
	No		Oxygen Burner		No	
Either	Yes		Thermic Lance	Either	Yes	
	No		Explosive Cutting		No	
	No		Laser		No	
	No		Mechanical Nibbler		No	

TABLE 6.1
(Continued)

Material: Stainless Steel				**Material:** Aluminum		
E	**F**	**R**		**E**	**F**	**R**
			Material Thickness ≤ 6"			
Either	Yes	Yes	Arc Saw	Either	Yes	Yes
In-Air	Yes	Yes	Plasma Arc	In-Air	Yes	Yes
	No		Oxygen Burner		No	
Either	Yes		Thermic Lance	Either	Yes	
Either	Yes	2	Explosive Cutting	Either	Yes	2
	No		Laser		No	
	No		Mechanical Nibbler		No	
			Material Thickness ≤ 4"			
Either	Yes	Yes	Arc Saw	Either	Yes	Yes
Either	Yes	Yes	Plasma Arc	Either	Yes	Yes
	No		Oxygen Burner		No	
Either	Yes		Thermic Lance	Either	Yes	
Either	Yes	2	Explosive Cutting	Either	Yes	2
	No		Laser		No	
	No		Mechanical Nibbler		No	
			Material Thickness ≤ 2"			
Either	Yes	Yes	Arc Saw	Either	Yes	Yes
Either	Yes	Yes	Plasma Arc	Either	Yes	Yes
	No		Oxygen Burner		No	
Either	Yes		Thermic Lance	Either	Yes	
Either	Yes	2	Explosive Cutting	Either	Yes	2
In-Air	Yes		Laser	In-Air	Yes	
	No		Mechanical Nibbler		No	
			Material Thickness ≤ 1/4"			
Either	Yes	3	Arc Saw	Either	Yes	3
Either	Yes	3	Plasma Arc	Either	Yes	3
	No		Oxygen Burner		No	
Either	Yes		Thermic Lance	Either	Yes	
Either	Yes		Explosive Cutting	Either	Yes	
In-Air	Yes		Laser	In-Air	Yes	
Either	Yes	Yes	Mechanical Nibbler	Either	Yes	Yes

TABLE 6.1
(Continued)

Material: Zirconium/Zircaloy				**Material:** Inconel		
E	F	R		E	F	R
			Material Thickness ≤ 12"			
Either	Yes	Yes	Arc Saw			
	No		Plasma Arc			
	No		Oxygen Burner			
Either	Yes		Thermic Lance			
	No		Explosive Cutting			
	No		Laser			
	No		Mechanical Nibbler			
			Material Thickness ≤ 4"			
Either	Yes	Yes	Arc Saw	Either	Yes	Yes
Either	Yes	Yes	Plasma Arc	Either	Yes	Yes
	No		Oxygen Burner		No	
Either	Yes		Thermic Lance	Either	Yes	
Either	Yes	2	Explosive Cutting	Either	Yes	2
	No		Laser		No	
	No		Mechanical Nibbler		No	
			Material Thickness ≤ 2"			
Either	Yes	Yes	Arc Saw	Either	Yes	Yes
Either	Yes		Plasma Arc	Either	Yes	Yes
	No		Oxygen Burner		No	
Either	Yes		Thermic Lance	Either	Yes	
Either	Yes	2	Explosive Cutting	Either	Yes	2
In-Air	Yes		Laser	In-Air	Yes	
	No		Mechanical Nibbler		No	
			Material Thickness ≤ 1/4"			
Either	Yes	3	Arc Saw	Either	Yes	3
Either	Yes	3	Plasma Arc	Either	Yes	3
	No		Oxygen Burner		No	
Either	Yes		Thermic Lance	Either	Yes	
Either	Yes		Explosive Cutting	Either	Yes	
In-Air	Yes		Laser	In-Air	Yes	
Either	Yes	Yes	Mechanical Nibbler	Either	Yes	Yes

TABLE 6.2

APPLICATION CHARACTERISTICS FOR CUTTING PROCESSES

Method	Application	Remote Operation Feasibility	Relative Cost
Arc Saw	All metals $\leq$ 36 in.	Excellent	High
Plasma Arc	All metals $\leq$ 6 in.	Excellent	High
Oxygen Burner	Mild steels, all thicknesses	Excellent	Low
Thermic Lance	All metals, all thicknesses	Poor	Low
Explosive Cutting	All metals $\leq$ 6 in.	Good	High to Very High
Laser	All metals $\leq$ 2 in.	Poor	Very High
Mechanical Nibbler	All metals $\leq$ 1/4 in.	Good	Low

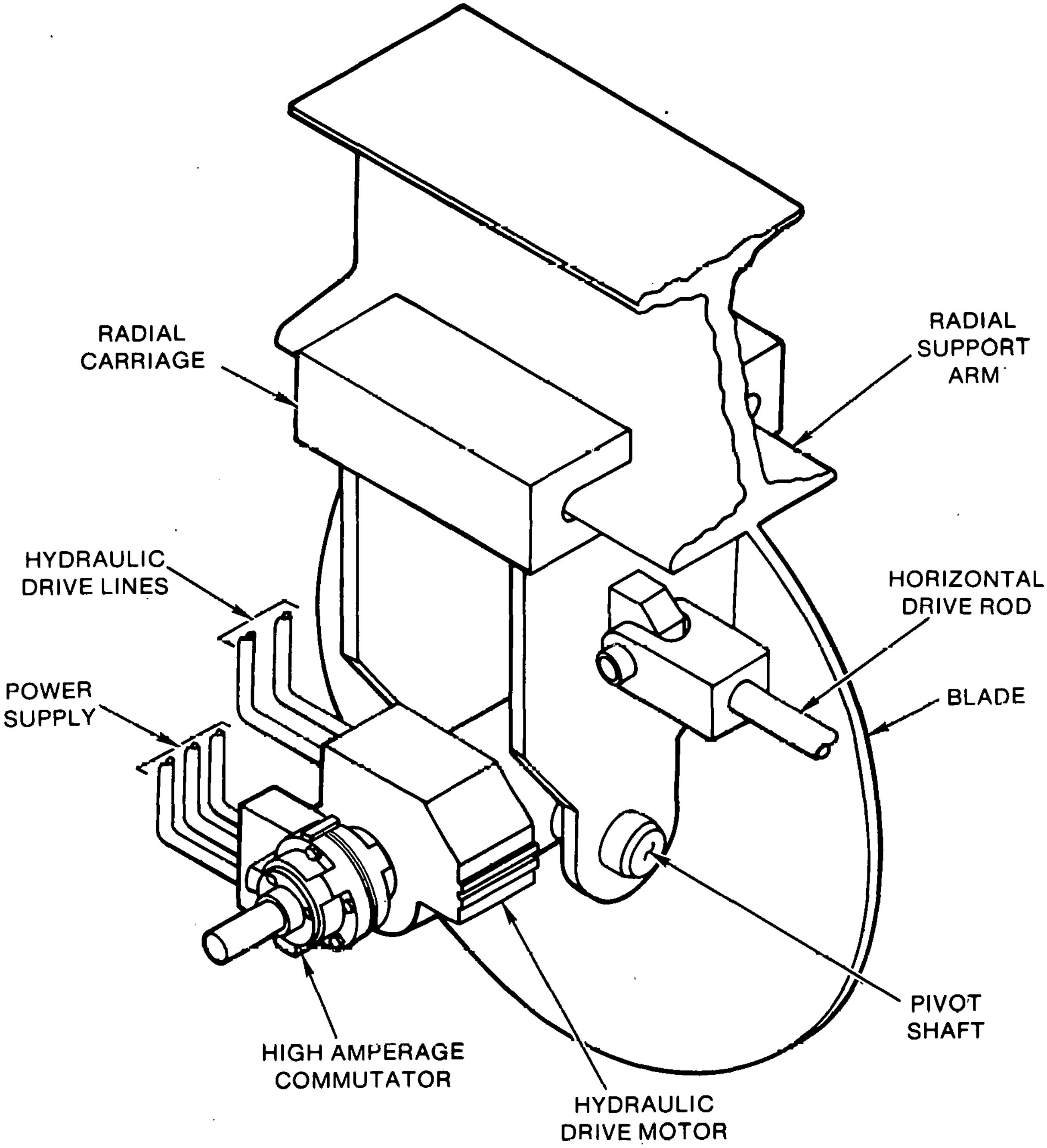
TABLE 6.3

ARC SAW SYSTEM OPERATIONAL CHARACTERISTICS

Item	Comment
Material applicability	All conducting metals
Material thickness	Up to 36 inches
Relative cutting speed	Rapid
Material geometry limitation	None
Cutting environment	Underwater or in-air
Preferred cutting environment	Underwater
Major drawback	Space access to accommodate blade diameter
Cost	High

FIGURE 6.1

TYPICAL ARC SAW CUTTING HEAD



Rotation of the blade is essential to operation but rotational speed is not a critical parameter; 300 to 1800 rpm is acceptable. Blade rotation effects removal of the molten metal generated by the arc in the kerf of the workpiece. The molten material condenses in the form of highly oxidized pellets as it is expelled from the kerf. Rotation aids in cooling of the blade and maintenance of its structural integrity. The arc saw can operate underwater or in-air. The depth of cut is limited by blade diameter. A depth of cut of three feet is considered achievable.

The arc saw is usually operated in a constant voltage mode using a very fast response regulated D.C. power supply. The saw blade is connected to the power supply by a high current slip ring device and is at a positive potential of 35 to 50 volts with respect to the workpiece. The cutting process requires maintenance of an arc current the magnitude of which is dependent on the material being cut. The mechanical feed of the saw blade into the workpiece is automatically controlled by a servo mechanism designed to monitor arc current and position the saw blade to an accuracy of about 0.1 mm. The system requires a specialized power supply with a response time of less than 10 milliseconds. This is orders of magnitude faster than typical melting or welding equipment supplies.

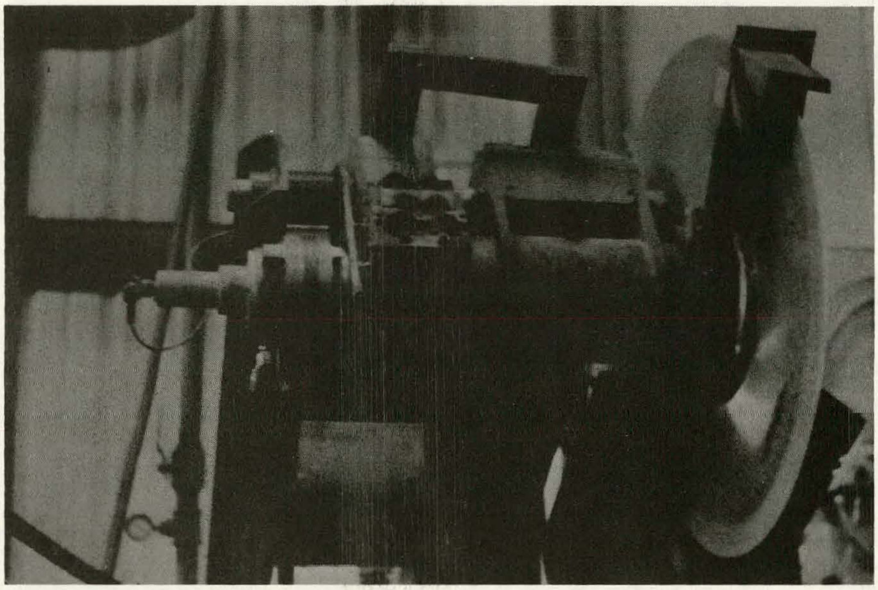
Figure 6.2 is a photograph of a fixed location arc saw system and associated control panel and power supply.

An example of the relationship between arc length in the workpiece and the required power supply is shown below:

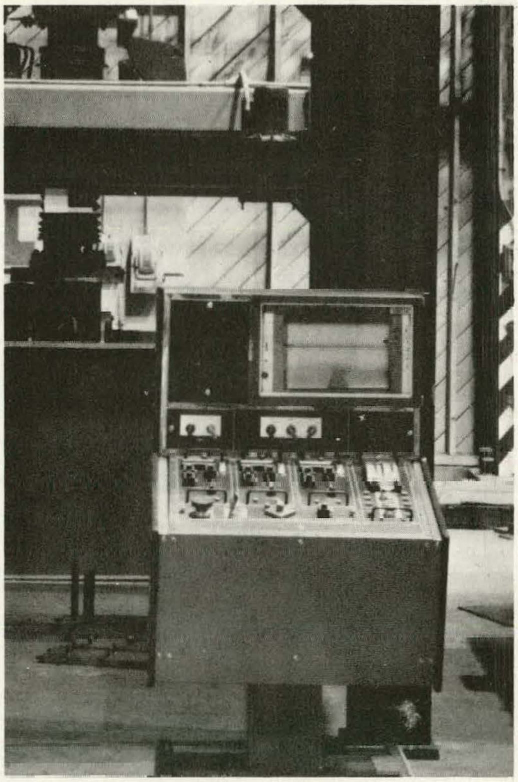
> Calculate the threshold current for an arc saw of 0.120 inches in width and an effective arc segment length of one inch in stainless steel.
>
> $I^o = (a)(s)$ (For stainless steel, $a = 5$)
>
> $s = (W)(1)$

FIGURE 6.2

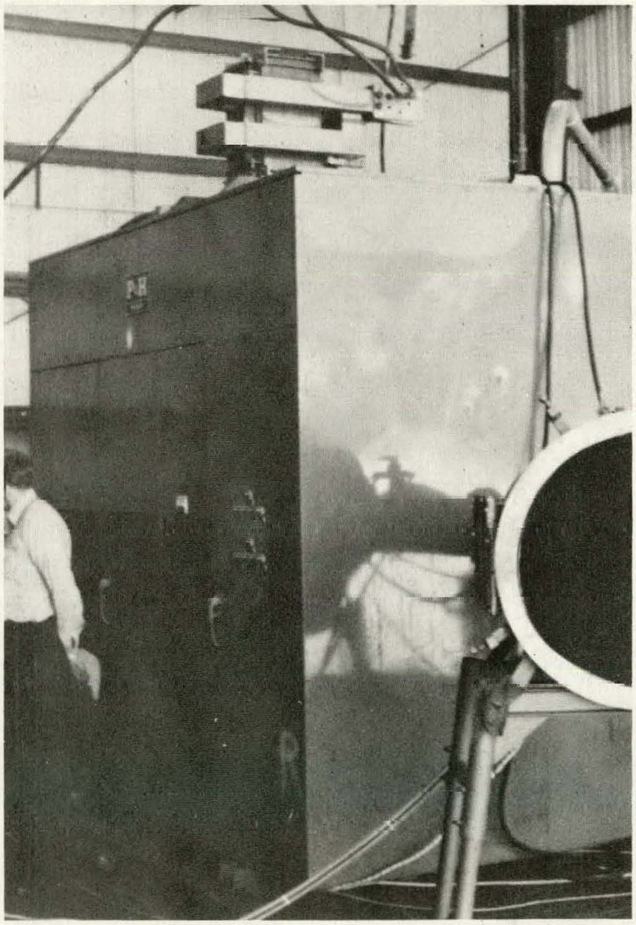
FIXED LOCATION ARC SAW COMPONENTS



FIXED SYSTEM HEAD



CONTROL CONSOLE



REGULATED D.C. POWER SUPPLY

$W = (0.12 \text{ in})(25.4\text{mm/in}) = 3.05\text{mm}$

$l = (1 \text{ in})(25.4\text{mm/in}) = 25.4\text{mm}$

$I^{o} = (5)(3.05)(35.4) = 387 \text{ amps}$

Cutting speed is primarily a function of the electrical and thermal properties of the metal. Cutting speed in terms of cross sectional area of cut in the workplace per unit time is expressed in the following equation:

$$V = \left(\frac{400}{w}\right)\left(\frac{I - I_0}{1000}\right)$$

Where:

V = cutting speed in cm^2/min

w = blade width in millimeters

I = actual cutting current in amperes

I_o = threshhold current in amperes

As indicated in the equation, an increase in the cutting current will increase the cutting speed.

Thin blades (thickness to diameter ratio of about 0.001) have the benefit of greater cutting speeds whereas thick blades (thickness to diameter ratio of about 0.01) are capable of withstanding large mechanical forces. There is an obvious trade-off depending on the application. Blade loss through operation of wear has been shown to be less than 5% of the material removed from the kerf.[1]

2. Applications

The arc saw is capable of cutting any electrical conducting material. High conductivity materials such as stainless steels, high alloy steels, aluminum, copper and inconel can be cut rapidly and cleanly at rates independent of material strength and ductility properties. Carbon steel cuts are most difficult to make since slag buildup in the kerf impedes the cutting rate of speed. Magnesium, titanium and zirconium can be cut; however, the arcing will produce some hydrogen gas resulting in the possibility of small localized ignitions or detonations.

Operation of the arc saw underwater provides a smooth, uniform kerf and is the preferred environment. Cutting may be performed in-air, with or without a water spray to facilitate blade cooling; however, in-air cutting will generate significant amounts of smoke, greater noise and produce a rougher cut surface.

The depth of cut may span solid material or any number of continuous or discontinuous layers of varying thickness and type of materials. The arc saw has been used to cut solid metals up to 8 inches in thickness and complex assemblies up to 12 inches thick.[2] Cuts can be made in vertical and horizontal planes. The angle of entry is not critical. Since there is no metal-to-metal contact between the blade and the workpiece, reaction forces are small. Therefore, the workpiece does not require rigid clamping.

Cutting speeds reported by Retech are as follows:

Material	Cutting Speed Achieved
Stainless Steel	1750 cm^2 */min
Tool Steel	1750 cm^2/min
Mild Steel	1750 cm^2/min
Aluminum	5000 cm^2/min

NOTE: These speeds are many times faster than any torch cutting technique.

A test program is in progress at Richland, Washington, under the direction of Rockwell Hanford, which will demonstrate arc saw cutting of metal sections up to 18 inches in thickness.[3]

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* Area of cut surface parallel to the plane of the blade.

The arc saw system is considered a prime candidate for use in the segmenting of activated reactor vessels and vessel internals. The complex geometries of the internal structures, supports, and flow distributors pose no problem to initiation or continuance of the cutting arc. These cuts can be made underwater, which will provide smooth cuts, less operational noise, high power cutting efficiency with maximum blade cooling, and good control of the molten radioactive metals. The thick clad sections of the reactor vessel can be cut with the arc saw system; however two practical problems are introduced. First, the wall thickness of a reactor vessel (10 -13 inches) will require a blade diameter of 30 - 40 inches. This poses certain saw head assembly access problems as well as blade positioning concerns. Secondly, most reactor vessels will be best suited for in-air segmenting rather than underwater cutting. This means that the vessel cuts will generate a great deal of noise and smoke and will require larger capacity contamination control envelopes around the reactor cavity with appropriate air supply and absolute filtration of the effluent. This approach has been successfully accomplished at the Elk River Reactor. A sketch of such a contamination control envelope is shown in Figure 6.3

Table 6.4 is a tabulation of the physical characteristics of arc saw systems developed or proposed by Retech, Inc.

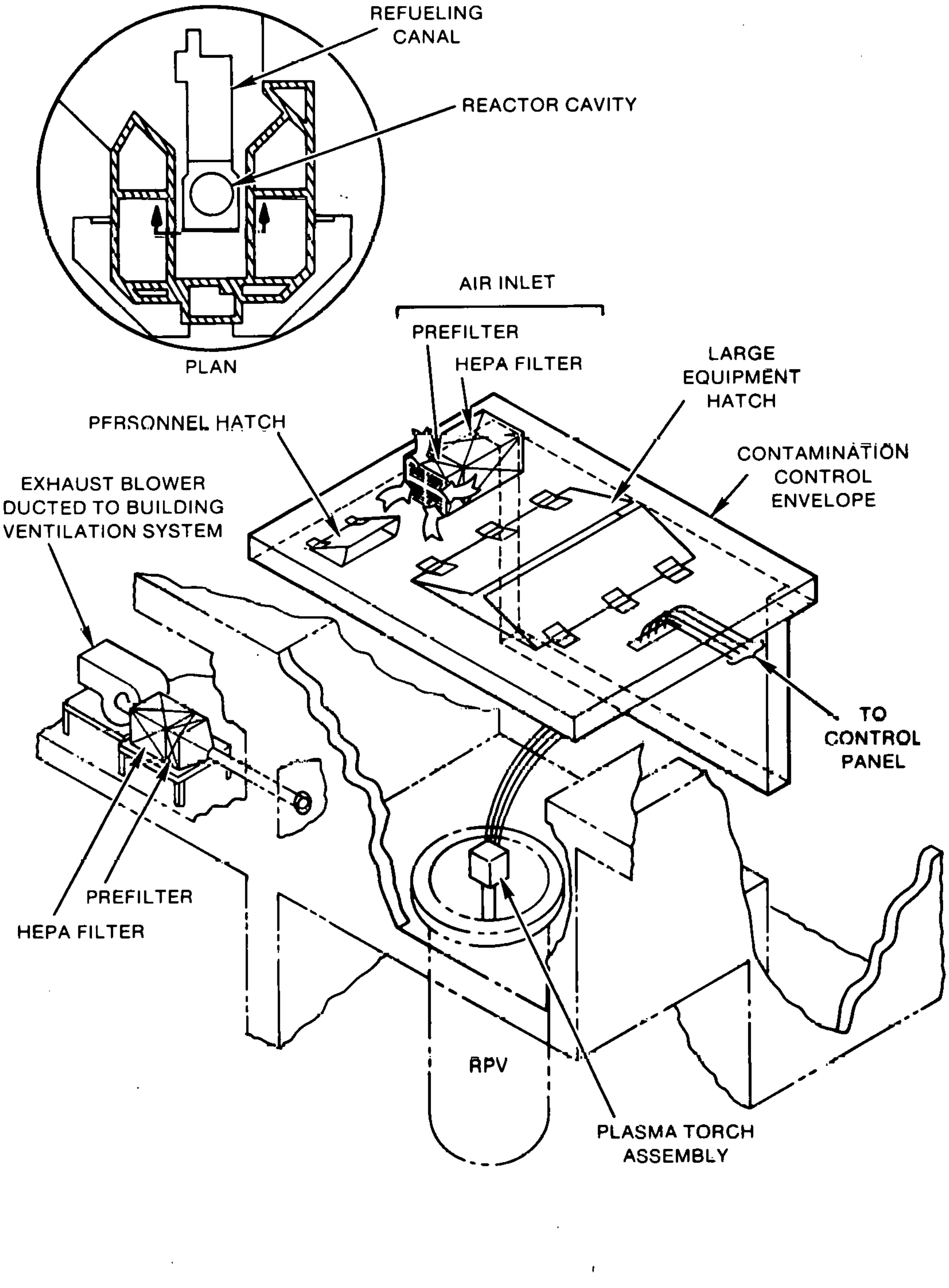
TABLE 6.4

ARC SAW SYSTEM CHARACTERISTICS

	Parameters		
Saw Head Size, inches	7	12	16
Max Blade Diameter, inches	30	50	72
Max Depth of Cut, inches	9	15	30
Current Capacity, amperes	6,000	15,000	25,000
Operating Voltage Differential, volts	25	25	25
Weight of Head and Motor, pounds	400	1,170	2,729

FIGURE 6.3

CONTAMINATION CONTROL ENVELOPE



The power supplies for the Retech arc saw systems have been manufactured by Kirkhoff of Grand Rapids, Michigan to the specifications of Retech. Two sizes have been built rated at 5,000 amperes and 10,000 amperes, respectively. Each is available with primary voltages of 480, 2,400 and 4,160V. Since the largest unit presently available is rated at 10,000 amperes, applications requiring large amounts of power have been accommodated by using multiple power supplies connected in parallel.

3. Cost Information

Table 6.5 presents the approximate cost in 1979 dollars of the basic arc saw head systems described above. These costs exclude the remote handling and positioning equipment that would be required for application to a project such as segmenting of an irradiated reactor vessel.

TABLE 6.5

ARC SAW SYSTEM COSTS*

	Approximate Cost, 1979 Dollars		
		Saw Head Size	
Component	7 inch	12 inch	16 inch
Individual Blades	$ 100	$ 400	$ 1,000
Controller Console	33,000	33,000	33,000
Power Supply	45,000	116,000	187,000
Hydraulic System	33,000	33,000	33,000
Cost of Basic System	$111,100	$182,400	$254,000

The operation of the unit requires only a single individual at the console. The field application would probably require a three-man

---

* Obtained from D. Warren, Retech, Inc., July, 1978.

team, considering operation of the positioning equipment and handling of the workpiece segments.

Blade wear, at a rate of 2% of the kerf, would equate to a blade cost of about \$0.25 per linear inch of cut of a thick-walled reactor vessel. This would amount to blade cost of less than \$5,000 for an entire large light water reactor vessel segmenting program.

6.3.2 Plasma Arc Cutting

1. Description of Process

The plasma arc cutting process is based on the establishment of a direct-current arc between a tungsten electrode and any conducting metal. The arc is established in a gas, such as argon, that flows through a constricting orifice in the torch nozzle to the workpiece.

The constricting effect of the orifice on both the gas and the arc results in very high current densities and high temperatures in the stream (10,000 - 24,000°k).[4] Figure 6.4 illustrates the basic components of a plasma arc torch. Table 6.6 summarizes the important operational characteristics of the plasma arc system.

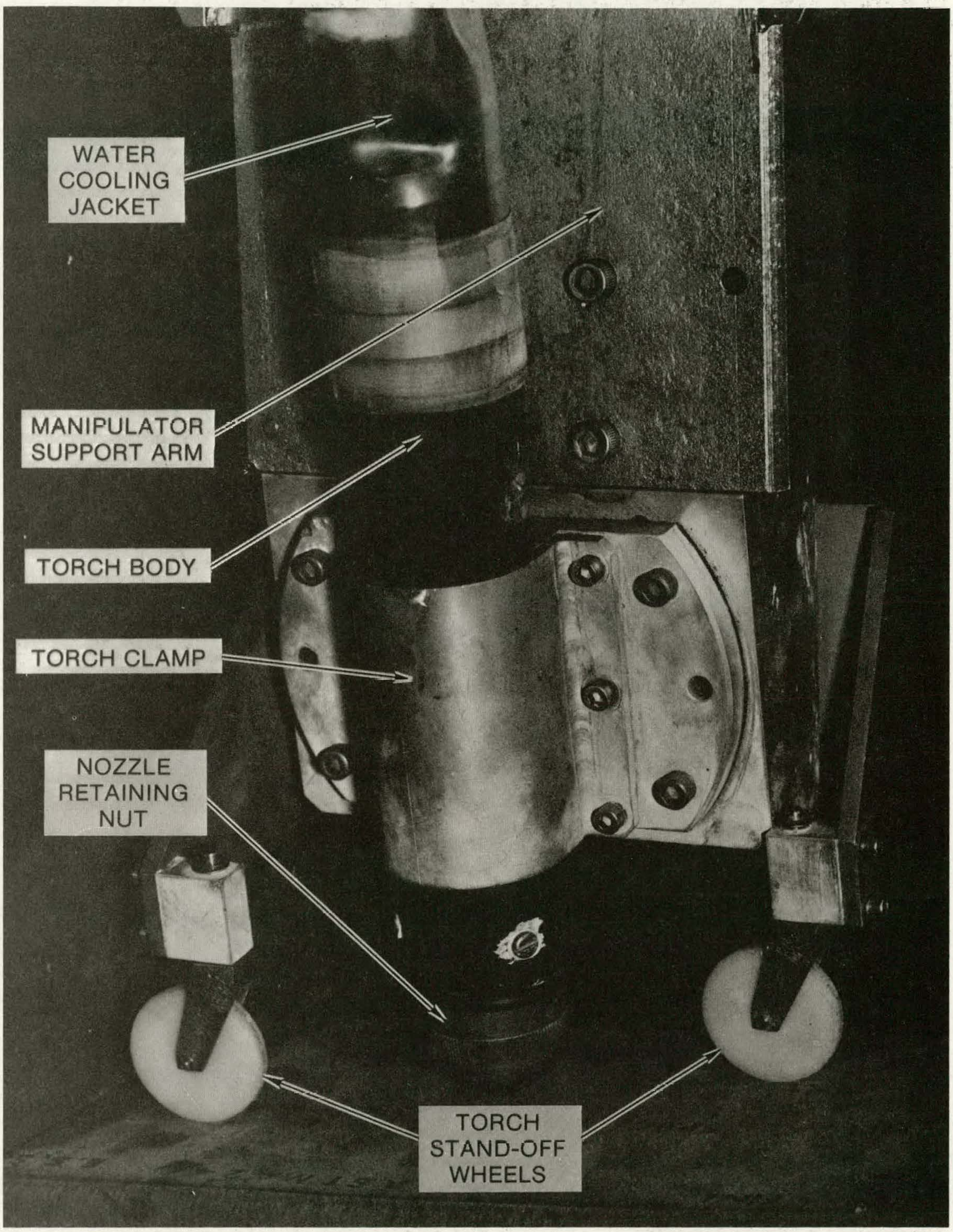
TABLE 6.6

PLASMA ARC SYSTEM OPERATIONAL CHARACTERISTICS

Item	Comment
Material Applicability	All conducting metals
Material Thickness	Up to 7 inches
Relative Cutting Speed	Rapid
Material Geometry Limitation	Space required behind workpiece to accept flow of molten metal
Cutting Environment	Underwater or in-air
Preferred Cutting Environment	Either; thicker cuts can be made in-air
Major Drawback	Required relief space behind the workpiece
Cost	High

FIGURE 6.4

PLASMA ARC TORCH AND COMPONENTS



The stream or plasma consists of positively charged ions and free electrons. The plasma is ejected from the torch nozzle at a very high velocity and, in combination with the arc, melts the contacted workpiece metal and literally blows the molten metal away. A typical cut starts at the metal edge and a through cut is made in a single pass by simply moving the torch at a fixed rate of speed in the direction of the cut with a fixed nozzle spacing relative to the workpiece.

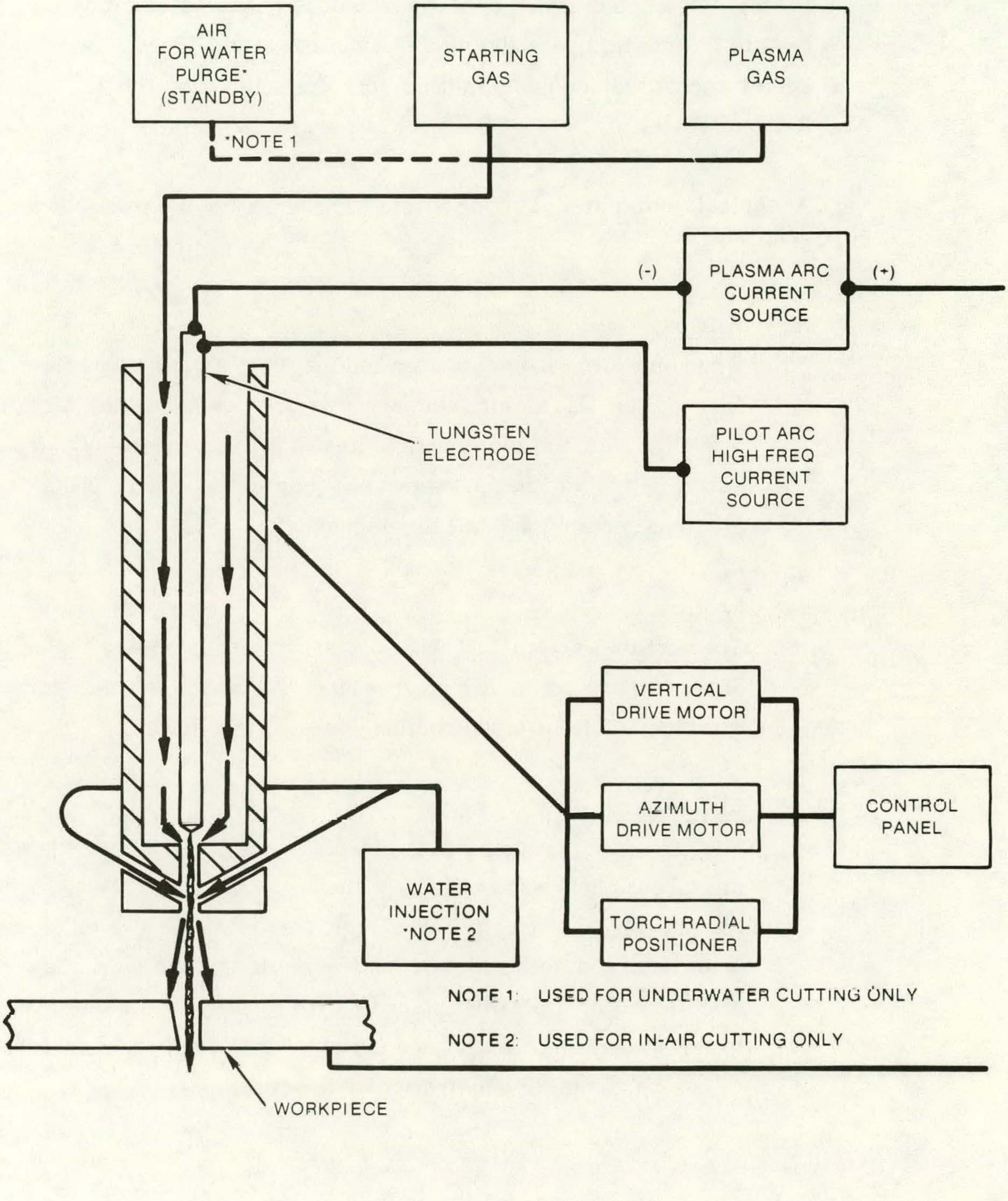
The plasma arc process has also been used with a water-injection option. This technique directs a radial jet of water that impinges on the plasma stream near the torch nozzle. The effect of the water jet is to further constrict the plasma stream, which results in even higher current densities. The cutting effect is a narrower kerf, higher quality cut surface, and reduced smoke generation. The water-injection technique was used in the plasma arc segmenting of the Elk River Reactor vessel. Vessel internals segmenting was performed underwater with a resultant reduction in radioactive particulates and gases.[5]

The depth of cut achievable is reported as approximately 7 inches in-air and 5-1/2 inches underwater.[6] However, Atomics International reports that 5-1/2 inch carbon steel was satisfactorily cut in-air but was not successful underwater.[7] It is the consensus of the manufacturers that the depth of cut could be extended with further development effort. It should be noted that the Elk River Reactor usage of the plasma arc technique required an improvement in the state-of-the-art of about a factor of two. The development work that led to this success was directed by Mr. Robert Blumberg of the Oak Ridge National Laboratory.[8]

A typical plasma arc system requires a direct current power supply of up to 1000 amps. A schematic of a plasma arc cutting system is shown in Figure 6.5. An automatic plasma arc cutting system would include: torch positioning equipment; torch travel system; air,

FIGURE 6.5

REMOTE PLASMA ARC CUTTING SYSTEM SCHEMATIC



NOTE 1: USED FOR UNDERWATER CUTTING ONLY

NOTE 2: USED FOR IN-AIR CUTTING ONLY

starting gas, and plasma gas supply systems; pilot arc high frequency power supply; plasma arc power supply; and associated gas flow, arc, and mechanical travel controls.

Figure 6.6 shows a schematic representation of a torch assembly unit in position for segmenting a reactor vessel. Figure 6.7 is a photograph of the instrument and control panel associated with a remote automatic operation of a plasma arc torch. These figures all depict the actual equipment used for disassembly of the Elk River Reactor vessel.

A typical automated cutting cycle is comprised of the following stages:

A. Airflow

When the torch is underwater and inactive, a continuous flow of filtered air is maintained through the unit. This airflow prevents water and/or particulates, e.g., suspended slag, from entering the nozzle passages and eliminates water-promoted electrode erosion and nozzle clogging.

B. Preflow

The airflow is replaced with a starting gas mixture, typically argon and nitrogen. A high frequency generator is energized to establish a pilot arc and cooling water flow initiated.

C. Cut Through

The pilot arc ignites, firing the plasma arc. The starting gas mixture is changed to eliminate the argon, leaving only nitrogen for the plasma stream. The high frequency generator is de-energized and the pilot arc is terminated. The workpiece is maintained at a positive polarity with respect to the electrode. In this stage, torch travel is maintained at a slow speed in order to ensure complete penetration of the cut.

FIGURE 6.6

PLASMA TORCH SYSTEM FOR REACTOR VESSEL

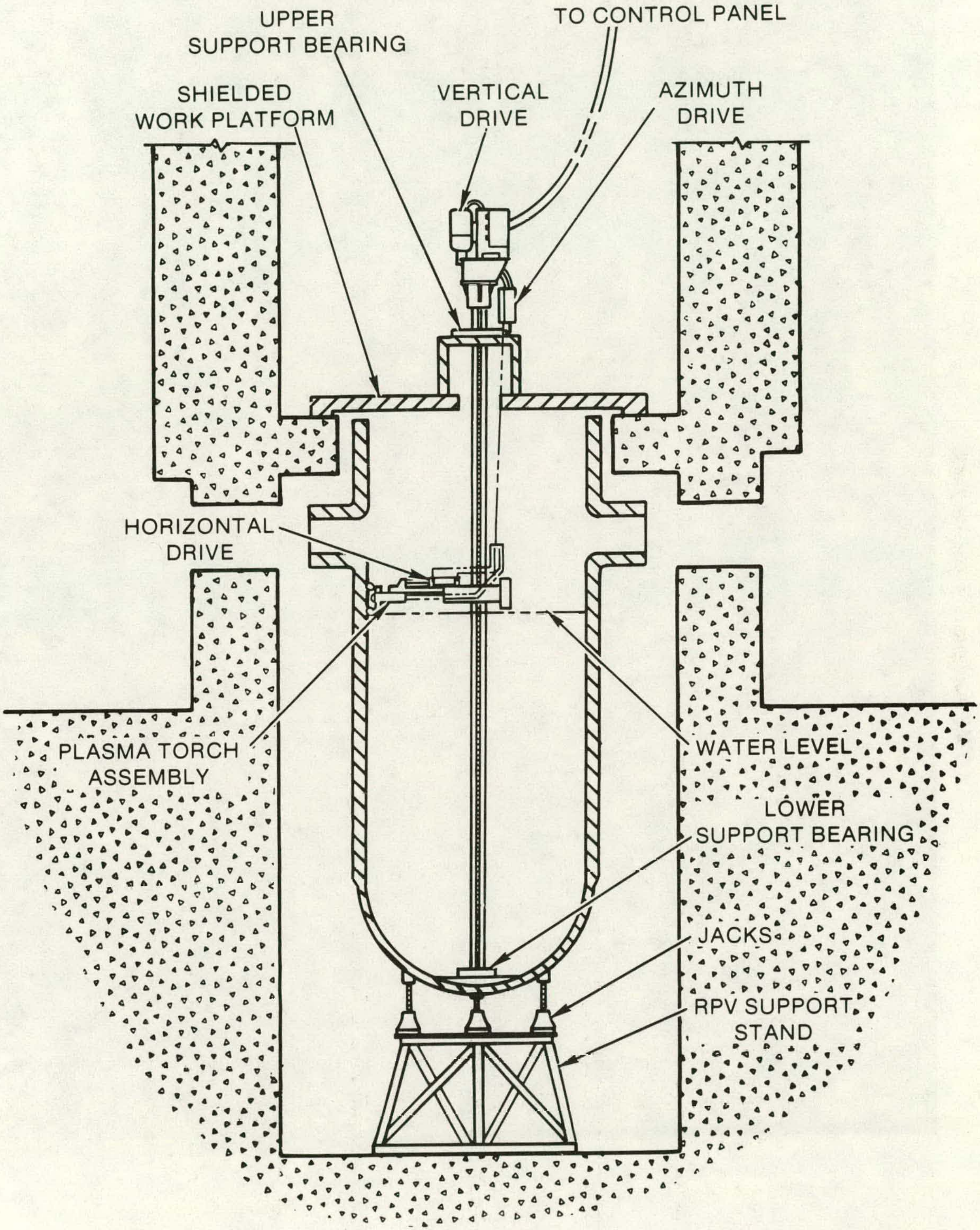
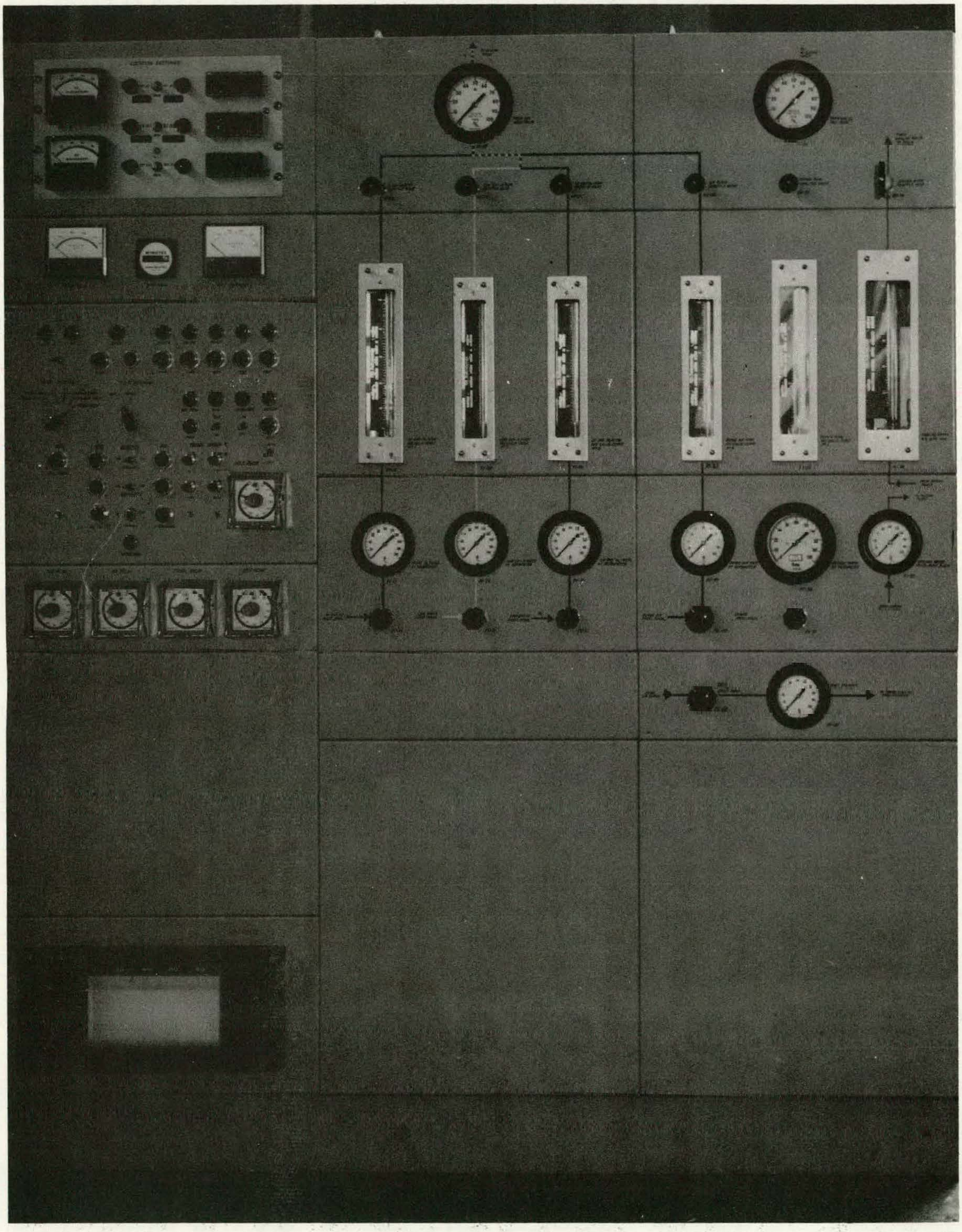


FIGURE 6.7

PLASMA ARC SYSTEM CONTROL PANEL



D. Cut

Torch travel speed is increased to the programmed normal speed and the required cut is made.

E. Cutoff

The torch travel speed is decreased to ensure complete cutoff as the edge of the workpiece is approached. As the torch passes the edge of the workpiece, the arc is lost. The power supply is de-energized and torch travel is stopped.

F. Postflow

The plasma gas flow is replaced by the starting gas mixture for a short time. Cooling water flow is then terminated and filtered air flow introduced to replace the starting gas.

2. Applications

The plasma arc process is capable of cutting all metals. In-air use will penetrate thicker sections than underwater. Present state-of-the-art maximum cutting thicknesses for typical steels, using an automated system, are as follows:

	In Air	Underwater
Stainless Steel	6 in.	3 in.
Carbon Steel	7 in.	5-1/2 in.

Manual (hand-held) torch operation cannot be used for materials greater than 1-1/2 inches in thickness due to the reaction force of the gas flow and plasma jet.

The plasma arc can be used to pierce metals. This means that a cut does not have to be initiated from the edge of the segment to be cut. Experience at Elk River indicated that piercing was achievable with a nozzle standoff distance from the workpiece of 0.625 inches. This gap, which is about twice the standoff distance used during cutting, minimized blowback of the molten metal and extended torch life.[9,10]

At times during operation of the plasma arc system, a phenomenon called "double arcing" occurs. This means that an arc is established between the electrode and the nozzle as well as with the workpiece. It may be caused by an eccentric electrode, shorting of the nozzle to the workpiece, or blowback of removed metal particles effecting a short circuit. Nozzle damage is likely in this condition.

The operating life of the components of a typical torch assembly is as follows:

nozzle - 30 minutes
retaining unit - 30 minutes
electrode - 3 hours

Typical cutting speeds for the plasma arc technique applied to carbon and stainless steels are listed in Table 6.7. They represent a compilation of numerous industry sources.

The plasma arc process has been demonstrated in the segmenting of the Elk River Reactor activated vessel internals and reactor vessel and in the on-going Sodium Reactor experimental dismantlement program. The ability of the plasma arc to cut thick sections of a large light water reactor pressure vessel would have to be demonstrated by a development program. It is expected that such a demonstration program could be successfully performed; however, blowback of the molten metal against the torch may preclude piercing of the thick sections by the plasma arc process. In this case, all cuts would have to be initiated from an edge of the workpiece.

Use of the plasma arc for remote cutting of activated or contaminated components would have to be accomplished within the

TABLE 6.7

TYPICAL CUTTING SPEEDS FOR THE PLASMA ARC TECHNIQUE

Material To be Cut	Material Thickness, in.	Cutting Environment	Cutting Speed, in/min *
Stainless Steel	1		100
	1-1/2	Underwater	35
	3		6
	1/2		75
	1-1/2	In-Air	25
	3		8
Carbon Steel	2-1/2		6
	5-1/2 (extrapolated)	Underwater	3
	1/2		40
	1-1/2	In-Air	20
	3		6

confines of a contamination control envelope similar to the one shown in Figure 6.3.

3. Cost Information

The approximate cost in 1979 dollars of the plasma arc cutting system, capable of cutting three inch thick stainless steel in-air, is \$15,000. A similar system for cutting four inch thick stainless steel in-air, costs approximately \$25,000. Each system includes the torch assembly, power supply, control console, and cooling water system. The automation of the plasma arc system would result in much higher costs associated with torch positioning, cutting speed control and automatic arc control. In addition, the development program required to extend the state-of-the-art to accommodate large reactor vessel sections has been estimated broadly by the authors at

---

* Cutting speed is the maximum linear travel rate of the torch in the direction of the cut with complete single-pass penetration of the workpiece.

one million dollars. This includes the complete hardware, plasma arc control systems, mount mast, positioning equipment and automatic drive units for use in an actual large reactor field application.

The operation of an automated system would require only a single individual at the control console. The field application would probably require a three man team, considering operation of the positioning equipment and handling of the workpiece segments.

Gas consumption has been up to 600 ft^3/hr for underwater cutting and about 300 ft^3/hr for in-air cutting. Considering the life expectancy of the torch components, the total consummables cost for a 40 hour per week underwater cutting program would be approximately $1600.00. This includes the following:

gas	$600.00
electric power	$120.00
electrodes	$ 80.00
nozzle tip and nut	$800.00

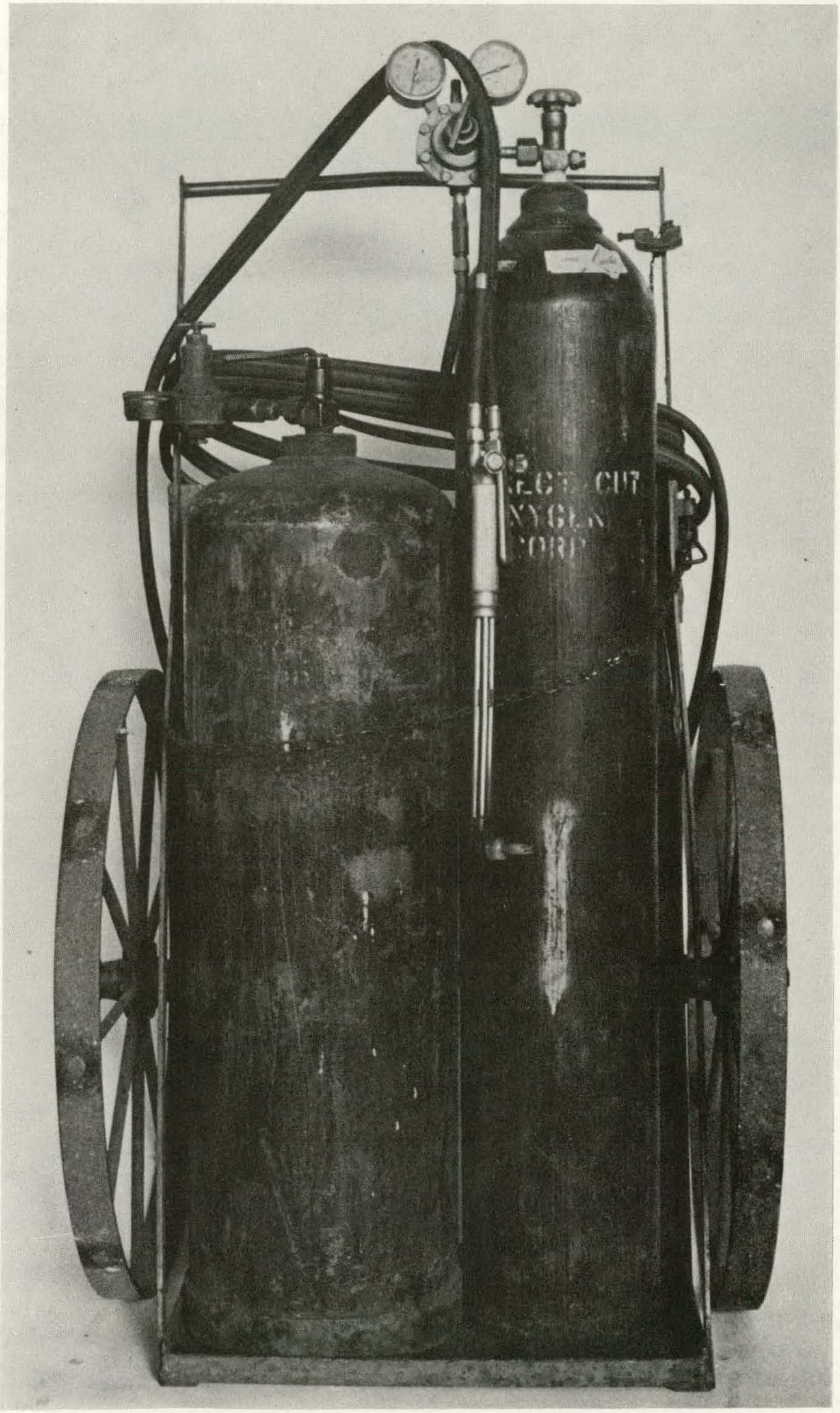
6.3.3 Oxygen Burning

1. Description of Process

Oxygen burning, sometimes referred to as oxyacetylene cutting, consists of a flowing mixture of a fuel gas and oxygen ignited at the orifice of a torch. The fuel gas may be acetylene, Mapp gas, propane, or hydrogen. A hand-held torch is the general method of usage of this process although it is readily adaptable to automated positioning and travel. The cutting tip of the torch consists of a main oxygen jet orifice surrounded by a ring of preheater jets. The fuel gas is exothermically oxidized through the preheater jets. When the metal to be cut reaches approximately 1500° F, the main oxygen jet is turned on, the heated metal is "burned" away leaving a reasonably clean cut surface. Figure 6.8 depicts a typical oxygen burning torch assembly.

FIGURE 6.8

TYPICAL OXYGEN BURNING TORCH ASSEMBLY



Oxygen burning refers to the rapid exothermic oxidation of the metal to be cut. Therefore, only those metals that will undergo this process can be cut with an oxygen burning torch. In general, these are the ferrous metals including steel products such as sheet, plate, bar, piping, forgings, castings and wrought iron products.

An oxygen burning torch is ordinarily unable to cut stainless steel, aluminum, and other non-ferrous or ferrous/high percent alloy metals, due to the formation of refractory oxides, (e.g. CrO_2 and Al_2O_3) with high melting point temperatures. These metals can be cut if either the temperature of the torch flame can be increased above the melting point of the oxides or the oxide formation can be prevented. An iron powder or an iron/aluminum powder flowing mixture can be introduced at the torch nozzle and the torch flame temperature significantly increased. The iron/aluminum powder results in a higher temperature due to a thermite reaction. The increased flame temperature will melt the refractory oxides formed by the oxygen. The powder is introduced either through the oxygen jet, or by a seperate nozzle feeding into the cutting zone. In addition to the higher temperatures, the cutting action is assisted by the increased mass flux in the torch flame. This produces an erosion effect on the metal facilitating the cutting action.

A chemical flux can also be introduced into the reaction by a powder, again, either through the oxygen jet or by a separate nozzle. The flux chemically inhibits the formation of the refractory oxides. In practice a mixture of both iron and flux powders is generally used for the best results.

Alloying elements in the steel to be cut will, in general, not effect the cutting operation. Precautions that are normally necessary for protection of the workpiece, such as preheating high carbon steels, are not necessary in a dismantling program. Cracks that may be introduced into the metal in the area of the cut have no significance since the metal will either be stored at a waste disposal site or scrapped.

The selection of a fuel gas for a standard oxygen burning is usually based on cost of fuel gas, consumption rates, and impact on cutting speed due to the preheating rate. Although the actual cut is accomplished by burning the metal with the oxygen jet, a more rapid preheat will permit a faster cutting speed. The preheating impact is obviously more important to thick workpieces than to thin. Acetylene (C_2H_2) produces a flame temperature significantly higher than the flame temperatures of the other fuel gases.

2. Applications

The oxygen burning process is quite effective in cutting carbon steels. Oxyacetylene cutting has been used in production runs for cuts of material up to 60 inches in thickness. The cutting speed and oxygen consumption for in-air segmenting of carbon steel is as follows:

	Thickness in Inches							
	0.25	0.5	1	2	4	6	8	10
Manual Speed (in/min)	16-18	12-14.5	8-12	5-7	4-5	3-4	2.5-3.5	2-3
Machine Speed (in/min)	20-26	17-22	14-18	7-9	7-9	5-7	4-6	3-4
Oxygen Consumption (cfh)	59-90	90-125	130-200	200-300	300-400	400-500	500-600	700-1000

For thickness from 12 to 48 inches, cutting speed ranges from 6 to 2 inches per minute.[11] The fuel gas volume usually ranges from 10 to 15% of the oxygen consumption.

The application of oxygen burning cutting of metals can be accomplished underwater using either a fuel gas or an electric arc to preheat the metal. For safety reasons acetylene is not used underwater, except for shallow depths, since it becomes explosively unstable at pressures greater than 15 psig. Hydrogen is generally used as the fuel gas underwater.

Oxygen arc underwater cutting is performed with a special hollow, shielded and insulated electrode. A fully insulated electrode holder conducts current and oxygen to the electrode. Striking the arc preheats the metal and the oxygen burning makes the cut as before. The oxygen-fuel gas method applied underwater requires surrounding the torch with an annular bell through which compressed air is forced to clear the torch and the adjacent workpiece of water.

Underwater cutting is somewhat more difficult to accomplish. The maximum thickness of metal that can be cut is 3.5 inches. This is due to the greater heat loss in the water environment.

Principle application of oxygen burning in decommissioning work would be the general disassembly of structural carbon steel members such as beams, columns, and supports. Since the process is so widely known, skilled workers who can handle the equipment will be readily available. The equipment is inexpensive to obtain and maintain, and is quickly and easily set up. If necessary, the oxygen torch can be mounted on a remotely operated torch positioner and used to cut in an environment that is too hazardous for direct exposure of workers. This will, of course, increase the cost and complexity of the operation.

3. Cost Information

The oxygen burning cutting technique is a relatively inexpensive method. A typical hand-held torch costs approximately $200.00. The only significant consumables cost is the operating gas since the cutting tip life-time is quite long if the jet orifices are cleaned regularly. Typical gas costs are included in Table 6.8.

The cutting speed of oxygen burning is less than 50 percent of plasma arc. Therefore, the system would not be recommended for extensive remote cutting of carbon steels where the consumables cost is small compared to the cost of the positioning equipment and the cost of the operating crew required to perform the cutting program.

TABLE 6.8

TYPICAL OXYGEN BURNING GAS COSTS

Material Thickness Inches	Cost for 10 Linear Feet of Cut, $ Fuel Gas	Oxygen	Total Gas
1	.40	1.60	2.00
2	.84	3.36	4.20
6	2.97	12.00	14.97
10	7.53	30.38	37.91
30	39.79	160.00	199.79

6.3.4 Thermite Reaction Lance

1. Description of Process

The thermite reaction lance is an iron pipe packed with a combination of steel, aluminum and magnesium wires through which a flow of oxygen gas is maintained. The lance cuts are achieved by a thermite reaction at the tip of the pipe in which all constituents are completely consumed. Temperatures at the tip range from 4,000° F to 10,000° F depending on the environment (in-air or underwater) and the ambient conditions of that environment.[12] The lance is ignited in-air by a high temperature source such as oxygen burning torch or an electric arc. Typical lances are 10-1/2 feet in length and either 3/8 inch or 1/4 inch diameter. Use of the lance is practical only in manual (hand-held) mode.

A thermic reaction lance cutting system consists of a lance holder, lance, oxygen supply, 125 psi gas regulator, and an oxygen hose of no less than 3/8 inch diameter. The lance operator must also be provided with complete fireproof protective clothing and faceshield. Figure 6.9 depicts a typical thermite lance in use and in closeup.

2. Applications

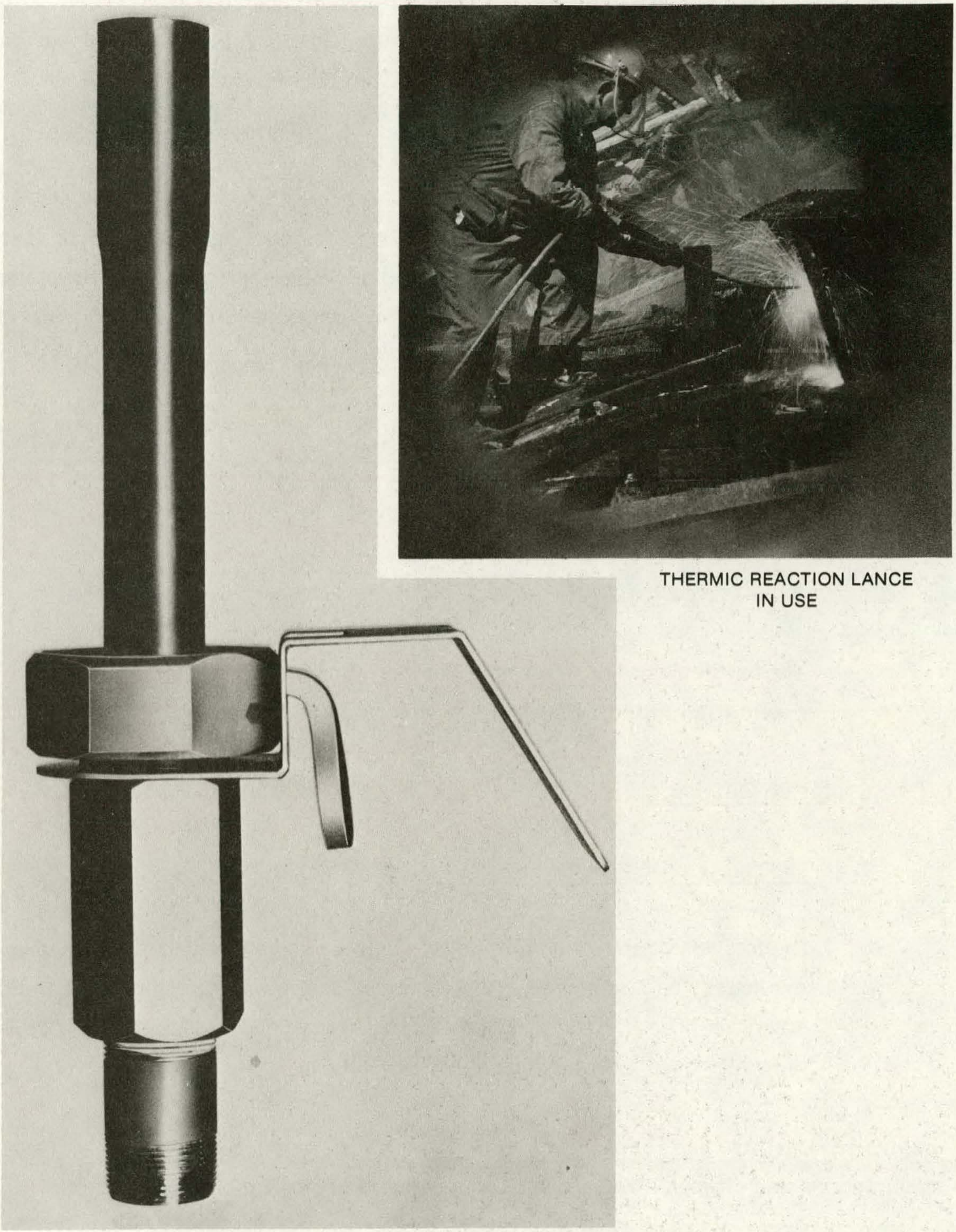
The thermite reaction lance is capable of cutting any metal. The maximum depth of cut is only limited by the ability to keep kerf clear of the molten metal. Therefore, the geometry of the workpiece relative to the flow path necessary for removal of the molten metal is the determining factor in technical feasibility of this technique of metal cutting.

The thermite reaction lance can be used in-air or underwater. The operational procedure is the same in either environment except that the lance must always be ignited in-air and the incident angle relative to an underwater workpiece must be considered in order to preserve the operator's visibility since large amounts of bubbles form during the process. The rate for metal cutting has been reported as generating approximately a one inch diameter hole at the rate of 12 inches of depth per minute provided the molten metal is free to flow away from the kerf.[13]

Complete consumption of the lance is possible by stopping the oxygen flow when the torch has burned down to about a two foot length or longer; removing the pipe from its holder and inserting a new one, then coupling the old pipe to the new using the device provided with each lance. This procedure eliminates waste while still assuring protection to the operator. In the same manner, two or three lances can be coupled together if the application warrants. Coupling of more than three lances is not recommended due to excessive flexure and difficulty of control.

FIGURE 6.9

TYPICAL THERMIC REACTION LANCE



THERMIC REACTION LANCE
IN USE

The thermite reaction lance can be classed as a gross manual cutting technique. As such, it will have limited use in segmenting highly activated and contaminated components. However, it is well suited for cutting irregular surfaces with minimum access. The process also generates significant smoke, therefore, adequate ventilation must be provided particularly if a contamination concern is present.

3. Cost Information

It is difficult to relate cost data to cutting rates since the effectiveness of the lance is greatly influenced by the workpiece geometry. Each lance will burn for approximately six minutes and consume about 60 cubic feet of oxygen. Typical unit costs associated with this method are as follows:

Item	Cost
Lance Holder	\$50.00
Lance (10-1/2 ft)	\$ 7.00
Oxygen, 100ft^3	\$ 6.00

The system only requires a single operator although a particular application might require a two-man team.

6.3.5 Explosive Cutting *

1. Description of Process

Explosive cutting is a method of segmenting metal via the use of an explosive that is formed in a geometric shape especially designed and sized to produce the desired separation of the workpiece. RDX is normally used as the explosive.

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* Explosive cutting has been used for underwater cutting of small metallic appurtences and piping. Process details are included in Chapter 8.

2. Applications

Explosive cutting can be used on any material and is not configuration limited. This technique was successfully used for underwater segmenting of a 3/4 inch thick stainless steel, core tank liner attachment in the reactor vessel of the Sodium Reactor Experiment. It has been reported that explosive cutters have been used for materials greater than six inches in thickness and also used in-air or underwater.[14] Obviously, the technique is limited by the effect of the blast on mechanical integrity of the surrounding structures and ability to preclude the uncontrolled spread of radioactive material. It is envisioned that explosive cutting of metals will find limited use in a decommissioning program and then only where other techniques are simply not feasible nor practical.

6.3.6 Laser Cutting

1. Description of Process

High-power carbon dioxide lasers have been used to cut metals. Cutting is accomplished by heating the metal to its melting point then removing the molten metal with an inert gas stream. The process can only be accomplished in-air since water would excessively diffuse the laser beam. A high-power laser cutting system contains relatively large equipment, is operated in a fixed position, and is effective only on relatively thin metals. As such, the present state-of-the-art of laser cutting will have little or no use in a decommissioning program.

Figure 6.10 is a photograph of a high-power (15 kilowatt) CO_2 laser set up for a welding/cutting station. The carbon dioxide laser uses an inert gas as the lasing medium. A typical gas composition is 78% helium, 18% nitrogen, and 4% carbon dioxide.

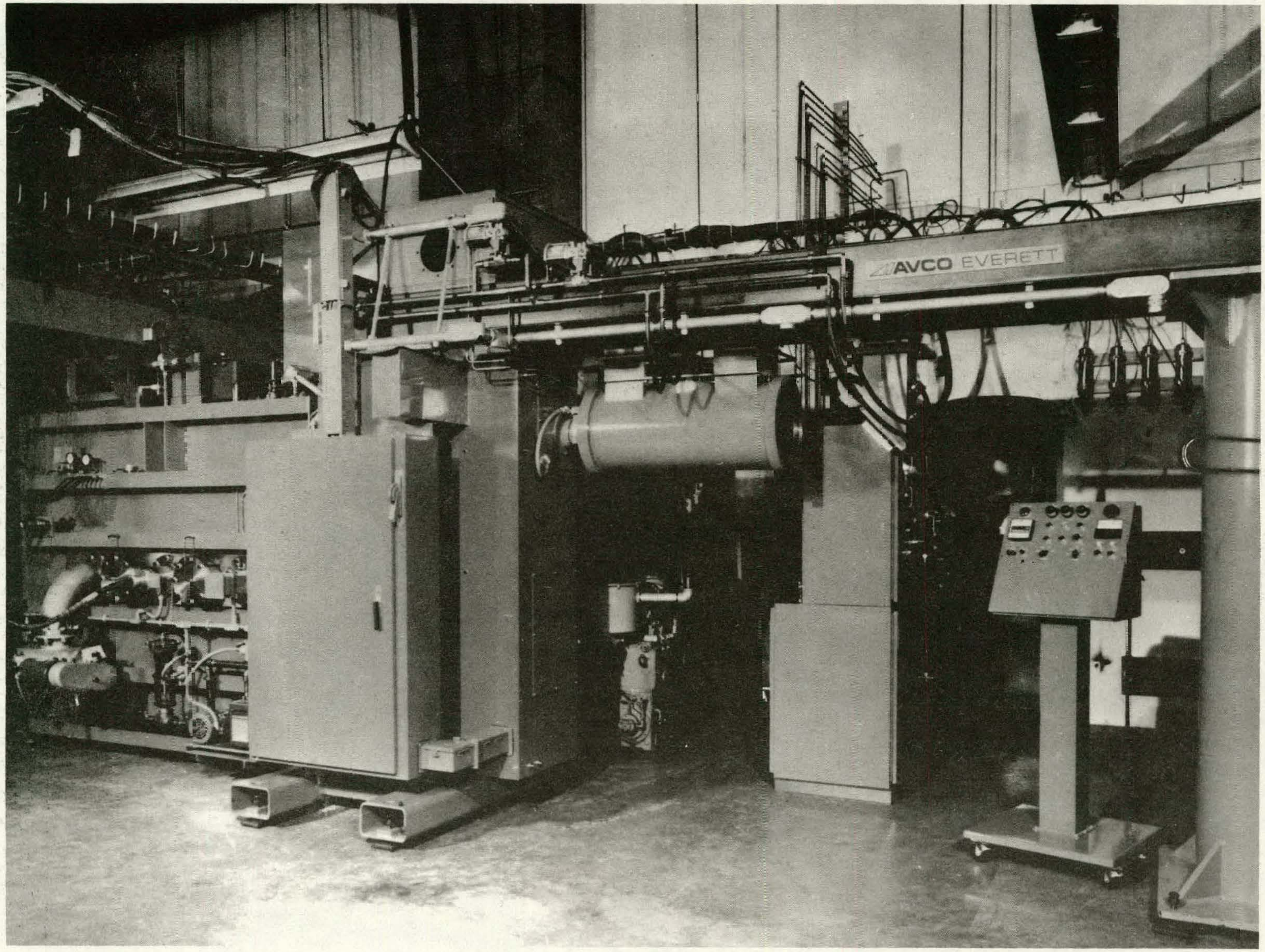


FIGURE 6.10

HIGH POWER FIXED STATION CO_2 LASER

2. Applications

A high-power carbon dioxide laser has been used to cut metal up to 2 inches in thickness although the speed is slow and cut quality poor.[15] This represents the extent of the state-of-the-art of this technique.

Approximate metal cutting speeds for high-power lasers are included in Table 6.9.

TABLE 6.9

METAL CUTTING SPEEDS FOR HIGH POWER LASERS

Material	Thickness in inches	Cutting Speed inches per minute
Aluminum	0.5	100
Carbon Steel	0.5	60
	0.75	20
Stainless Steel	0.25	200
	0.5	55
	1.0	20
	2.0	2

As previously stated, laser cutting is not a practical method of cutting metal for decommissioning applications. The available systems are not powerful enough for thick sections and not portable enough for field use.

3. Cost Information

The cost of a 12 kilowatt high-power carbon dioxide laser, including laser generator, power supply and controls capable of cutting one-inch thick stainless steel, is approximately $600,000.

6.3.7 Remote Cutting with Power Nibblers and Shears

1. Description of Process

A nibbler is a punch and die cutting tool that normally operates at a rapid reciprocation rate of the punch against the die, "nibbling" a small amount of sheet metal workpiece with each stroke. This process is ideal for cutting intricate shapes and turning corners.

A shear is a two-bladed or two-cutter tool that operates on the same principle as a conventional pair of scissors. A bladed shear is primarily used for in-line cutting of sheet metal. A rotary shear is capable of producing irregular or circular cuts.

2. Applications

Heavy duty power nibblers and shears attached to long support tubes can be utilized for remotely cutting mild steel and stainless steel components. Electric nibblers and shears can be used for remote dry applications with a power take-off. Pneumatic nibblers and shears can be used for remote wet and dry applications. For wet applications the standard nibbler or shear can be adapted with an exhaust manifold that will permit exhaust of the air away from the cut. This eliminates air bubbles at the cutter thereby improving operator visibility. Typical cutter capacities and cutting speeds are shown in Table 6.10. A typical pneumatic shear arrangement is shown in Figure 6.11. A typical pneumatic nibbler or shear requires a 90 psig air supply.

During the Elk River dismantling program, the core shroud was segmented into shippable sections remotely and underwater by a sheet metal cutting pneumatic nibbler. The materials of the two-piece shroud were 3/32-inch stainless steel and 1/16 inch zircaloy. Numerous cuts up to five feet in length were made. The operating

TABLE 6.10

CUTTING CAPACITIES AND SPEEDS

	Capacity		Cutting Speed
Cutter Type	Mild Steel	Stainless Steel	Feet/Min
Heavy Duty Shear	7 gauge (0.187inch)	8 gauge (0.172 inch)	15 to 20
Heavy Duty Nibbler	1/4 inch plate	7 gauge (0.187inch)	4

air pressure of the nibbler was increased from the manufacturer's recommended 50 psig to 90 psig in order to achieve satisfactory segmenting of the 3/32 inch radiation hardened stainless steel. The tool chisel lifetime for this operation was 30 linear feet of stainless steel.[16]

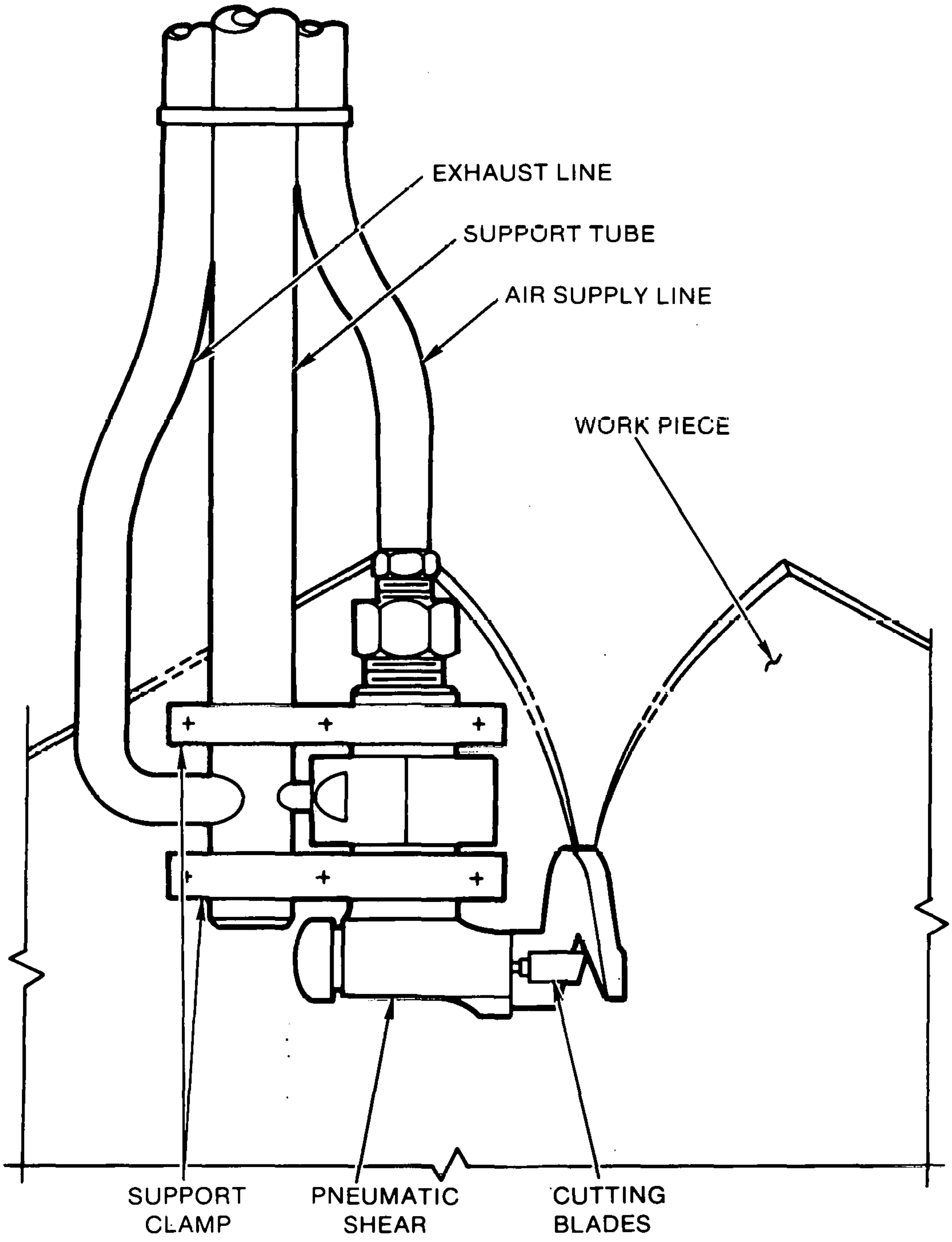
A remotely operated underwater pneumatic shear was recently used for segmenting a 16 guage (0.0625 inch) stainless steel core shroud for removal from the LaCrosse Boiling Water Reactor pressure vessel. Louvers on the shroud prevented direct access to the sixteen shroud hold-down bolts. The pneumatic shear was used to make vertical cuts in the shroud at each side of the louvered panels. Twenty-four vertical cuts were made in the shroud. Each cut was approximately 17 inches in length.[17] The shear worked freely when unobstructed by louvers; however, in areas where there were louvers, the shear would jam if lower contact were made with the shear anvil. In areas where the shear was stopped by louvers or cutting became difficult, the downward force on the shear was increased to complete the cut. This was successful; however, the increased force caused the shear blades to loosen.

3. Cost Information

Heavy duty nibblers or shears cost up to $1,000 each. Remote operating extensions would add to this cost.

FIGURE 6.11

TYPICAL PNEUMATIC SHEAR ARRANGEMENT



6.4 REFERENCES

1. Schlienger, M.P., of Retech, Inc. and Beitel, G.A., of Atlantic Richfield Hanford Company: Arc Saw Testing (Contaminated Equipment Volume Reduction Program) (February 18, 1976)

2. Beitel, G.A., of Atlantic Richfield Hanford Company: Remote Disassembly of Radioactively Contaminated Vessels by Means of an Arc Saw, ARH-SA-289 (June, 1977)

3. Private Communications with George Beitel of Rockwell Hanford Operations (September 12, 1978 and August 31, 1979)

4. American Welding Society: Welding Handbook, "Plasma Arc Cutting," Sixth Edition, Section 3, Part A, pp. 43.27 to 43.36, Miami, Florida.

5. Wodtke, C.H. and Plunkett, W.A.: Development of Techniques for Remote Plasma Arc Cutting of a Nuclear Reactor Vessel, Welding Journal (reprint) (December, 1977)

6. Private Communications with G. Johnson of Airco Welding Products, Union, N.J., and M. Fields of the Linde Division, Union Carbide Corporation, Moorestown, N.J. (1978)

7. Myers, G.W.: Presentation to the International Atomic Energy Agency Technical Committee Meeting on Decontamination and Decommissioning, Vienna, Austria (October 24 through 28, 1977)

8. Beckers, R.M., Blumberg, R., and Wodtke, C.H.: Remotely Operated Plasma Torch - A Tool for Nuclear Reactor Dismantling, CONF-731105-2, 94th Winter Annual Meeting of ASME, Detroit, Michigan (November 11-15, 1973)

9. United Power Association: Removal of Inner Thermal Shield, Detailed Procedure 5.8, Elk River Reactor Dismantling Program

10. Wodtke, C.H., Plunkett, W.A. and Frizzel, D.R.: Development of Underwater Plasma Arc Cutting, Welding Journal (reprint) (January, 1976)

11. Baumeister, T. and Marks, L.S.: Standard Handbook for Mechanical Engineers, 7th Edition, pp. 13-51, McGraw-Hill.

12. Private Communcation with R. Gout of Thermo Lance Company, Albany, N.Y. (1978)

13. Oxylance Corporation: The WEKA Oxylance, Engineering Report, 721-1, Atlanta, Georgia.

14. Private Communication with B. Guerry of Jet Research Corporation, Arlington, Texas (1978)

15. Private Communications with D. Belforte of AVCE Everett Research Laboratory, Inc., Somerville, MA. (1978)

16. Nemec, J.F., Beckers, R.M., and Blumberg, R.: Radioactive Operations in the Dismantling of the Elk River Reactor, presented at the 19th Annual Meeting of the American Nuclear Society, Chicago, Illinois (June 10-14, 1973)

17. Field Installation Report: LACBWR Replacement Peripheral Shroud, NES 5101-504, Nuclear Energy Services, Inc. (May 10, 1979)

CHAPTER 7

DEMOLITION AND SURFACE DECONTAMINATION OF CONCRETE STRUCTURES

7.1 INTRODUCTION

Concrete is universally used in all nuclear facilities such that nearly every decommissioning program must address itself to either the demolition or surface decontamination of concrete structures. Certain structures become radioactive during the operating period of a nuclear facility. Direct activation from the neutron flux leakage of a reactor core will irradiate the concrete biological shield and/or certain reactor vessel cavity support structures. Activated concrete in the region immediately surrounding the core beltline, represents the most difficult concrete removal activity. This is due to the relatively high radiation dose and potential for release of radioactive particulates during demolition. Radioactive fluid leaks may contaminate floor or wall surfaces of a facility which, because of the porosity of concrete, prove to be resistent to nondestructive cleaning methods. Although non-radioactive concrete structures do not represent any unique demolition difficulty, the volume of such concrete coupled with significant reinforcement represents a difficult dismantling task.

Typically, the biological shield surrounding a reactor vessel, hot cell or other radioactivity source will consist of massive sections (2 to 10 ft thick) of standard (140-150 lb/ft^3) or high density concrete (magnetite or metal aggregate, 250-325 lb/ft^3). In some cases the biological shield may be heavily reinforced to meet seismic design criteria.

The reactor basemats or facility foundation footings may also consist of massive heavily reinforced concrete. Basemats may be as much as 25 feet thick, which would preclude some of the slower concrete removal methods.

Floors and walls within nuclear facilities may have become contaminated during facility operation. If the facility is to be converted to other uses, it may be advantageous to remove the contamination without demolishing the structures, particularly in the case of thick walls (greater than 2 ft).

This chapter provides guidance on the selection of concrete demolition and scarifying processes for various concrete types and thicknesses. The following sections present a tabulation of available processes and detailed information important to the selection of a method.

7.2 PROCESS SELECTION

There are many concrete removal techniques that have been adopted from the conventional demolition industry and successfully applied to nuclear facility decommissioning, with some modification. The selection of a specific process should be based on the experience learned from the conventional demolition industry, and applicable experience from actual decommissioning programs. Table 7.1 presents a tabulation of processes that may be used for the various concrete types and thicknesses. The user may make a preliminary selection of a process from this table taking note of the major limitations and recommendations. The detailed information on each process provided in the following section will aid in selection of the optimum process.

7.3 DETAILED DESCRIPTION

The concrete removal processes presented for detailed description in this chapter include:

1. Controlled Blasting
2. Wrecking Ball/Slab
3. Backhoe Mounted Rams (Hydraulic Ram & Air Ram)
4. Flame Cutting
5. Thermic Lance
6. Rock Splitter
7. Bristar Demolition Compound
8. Wall and Floor Sawing
9. Core Stitch Drilling
10. Explosive Cutting
11. Paving Breaker Power Hammer and Chisel
12. Drill and Spall
13. Scarifier
14. Water Cannon
15. Grinding

A summary of application characteristics of each process is shown in Table 7.2.

TABLE 7.1

CONCRETE REMOVAL METHODS - SUMMARY OF APPLICATIONS

Material:	**Depth or Thickness:**
Heavily Reinforced Concrete	Massive (Biological shields, basemats, foundations, walls > 2 feet thick)

Process	Feasibility	Limitations	Recommended
Controlled Blasting	Yes	Rebar must be cut after fracture	Yes
Wrecking Ball/Slab	Yes	Slow. Max drop height is 110 ft; max swing height is 50 ft	No
Backhoe Mounted Rams (hydraulic and air operated)	Yes	Slow	No
Flame Cutting	Yes	Generates copious quantities of toxic gas and smoke	Only where adequate ventilation is available
Thermic Lance	Yes	Generates moderate gas and smoke; rock splitter required	No
Rock Splitter	Yes	Slow. Rebar must be cut after fracture. Backhoe required to separate rubble. May be impractical on sections > 1 ft thick	Yes, but only where noise and vibration must must be controlled
Bristar Demolition Compound	Yes	Slow. Requires rebar cutter and backhoe to separate rubble	Yes, suitable where noise and vibration must be controlled
Wall and Floor Sawing	No	Not suited to this application	No
Core Stitch Drilling	Yes	Slow. Requires rock splitter and rebar cutter	Only where low noise/vibration allowed
Explosive Cutting	Yes	For beams only; not suited for long slabs	Where sawing is inaccessible
Paving Breaker	No	Very slow	No
Chipping Hammer and Chisel	No	Not suited for this application	No

TABLE 7.1
(Continued)

Material:	**Depth or Thickness:**
Heavy Concrete (Metal or Magnetite Aggregate Concrete, Non-reinforced)	Massive (Biological shields, ≤ 2 feet thick)

Process	Feasibility	Limitations	Recommended
Controlled Blasting	Yes	Metal aggregate slows drilling speed	Yes
Wrecking Ball/Slab	Yes	Slow. Max drop height is 110 ft; max swing height is 50 ft	No
Backhoe Mounted Rams (hydraulic and air operated)	Yes	Slow	No
Flame Cutting	Yes	Generates copious quantities of toxic gas and smoke	Only where adequate ventilation is available. Metal aggregate speeds cutting
Thermic Lance	Yes	Generates moderate gas and smoke. Rock splitter required	No
Rock Splitter	Yes	Slow. Backhoe required to separate rubble	Yes, suitable where where noise and vibration must be controlled
Bristar Demolition Compound	Yes	Slow. Backhoe required to separate rubble	Yes, suitable where noise and vibration must be controlled
Wall & Floor Sawing	No	Metal aggregate tears diamonds from saw	No
Core Stitch Drilling	No	Metal aggregate tears diamonds from core drill	No
Explosive Cutting	No	Not suited for this application	No
Paving Breaker	No	Very slow. Difficult to achieve penetration	No
Chipping Hammer and Chisel	No	Very slow. Difficult to achieve penetration	No

TABLE 7.1
(Continued)

Material:
Lightly Reinforced or
Non-reinforced Walls and Floors

Depth or Thickness:
≤ 2 feet

Process	Feasibility	Limitations	Recommended
Controlled Blasting	Yes	Costly. Creates flying missiles	No
Wrecking Ball/Slab	Yes	Slow. Max drop height is 110 ft; max swing height is 50 ft	Yes. Suitable for low structures and breaking rubble
Backhoe Mounted Rams (hydraulic and air operated)	Yes	Cannot reach tall structures. Max reach is 20 ft	Yes
Flame Cutting	Yes	Generates copious quantities of toxic gas and smoke	Only where adequate ventilation is available
Thermic Lance	Yes	Generates moderate gas and smoke. Rock splitter and rebar cutter required	No
Rock Splitter	Yes	Rebar cutter required after fracture	Yes
Bristar Demolition Compound	Yes	Limited to thickness > 1 ft	Yes, suitable where noise and vibration must be controlled
Wall & Floor Sawing	Yes	Slow cutting through rebar. Diamonds are stripped from blade	Yes
Core Stitch Drilling	Yes	Slow. Rock splitter and rebar cutter required	No
Explosive Cutting	Yes	Suited for cutting concrete beams	Yes
Paving Breaker	Yes	Slow	Yes
Chipping Hammer and Chisel	No	Very slow	No

TABLE 7.1
(Continued)

Material:
Contaminated Concrete Surfaces

Depth or Thickness:
All Thicknesses

Process	Feasibility	Limitations	Recommended
Controlled Blasting	Yes	Will be practical only in difficult geometries	No
Wrecking Ball/Slab	No	Not suitable for this application	No
Backhoe Mounted Rams (hydraulic and air operated)	Yes	Max reach approximately 20 ft	Yes
Flame Cutting	Yes	Generates radioactive gases and smoke	No
Thermic Lance	Yes	Generates radioactive gases and requires a rock splitter	No
Rock Splitter	Yes	Requires two free faces. May be impractical for sections > 1 ft thick	No
Bristar Demolition Compound	No	Unsuitable for thin sections	Yes
Wall & Floor Sawing	Yes	Unsuitable for thicknesses > 3 feet	Yes. For removal of an entire wall or floor section
Core Stitch Drilling	No	Unsuitable for thin sections	No
Explosive Cutting	No	Not suited for this application	No
Paving Breaker	Yes	Slow. Requires worker near surface - occupational exposure	Only for low contamination surfaces
Chipping Hammer and Chisel	Yes	Slow. Potentially high radiation exposure	Only for localized low contamination surface

TABLE 7.1
(Continued)

Material: Contaminated Concrete Surfaces

Depth or Thickness: All Thicknesses

Process	Feasibility	Limitations	Recommended
Drill and Spall	Yes	Leaves roughened surface	Yes
Scarifier (Scabbler)	Yes	Suitable for shallow surface contamination	Yes
Water Cannon	Yes	Suitable for shallow surface contamination	Yes
Grinding	Yes	Slow. Suitable for paint and thin surface removal	Yes

TABLE 7.2

SUMMARY OF APPLICATIONS AND RELATIVE COSTS

Process	Application	Feasibility	Relative Equipment Cost
Controlled Blasting	All Concrete ≥ 2 ft	Excellent	High
Wrecking Ball	All Concrete ≤ 3 ft	Excellent for nonradioactive concrete. Not recommended for radioactive concrete.	Low
Air and Hydraulic Rams	Concrete ≤ 2 ft	Good	Low
Flame Cutting	Concrete ≤ 5 ft	Fair	Low
Thermic Lance	Concrete ≤ 3 ft	Poor	Low
Rock Splitter	Concrete ≤ 12 ft	Good	Low
Bristar Demolition Compound	All Concrete ≥ 1 ft	Fair	Low
Wall & Floor Sawing	All Concrete ≤ 3ft	Good	Low
Core Stitch Drilling	Concrete ≥ 2 ft	Poor	High
Explosive Cutting	Concrete > 2 ft	Good	High
Paving Breaker	Concrete ≤ 1 ft	Poor	Low
Chipping Hammer & Chisel	Concrete ≤ 3 in.	Poor	Low
Drill & Spall	Concrete ≤ 2 in.	Excellent	Low
Scarifier	Concrete ≤ 1 in.	Excellent	Low
Water Cannon	Concrete ≤ 2 in.	Fair	High
Grinding	Concrete ≤ 0.25 in.	Poor	Low

7.3.1 Controlled Blasting

1. Description of Process

Controlled blasting is ideally suited for demolition of massive or heavily-reinforced, thick concrete sections. The process consists of drilling holes in the concrete, loading them with explosives and detonating using a delayed firing technique. The delayed firing increases fragmentation and controls the direction of material movement. Delayed firing also reduces the vibration impact on adjacent structures. Each borehole fractures radially during the detonation. The radial fractures in adjacent boreholes form a fracture plane. The detonation wave separates the fractured surfaces and moves the material towards the structure's free face. Figure 7.1 illustrates a typical "blasting round" for massive concrete demolition, and explains the terminology used in designing a blast; for example, the burden is the distance from the free face.

FIGURE 7.1
BLASTING ROUND

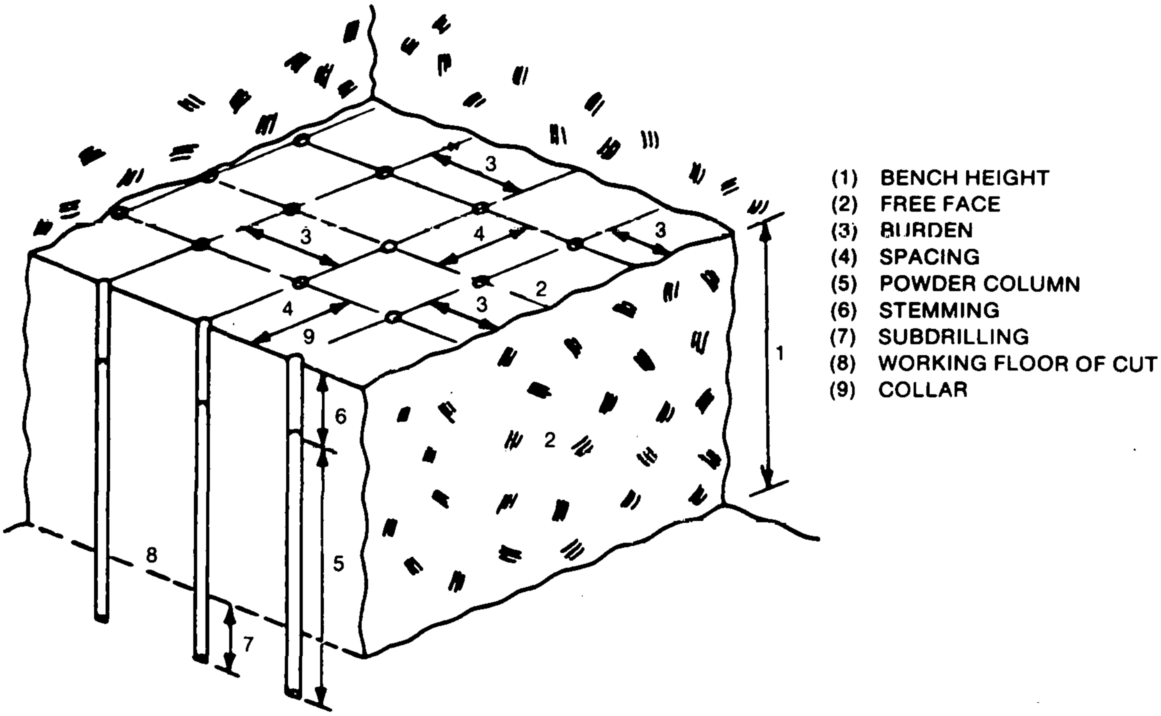


Table 7.3 summarizes the important operational characteristics of the controlled blasting technique.

TABLE 7.3

CONTROLLED BLASTING OPERATIONAL CHARACTERISTICS

Item	Comment
Material Applicability	Massive concrete; reinforced concrete walls and floors
Maximum Depth or Thickness	Limited by drilling depth only
Bulk Removal Rate	Rapid
Vibration/Shock/Noise	Moderate with controls
Dust	Moderate using fog sprays
Missile Generation	Must use blasting mat
Contamination Control	Controlled with blasting mat and fog spray
Consumables	Drill bits, explosives, detonators
Safety (Industrial)	Requires certified blasting technician
Relative Cost	May be high for small volumes of concrete

It should be noted that the guidance provided herein is intended to aid the user in understanding the controlled blasting technique. Such information is useful in planning a demolition program, estimating manpower, schedules and cost, and identifying the major safety aspects of concrete removal techniques.

CAUTION: Under no circumstances should the user embark on a blasting demolition program based only on the information provided herein. The services of a certified blasting technician should be retained for the duration of the blasting activities.

Blasthole design is based on a range of geometric relationships from which blast design can be developed using an incremental powder loading per borehole. Pages 19-28 of Reference 1 provide the following standard blasting ratios:

Burden	20 to 40 X diameter of explosive
Hole Depth	1.5 to 4.0 X burden
Subdrilling	0.3 (minimum) X burden
Stemming	0.5 to 1.0 X burden
Spacing	1 to 2 X burden

The burden standard for each job is modified to 20 to 25 for light-density explosives and to 40 for slurry explosives. The blasting expert may use these parameters to develop the "powder factor," or pounds of explosive (of a specific type) per bulk cubic yard removed. The explosive diameter may be selected on the basis of available explosive (cartridge type), or on the basis of available drilling equipment (diameter and length) using bulk or slurry explosives.

Drilling methods for blast hole preparation include percussion air-operated drills, electric, pneumatic or diesel driven rotary drills or diamond-core abrasive drills. Percussion drills are the most versatile and can economically drill 1-1/4 in. to 2 in. diameter holes over a wide range of hardness or abrasiveness. Typical percussion drilling equipment is capable of drilling a 6 foot deep hole in 3-1/2 minutes. Rotary drills are much larger in diameter (6 in. to 9 in.) and are best suited for light concrete without reinforcing rods. Diamond-core abrasive bits are more expensive than percussion drills but bit life is longer. When cutting through reinforcing rod, abrasive drilling is slower and diamond loss is common.

Various types of explosives are available for use in demolition applications. The selection of the best type of explosive requires an evaluation of the properties of the explosive and of the concrete itself. A blasting expert is qualified to select the best explosive for the purpose. The major types of explosives are listed in Table 7.4.[1,2]

TABLE 7.4

TYPES OF EXPLOSIVES FOR USE IN CONCRETE REMOVAL

PETN (Pentaerytritol Tetranitrate)

This explosive is used in the form of detonating cord. It is primarily used during the blasting of boreholes up to 5 m (16 ft) in depth. In addition, it has proven to be effective for surface spalling that requires the removal of very small burdens of about 200 mm (8 in) from exposed surfaces.

85% High Velocity Gelatin Dynamite

This explosive is primarily used in shallow holes ranging in depth from 0.45 m (18 in.) to 1.5 m (5 ft) and as a partial loading in some holes when a concentration of energy is needed in a particular area. Breakage is excellent, however, the explosive does produce a crushed zone around the borehole, thus generating a larger amount of dust than the PETN.

Cast TNT (High Detonation Pressure Primers)

This explosive is used where a high degree of fragmentation is desired with less of a heaving effect than with the conventional dynamite.

Binary Energy System (Liquid Explosives)

This explosive is mixed onsite and when not mixed it is not classed as an explosive in most states. It is used in place of Cast TNT during the spalling of surface contamination and to make shaped charges that can be used to punch holes in high density concrete.

Water Gel Explosives

A water gel explosive containing a large amount of aluminum is used as a partial replacement for the 85% dynamite. It has exhibited good shattering characteristics and produced larger rubble than any of the other explosives. Its primary use is in areas of little or no reinforcing rods where larger size rubble is desired.

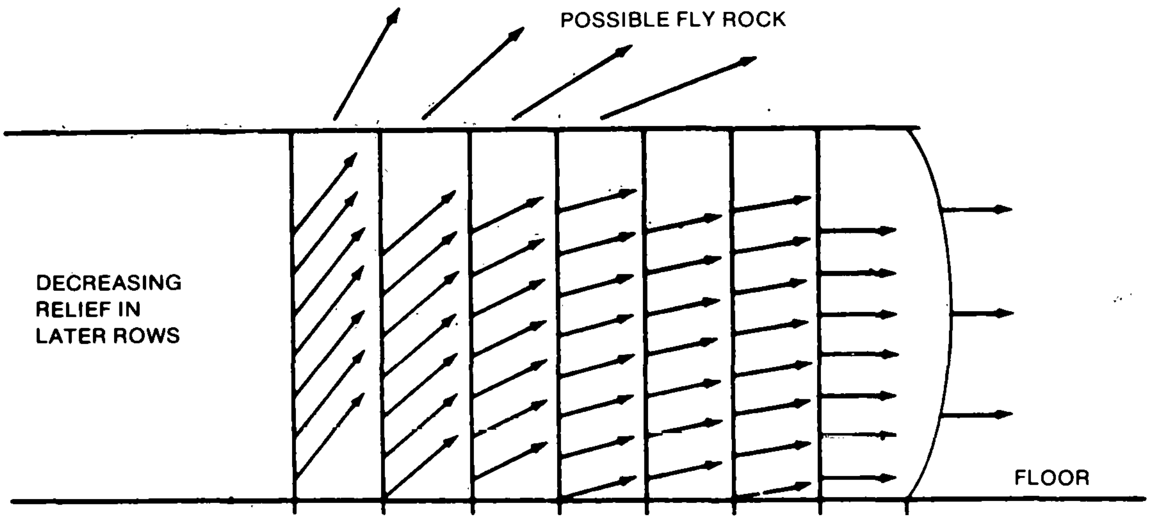
Others

High strength ammonia dynamite is less powerful and has a lower velocity than the foregoing explosives.

When blasting massive concrete sections with multiple charges, delayed detonation is used to direct the muckpile (rubble) and improve fragmentation. The first row of charges directs the burden perpendicular to the borehole plane. Subsequent burden plane charges would direct movement towards the vertical as shown in Figure 7.2 unless delayed sufficiently to allow forward movement of preceding burdens. A delay period of approximately one millisecond-per-foot of burden provides sufficient time for free face movement, and allows subsequent burdens to fragment perpendicular to the boreholes.

FIGURE 7.2

SIMULTANEOUS NON-DELAYED DETONATION



Vibration levels during blasts may be estimated by the formula:

$$V = 160\,(R/W^{1/2})^{-1.6}$$

Where:

V = Peak particle velocity of ground motion in ips
R = Distance between explosion and recording sites in feet
W = Maximum pounds-per-delay-period of eight milliseconds or more

Allowable values for the peak particle velocity of ground motion for normal confinement and heavy confinement are shown in Figure 7.3.[2] Table 7.5 provides approximate qualitative damage levels from blasts as a function of peak particle velocity ground motion near structure.[2] Blasting noise levels and effects on structures may be estimated from the methods given in Reference 2 using Table 7.6 and Figure 7.4 herein.

2. Applications

Controlled blasting is the concrete demolition method recommended for all concrete greater than two feet in thickness provided noise and shock in adjacent occupied areas are not limiting. The process is well suited to heavily-reinforced concrete demolition because with proper selection of the blast parameters a high degree of fragmentation may be achieved. The exposed reinforcing bar may then be cut with an oxyacetylene torch or bolt cutter.

The Elk River Reactor dismantling program used controlled blasting to demolish the eight-foot thick steel-reinforced radioactive biological shield. A blasting mat (composed of automobile tire sidewalls tied together) was placed over the blast area. Continuous fog sprays of water were used before, during and after the blast to hold down dust. Alternatively, a spray mixture of water and 5%-by-

FIGURE 7.3

PEAK PARTICLE VELOCITY AS A FUNCTION OF SCALED DISTANCE

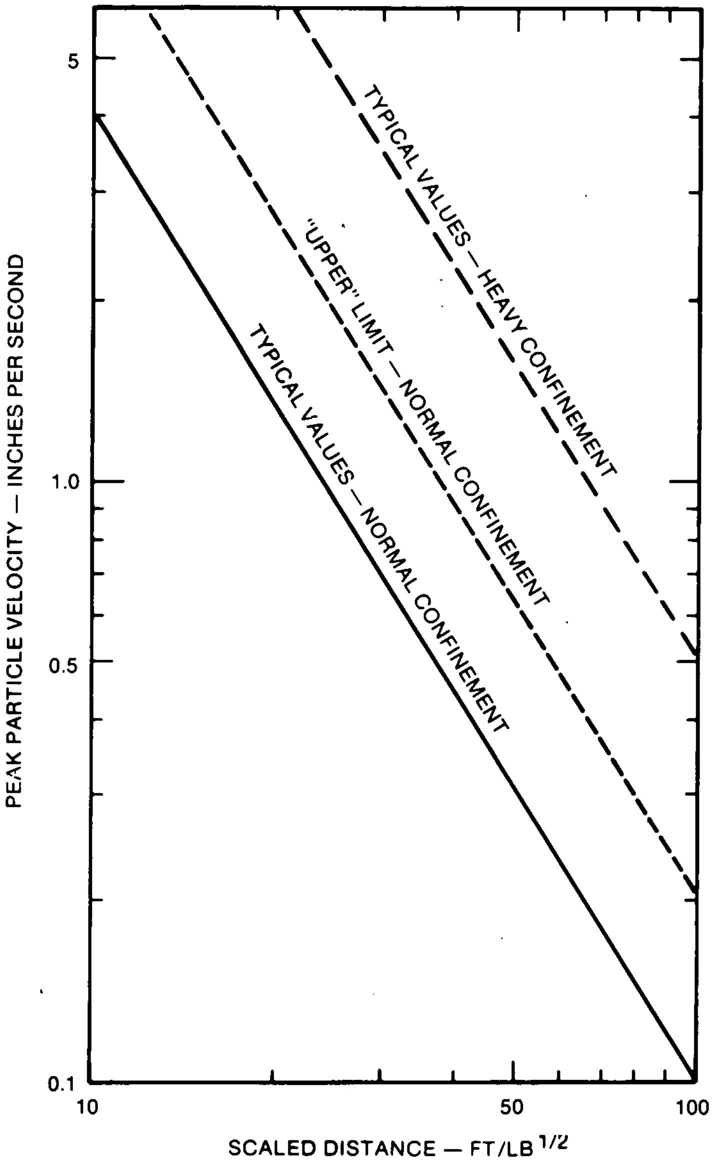


TABLE 7.5

APPROXIMATE DAMAGE LEVELS FROM GROUND VIBRATION NEAR STRUCTURES

Peak Particle Velocity inches/sec	Nature of Damage
12	Fall of rocks in unlined tunnels
7.6	50% probability of major plaster damage
5.4	50% probability of minor plaster damage
2.8 - 3.3	Threshold of damage from close-in blasting
2.0	Safe blasting criterion for residential structures recommended by U.S. Bureau of Mines

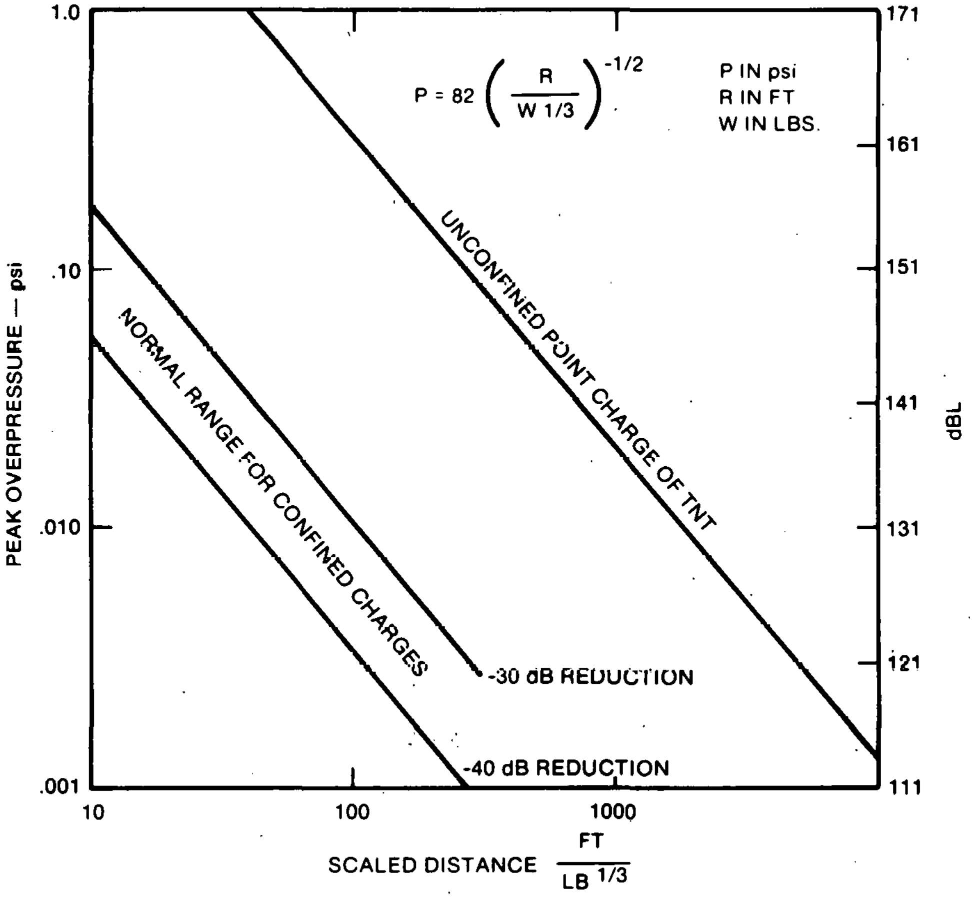
TABLE 7.6

AIR BLAST EFFECT AT MEASUREMENT LOCATION

Overpressure		Nature of Effect
dBL	psi	
181	3.0	Conventional structures severely damaged
171	1.0	Most windows break
161	0.3	
151	0.1	Some windows break
141	0.03	Some large plate glass windows may break
131	0.01	USBM interim limit of allowable air blast = 136 dBL

FIGURE 7.4

PEAK OVERPRESSURE AS A FUNCTION OF SCALED DISTANCE



weight sodium silicate (water glass) may be used for dust control as was used in the demolition of the Pratt-Whitney Hot Cell, Lockheed-Georgia Radiation Effects Laboratory and NL Industries Laboratory.[3] Typical concrete removal rates are shown in Table 7.7

TABLE 7.7

CONCRETE REMOVAL RATES USING CONTROLLED BLASTING

Concrete Type	Removal Rate yd^3/day	Reference
1. Massive Reinforced Standard Concrete (Non-Radioactive)	100-400	4
2. Massive Non-reinforced Standard Concrete (Non-radioactive)	250	5
3. Massive Reinforced Standard Concrete (Radioactive)	4-6 * 100 **	6 4
4. Lightly Reinforced Standard Concrete (Non-radioactive)	200	5
5. Non-reinforced High Density Concrete (Radioactive)	6-8*	6
6. Lightly Reinforced Standard Concrete (Radioactive)	6-8*	6

* Actual removal rates including inefficiency due to personnel and area contamination control and radiation work area control.

** Higher removal rate possible if adequate space is available to use large capacity loading and hauling equipment.

The wide range of concrete removal rates shown in Table 7.7 is strongly dependent on the work area conditions. Removal of radioactive concrete requires allowance for additional time to suit up with anti-contamination coveralls, boots, gloves, headgear and filtered facemasks (with appropriate time to de-suit for breaks and meals). The exposed face of concrete must be surveyed for radiation dose levels and sampled for radioactive isotopic identification. In many cases the radioactive concrete is contained in difficult geometric configurations. If access for blast hole drilling equipment is limited, high-speed track mounted drills may not be used necessitating the use of slower hand-held drills. Fog sprays must be used to hold down radioactive dust levels. The broken muckpile must be loaded into containers for burial in controlled burial facilities. These special considerations can severely limit the rate of radioactive concrete removal.

According to demolition experts, given adequate access for heavy-duty, state-of-the-art drilling and hauling equipment, much higher removal rates are possible than were achieved at Elk River. Mr. Mark Loizeaux of Controlled Demolition, Inc.[4] maintains that heavily-reinforced radioactive concrete can be removed at a rate of up to 100 yds^3/day with the use of proper equipment and removal techniques. While non-radioactive heavily reinforced concrete can be removed at rates of between 100 and 400 yds^3/day. Mr. Loizeaux reports having removed lightly reinforced non-radioactive concrete at rates of up to 1000 yds^3/day. These impressive rates include the drilling, loading, shooting, rebar cutting and loading the muckpile into hauling equipment.

3. Cost Information

Table 7.8 presents the approximate unit costs in 1980 dollars for controlled blasting. The unit cost includes crew cost, materials (explosives and dust control measures) and subcontractor overhead and profit. Shipping and disposal are not included. The range of the costs shown in Table 7.8 reflect the difficulties associated with each type of concrete and the inefficiency of crew-labor working in a radioactive environment. A typical blasting crew consists of the blasting expert, six laborers, one iron worker and one equipment operator.

TABLE 7.8

CONCRETE REMOVAL COSTS USING CONTROLLED BLASTING

	Concrete Type	Removal Cost, \$/yd^3 *	Reference
1.	Massive Non-reinforced Standard Concrete (Non-radioactive)	15	4
2.	Massive Reinforced Standard Concrete (Non-radioactive)	110	4
3.	Massive Reinforced Standard Concrete (Radioactive)	430	6
4.	Lightly Reinforced Standard Concrete (Non-radioactive)	40	4
5.	Non-reinforced High Density Concrete (Radioactive)	40	4
6.	Lightly Reinforced Standard Concrete (Radioactive)	215	6

* Escalated to 1980 dollars at the rate of 7% per year.

7.3.2 Wrecking Ball or Wrecking Slab

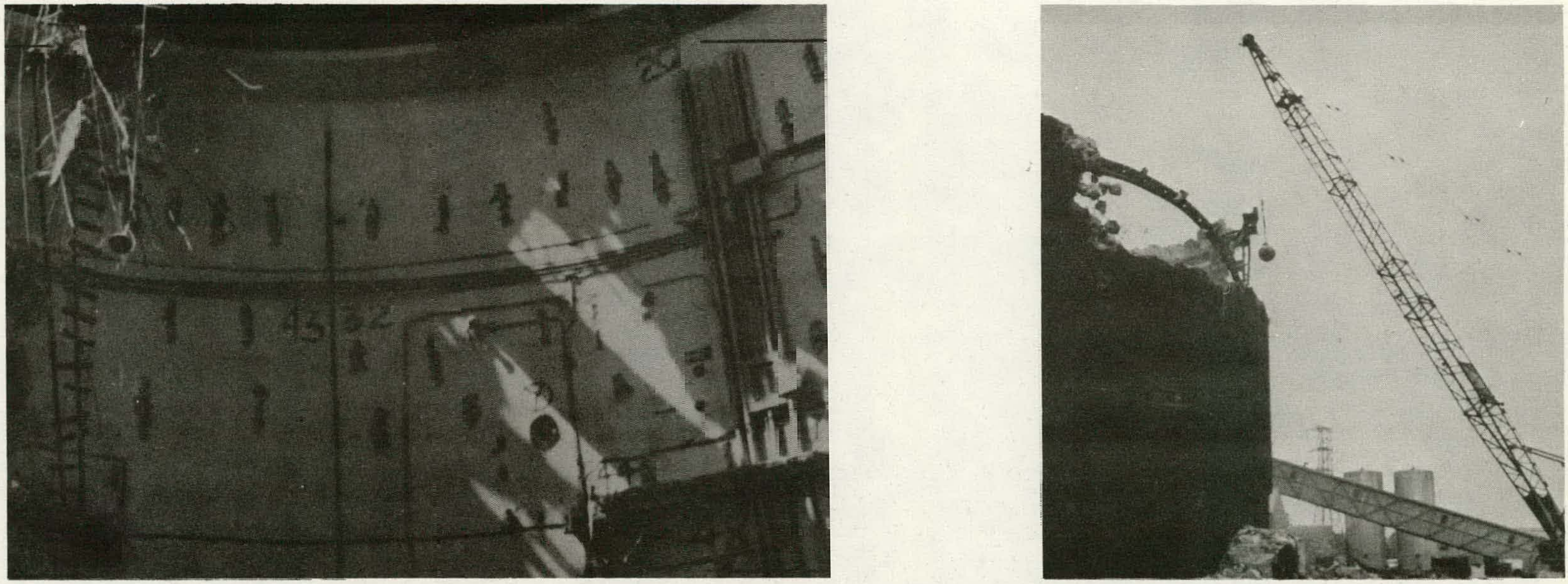
1. Description of Process

The wrecking ball is typically used for demolition on non-reinforced or lightly reinforced concrete structures less than 3 feet in thickness. The equipment consists of a 2-to-5 ton ball or flat slab suspended from a crane boom. The ball may be used in either of two techniques to demolish structures. The preferred method is to raise the ball with a crane 10-to-20 feet above the structure and release the cable brake allowing the ball to drop onto the target surface. The maximum height of structure is limited to about 100 feet. A 5-ton ball would require a 200 ton crane for the maximum height.[7] This method develops good fragmentation of the structure with maximum control of the ball after impact. The second method is to swing the ball into the structure using a suck line for recovery after impact. The maximum height of structure is limited to about 50 feet because of the crane instability during the swing and after impact. The latter method is not recommended because the target area is more difficult to hit and the ball may ricochet off the target and damage adjacent structures while putting side loads on the crane boom. The flat slab may only be used in the vertical drop mode, but offers the advantage of being able to shear through steel reinforcing rods as well as concrete.

2. Applications

The wrecking ball or slab is recommended for non-radioactive concrete structures less than 3 feet in thickness. It would be virtually impossible to control the release of radioactive dust during demolition due to the access needed for the crane to drop or swing the ball. The containment (or confinement) barrier would have to be breached to allow for access and there would be no method to filter the dust-laden air after impact. For non-radioactive structures, the wrecking ball is an effective method and provides good fragmentation to expose reinforcing rods.

A wrecking ball was used in dismantling the Elk River Reactor containment building cylinder and dome after the outer insulation and steel shell were removed, and after all radioactive material had been removed from within the structure. Photographs of the Elk River demolition by wrecking ball are shown in Figure 7.5. The containment building integrity was maintained until all radioactive material had been removed from within the structure and shipped off-site. A statistical sampling program was used to survey the



WALL SAMPLING FOR D.R.O.R.

BALLING OPERATION - POLAR CRANE RAIL

FINAL DEMOLITION

FIGURE 7.5

WRECKING BALL DEMOLITION OF ELK RIVER REACTOR remaining internal structures for detectable reactor-originated radioactivity (DROR), as shown in the photos by the pock-marked interior of the containment walls, before breaching containment.

Typical concrete removal rates with a wrecking ball are shown in Table 7.9, exclusive of loading or disposal.

TABLE 7.9

CONCRETE REMOVAL RATES USING A WRECKING BALL

Concrete Type	Removal Rate, yd^3/day	Reference
Lightly Reinforced Standard Concrete	40	7
Non-reinforced Standard Concrete	50	7
Concrete Block Structures	60	7
Heavily Reinforced Standard Concrete	Not Recommended	7

3. Cost Information

Table 7.10 presents the approximate unit cost in 1980 dollars for wrecking ball demolition. The unit cost includes crew cost, equipment rental and subcontractor overhead and profit. The range in costs reflect the accessibility to move large equipment to the muckpile for loading and hauling. Shipping and disposal are not included in these costs.

A typical wrecking ball crew consists of the crane operator, one crane oiler, two laborers and a foreman.

7.3.3 Backhoe Mounted Rams

1. Description of Process

Backhoe mounted rams are used for concrete structures less than 2 feet thick with light reinforcement. The method is ideally suited for

TABLE 7.10

CONCRETE REMOVAL COSTS USING A WRECKING BALL

Concrete Type	Removal Cost, $\$/yd^3$	Reference
Lightly Reinforced Standard Concrete	20 40	5 8
Non-reinforced Standard Concrete	13 27	5 8
Concrete Block Structures	10	5
Heavily Reinforced Standard Concrete	110	8

low noise, low vibration demolition and for interior demolition in confined areas. The equipment consists of an air- or hydraulic-operated impact ram with a moil or chisel point mounted on a backhoe arm. The ram starts impacting as soon as there is resistance to the point and stops when breakthrough occurs or when the ram head is lifted. The ram delivers about 600 blows per minute at up to 2000 ft-lb of energy per blow, depending on the size of the ram head. A backhoe mounted ram is shown in Figure 7.6. Many sizes of air and hydraulic rams are available from several suppliers. Table 7.11 summarizes the typical sizes and impact capacity of ram heads. With the ram head mounted on a backhoe, the operator has approximately a 20 to 25 foot reach, and the ability to position the ram in limited access structures.

2. Applications

The ram is recommended for applications with limited access for heavy equipment such as a wrecking ball, and where blasting is not permitted. The air rams need to be modified to direct air exhaust away from the work area to prevent the spread of dust (nuisance and radioactive dust). The hydraulic ram recycles the hydraulic fluid, so no modification is necessary.

FIGURE 7.6

BACKHOE MOUNTED RAM

TABLE 7.11

RAM IMPACT TOOL - SIZE AND CAPACITY

Unit Type	Air Ram	Air Ram	Air Ram	Hydraulic Ram
Unit Weight, lbs	485	830	1,640	1,280
Moil Point diam, in	2-1/2	3-1/2	5-1/4	4
Blows/Minute	600	600	600	500-600
Energy/Blow, ft lbs	500	1,000	2,000	500
Air Compressor Size, cfm	150	250	600	—
Hydraulic System	—	—	—	1,800 psi @ 18 gpm
Removal Rate yd^3/day (Non-reinforced Concrete)	Not available	20	Not Available	Not available

Dust and contamination control is maintained with water fog sprays before and during breaking activities.

The air ram was successfully used for light concrete demolition at the Sodium Reactor Experiment (SRE) in Santa Suzanna, California.[9] However, at Elk River a hydraulic ram proved to be too slow in demonstration tests for use on the massive, heavily reinforced biological shield. The ram was replaced with the more favorable controlled explosive demolition.

3. Cost Information

The approximate unit cost in 1980 dollars for backhoe-mounted ram breaking of concrete is \$43/yd^3.[10] The unit cost includes crew cost, equipment rental and subcontractor overhead and profit. Shipping and disposal are not included in the costs.

A typical crew consists of the ramhoe operator, one laborer and a foreman.

7.3.4 Flame Cutting

1. Description of Process

Flame cutting of concrete consists of a thermite reaction process whereby a powdered mixture of iron and aluminum oxidizes in a pure oxygen jet. The temperatures in the jet are approximately 16,000° F, which causes rapid decomposition of the concrete in contact with the jet. The mass flow rate through the flame cutting nozzle clears away the decomposed concrete, leaving a clean kerf. Reinforcing rods in the concrete add iron to the reaction to sustain the flame and assist the reaction.

The nozzle is mounted on a metal frame that straddles the area to be cut. The nozzle, with associated hoses, is tracked on the metal frame at a steady rate. The rate is dependent upon the concrete depth. A starting hole is cut through the concrete to prevent blowback of material and consequent torch damage. Once started, the torch is advanced along the workface by a variable speed electric motor controlled by the operator.

Heat and smoke may be removed with a 5 to 7 horsepower squirrel cage blower, and directed through a flexible duct that houses a water fogger to hold down smoke particulate. The high gas temperatures preclude the use of HEPA filters for contamination control, making the flame cutting technique unsuitable for use on radioactive concrete without pre-cooling the effluent gas.

2. Applications

Flame cutting of concrete is used when vibration to the surrounding area is intolerable, and when the thickness of the concrete to be cut exceeds the capabilities of mechanical cutters such as diamond saws. Flame cutters are capable of cutting through a maximum depth of 60 inches with or without reinforcing rod.

The operating characteristics of the flame cutting technique are shown in Table 7.12.[11] Figure 7.7 shows a photo of concrete cutting using the torch technique.

TABLE 7.12
FLAME CUTTING OPERATING CHARACTERISTICS

Cutting Speed:	1 hour/ft^2 of cut
Kerf Size:	4 in. through a 60 in. thick section
Fuel Type:	Propane and Oxygen (for starting) Powder iron/powder aluminum mixture with oxygen (operating)
Fuel Consumption per sq ft of cut:	Oxygen - 800 cu ft Iron Powder - 14 lbs Aluminum Powder - 6 lbs

3. Cost Information

The approximate unit cost in 1980 dollars for flame cutting is $190 per square foot of cut area. The unit cost includes crew cost, equipment and subcontractor overhead and profit. Shipping and disposal are not included.

A typical flame cutting crew consists of the torch operator and one laborer full time during cutting.

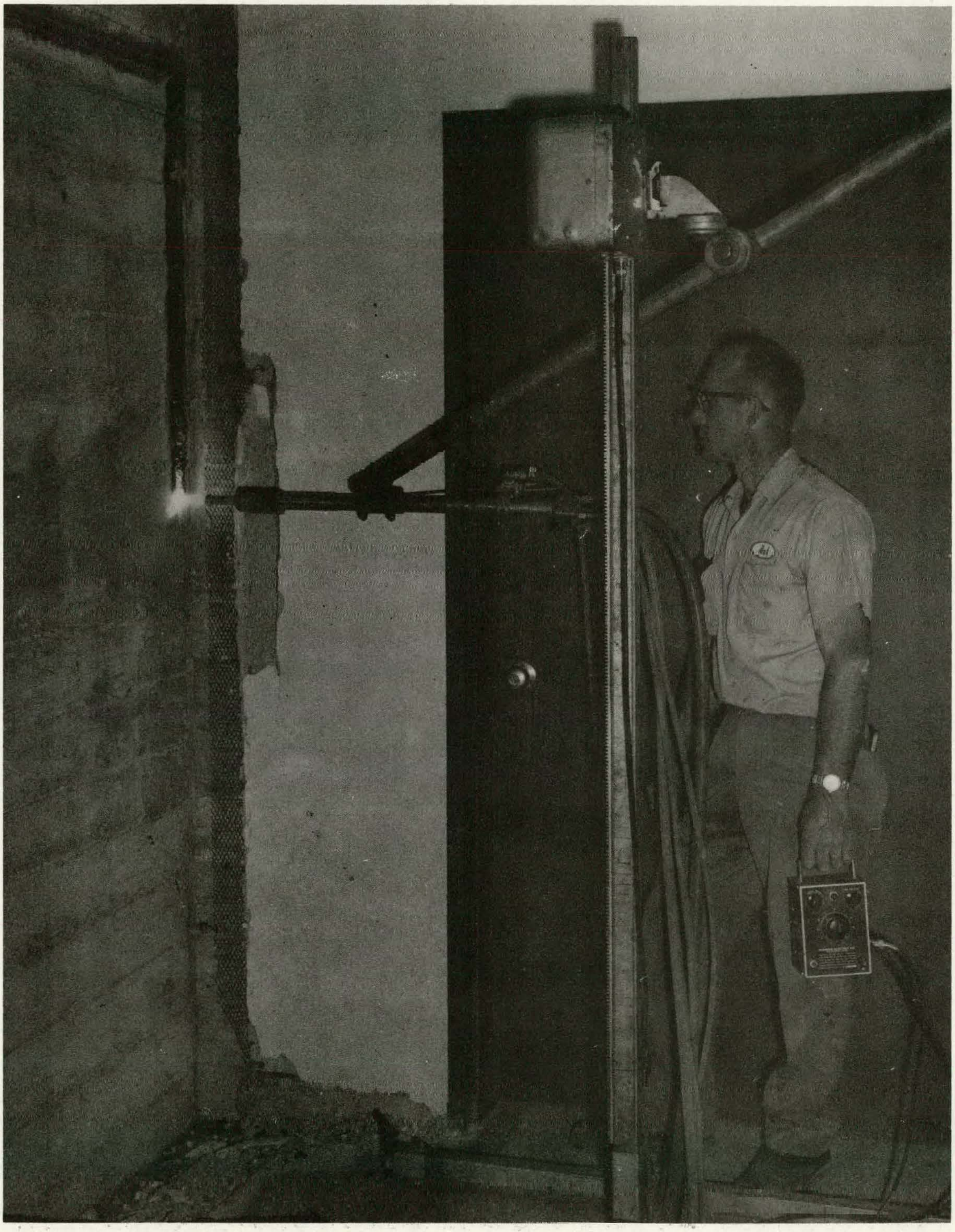
7.3.5 Thermic Lance

1. Description of Process

The thermic lance consists of an iron pipe packed with a combination of steel, aluminum, and magnesium wires through which a flow of

FIGURE 7.7

CONCRETE TORCH CUTTING



oxygen gas is maintained. The thermic lance cuts utilizing a thermite reaction at the tip of the iron pipe, in which the constituents are completely consumed. Temperatures at the tip range from 4000 to 10,000° F, depending upon ambient conditions. The lance is ignited using an oxyacetylene torch, thermal igniter or electric arc. Typical lances are 10-1/2 feet in length and 1/4 inch to 3/8 inch in diameter.

A thermic lance set-up will consist of the lance, an oxygen supply (generally two or more cylinders connected in tandem), associated regulator equipment to maintain oxygen pressure at 70-125 psi, hose of no less than 3/8 inch diameter, and protective clothing and faceshield for the operator.

Complete consumption of the lance is possible by stopping the oxygen flow when the lance is burned down to 2 to 5 feet. The iron pipe is removed from its holder, a new one is inserted into the handle, and the old pipe is inserted into the new pipe using a coupling provided with every lance. In this fashion, the lance (pipe) is completely consumed, with no lost or wasted pipe. Should standing near the material to be cut prove hazardous or impossible, two or three lances can be joined together for extra distance in a similar manner as described above.

NOTE: Coupling together of more than three lances is not recommended due to the flexibility of the pipe.

A thermic lance generates a large quantity of smoke and hot gases, the actual amount depending upon the material being cut. For this reason, a control envelope is necessary for radioactive concrete cutting to contain the vaporized material in order to prevent the contamination of the surrounding area. A photo of a thermic lance is shown in Figure 6.9 of Chapter 6.

2. Applications

The thermic lance will cut any material that is likely to be encountered in a nuclear facility. The 10-1/2 foot thermic lance will burn for at least 6 minutes. In this time the lance can burn a hole 1-1/2 to 2 inches in diameter through reinforced concrete to a depth of 1-1/2 to 3-1/2 feet. The reinforcing rods in the concrete speed the burning by adding more metal to the thermite process. Material further than 1 inch from the hole is not affected. However, the lance generates a significantly greater amount of smoke than any other method and is not recommended for remote operations.

The thermic lance can be used to cut holes, slits or openings in a wide variety of materials. To cut a slit in a material, a series of holes are burned through the material, and the material remaining between the holes is then removed, either with the lance or by mechanical methods such as air hammers or sledges. Openings are made by framing the area to be removed with slits, then removing the material inside the area.

3. Cost Information

Table 7.13 summarizes the approximate costs of lance cutting materials. Cost per unit of output are dependent upon the geometry of the cut.

TABLE 7.13

THERMIC LANCE - COST OF MATERIALS

	Cost, $
Lance Holder	50.00
Lance (10-1/2 ft)	7.00
Oxygen, 100 ft^3 @ STP	6.00

7.3.6 Rock Splitter

1. Description of Process

The rock splitter is a method for fracturing concrete by hydraulically expanding a wedge into a pre-drilled hole until tensile stresses are large enough to cause fracture. The tool consists of a hydraulic cylinder that drives a wedge-shaped plug between two expandable guides (called feathers) inserted in the pre-drilled hole. Figure 7.8 shows a schematic of the splitter operating principle.

The unit is powered by a hydraulic supply system, and operates at 7100 psi pressure. When the plug is extended and fracture occurs, an automatic pressure relief valve lowers the pressure to 900 psi. With the unit in neutral position the pressure drops to 50 psi. The hydraulic unit may be powered by either air pressure, gasoline engine or electric motor sources.

Units are available to develop splitting forces approaching 350 tons. The maximum lateral expansion of the feathers is approximately 0.75 inches. Concrete may be separated at the fracture line using a backhoe mounted air ram or similar equipment. The reinforcing rod in reinforced concrete must be cut before separation is possible. For heavily reinforced concrete, additional holes and fractures will be necessary to expose the reinforcing rod. Figure 7.9 shows a photograph of multiple splitter units used on an 8-foot thick reinforced concrete wall.

2. Applications

The splitter is ideally suited for fracturing concrete in limited access areas where large air rams cannot operate. The process is silent (except for hole drilling) and is used extensively for demolition near hospitals and other densely populated areas. Hole sizes range from 1-3/16 to 1-3/4 inch, and depth of 12 to 26 inches, depending on the

FIGURE 7.8

SCHEMATIC OF ROCK SPLITTER

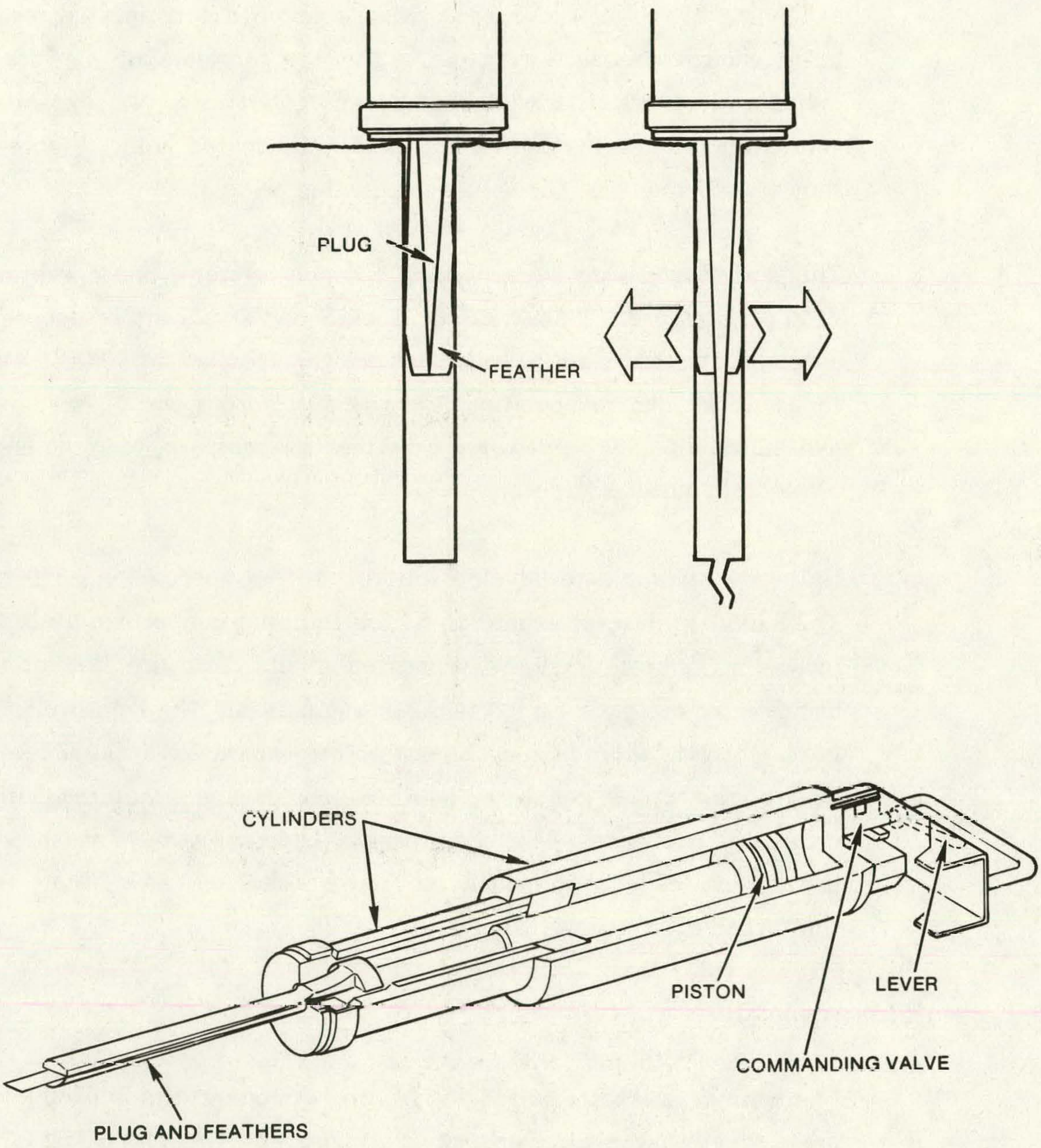


FIGURE 7.9

MULTIPLE SPLITTER UNITS ON AN 8-FOOT THICK WALL size of the unit selected. For massive concrete sections, holes may be drilled from 1 to 3 feet apart to establish a fracture line. Drilling and splitting time requires approximately 5 to 10 minutes per hole. Removal time is dependent on the amount of reinforcing rod, accessibility for heavy removal equipment, and the amount of radioactivity control measures necessary. For reinforced non-radioactive concrete, removal rates of 250 yd^3/day have been demonstrated.

Reinforced concrete sections up to 8-feet thick may be cut with a single large unit. Reinforced concrete sections of 10-foot thickness will require two or more large units operated simultaneously.

3. Cost Information

The approximate cost of the rock splitter and power unit range from $6500 to $8000 from the smallest to largest cylinder available. Cost per unit of output are dependent on the geometry and working conditions of the application.

7.3.7 Bristar * Demolition Compound

1. Description of Process

Bristar concrete demolition compound is a chemically expanding compound that is poured into pre-drilled holes and causes tensile fractures in the concrete upon hardening. Bristar is a proprietary compound of limestone, siliceous material, gypsum and slag. The powdered compound is mixed with water and kneaded to a fluid paste. The paste is filled into holes drilled in a fracture line of predetermined burden, spacing and depth. No hole caps are required if the hole depth is at least 6 times the hole diameter. Within 10-20 hours, Bristar pressure will develop to over 4300 psi (3000 t/m^3).

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* Registered trade name of Onoda Cement Co., Ltd., Tokyo, Japan.[12]

Concrete tensile strength ranges from 200 psi to approximately 425 psi, such that low grade concretes are likely to fracture easily. Cracks will form and propagate along the fracture line. The crack width will range between 1/4 inch after 10 hours to almost 2 inches after 15 hours. The fractured burden may then be removed with a paving breaker, backhoe or bucket loader. If reinforcing rod is encountered, it must be cut separately. The compound is not classified as a hazardous substance and can be readily stored and handled. There is no noise or vibration (except for drilling holes), or flyrock, dust or gas release. Contamination control is only required during drilling and removal.

The recommended hole sizes and their corresponding burden, spacing and depth for reinforced massive concrete structures is shown in Table 7.14. A test program would be required to select the optimum arrangement of parameters for each concrete type. Figure 7.10 shows the crack width versus time for fracturing limestone.

TABLE 7.14

BRISTAR DEMOLITION COMPOUND FRACTURING PARAMETERS

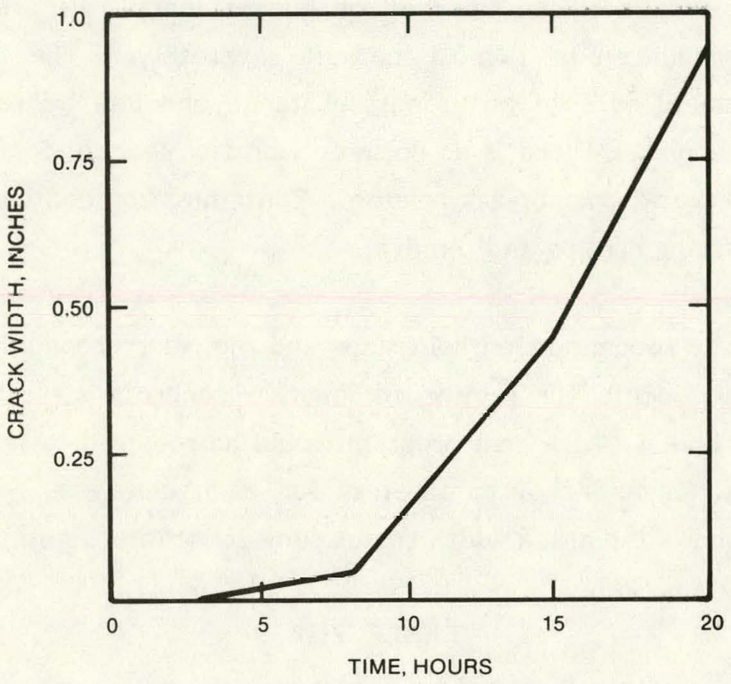
Hole Size, in	1-1/4	2
Burden	8-16	8-16
Spacing	8-16	8-16
Minimum Depth	7-1/2	12

2. Applications

Bristar is suited for use on massive non-reinforced concrete structures where noise, vibration, flyrock, dust or gas must be avoided. It is not recommended for slabs of concrete less than 12 inches in thickness. The compound can be used with reinforced concrete provided the holes are located along the plane of reinforcing rod so the fractured surface will expose the rods.

FIGURE 7.10

BRISTAR DEMOLITION CRACK - WIDTH VS. TIME



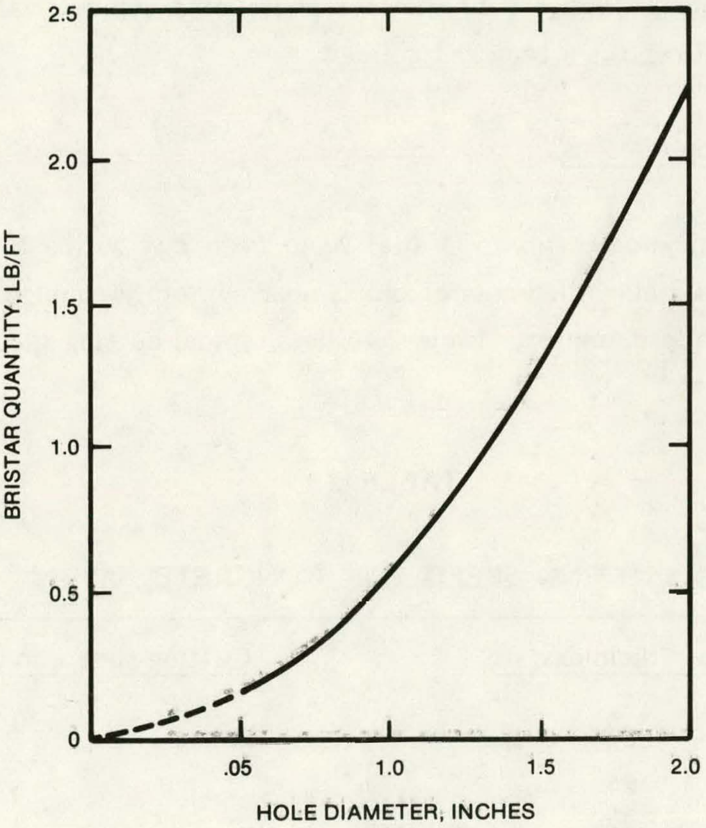
The rate of removal of massive non-reinforced concrete is dependent on the crack formation time (10-20 hours) and the quantity of concrete to be removed. For small jobs the removal rate will be slow because of the time to fracture. For large jobs, drilling may be continuous with mucking out following hole loading by about 20 hours. In this manner the removal rate may approach that of controlled blasting for the same material.

3. Cost Information

The quantity of Bristar required per foot of hole depth for various hole diameters is shown in Figure 7.11.[12] The approximate cost for Bristar is about $80.00 for a 44 pound container. The manufacturer claims the cost of removal is higher than for controlled blasting but lower than other concrete splitters. Quantity cost information may be obtained directly from the manufacturer.[12]

FIGURE 7.11

BRISTAR QUANTITY REQUIRED PER HOLE DIAMETER



7.3.8 Wall and Floor Sawing

1. Description of Process

Wall and floor sawing is generally used when disturbance of the surrounding material must be kept to a minimum. A diamond or carbide wheel is used to abrasively cut a kerf through the concrete. The blades can cut through reinforcing rods although the rods tend to break off the blade diamonds. The blade is rotated by an air or hydraulic motor. For most applications the saw will be mounted on a guide that also supports the saw's weight. The operator manually advances the blade into the work. The dust produced by the abrasive cutting is controlled using a water spray. The abrasive blade produces no vibration, shock, smoke, sparks, or slag and is relatively quiet. Figure 7.12 shows a photo of a typical wall saw and Figure 7.13 shows a typical floor saw.

2. Applications

Thicknesses up to 3 feet have been cut with concrete saws. The maximum thickness of cut is approximately equal to one-third of the blade diameter. Table 7.15 lists typical cutting speeds for a concrete saw.[11]

TABLE 7.15

CUTTING SPEED FOR CONCRETE SAW

Concrete Thickness, in	Cutting speed, in per minute
5	30
10	15
24	6
36	4

The saw cuts approximately 150 in^2 per minute of cut surface, regardless of thickness. Cutting can be done either manually or remotely.

FIGURE 7.12

WALL SAW

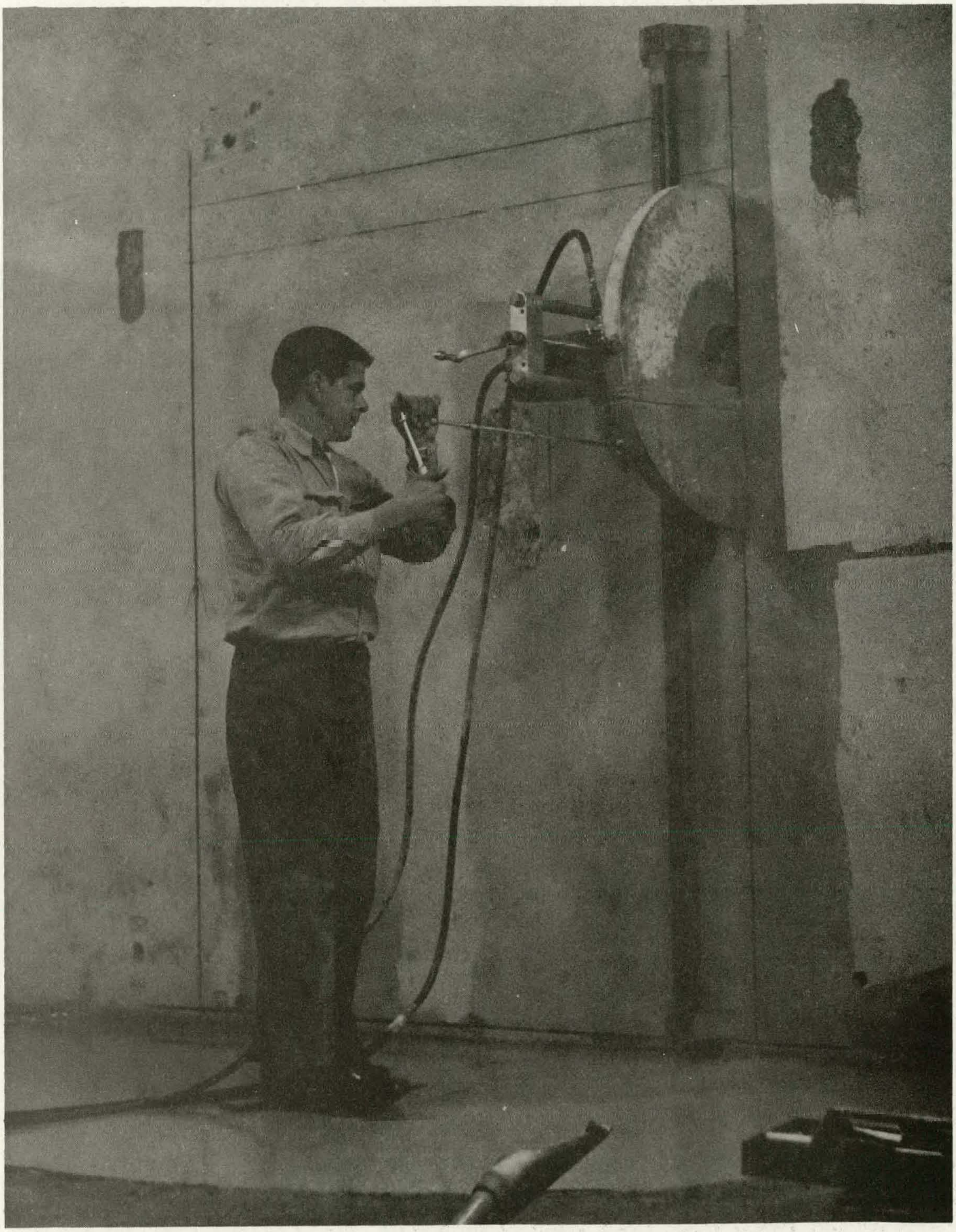
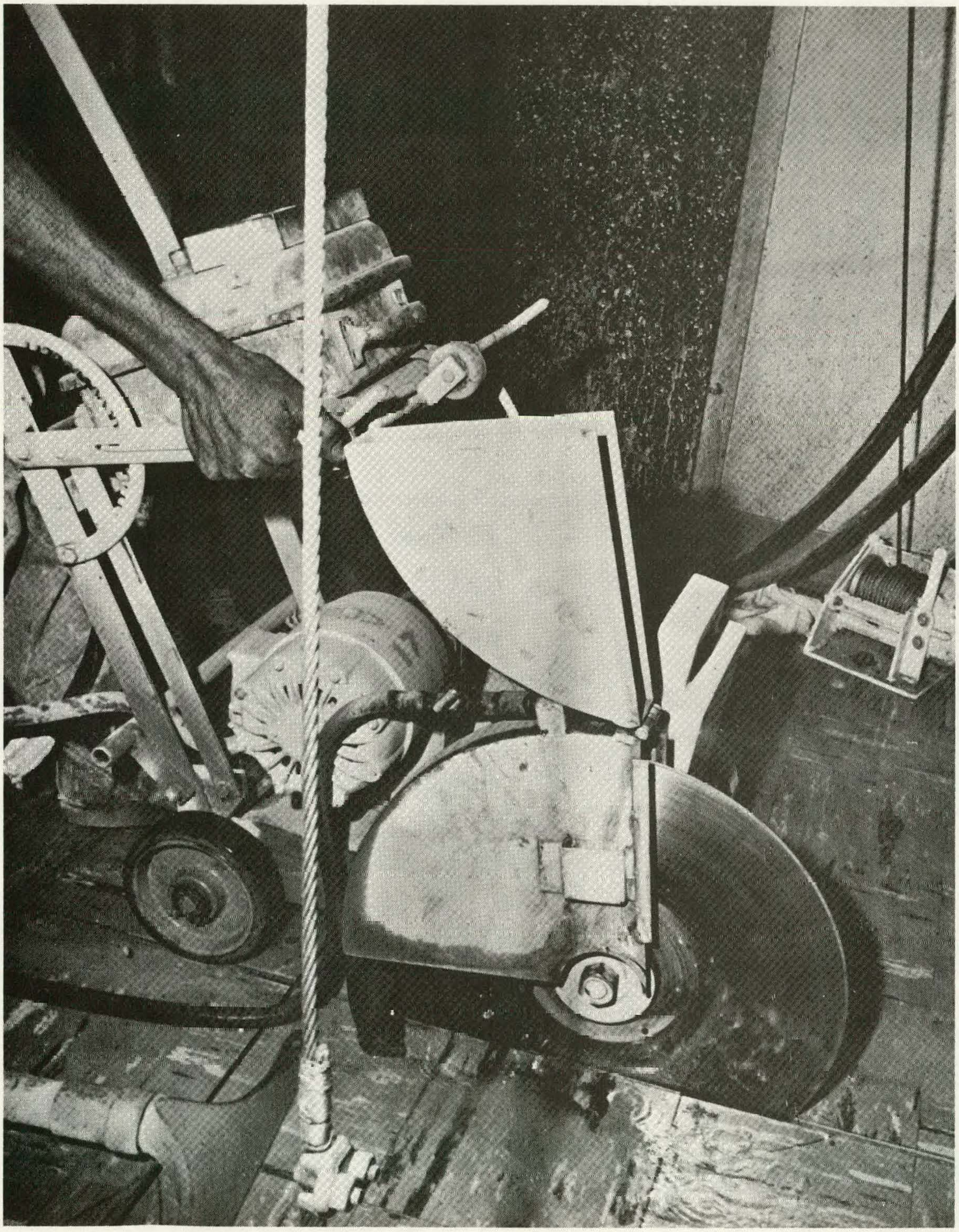


FIGURE 7.13

FLOOR SAW



3. Cost Information

The approximate cost of floor sawing concrete is \$8.00/ft^2 of cutting surface for non-radioactive, non-reinforced concrete. Reinforced concrete cutting costs are dependent on the number of replacement diamond saw blades necessary, and the increased time to cut through heavy rebar. Accordingly, reinforced concrete cutting is priced per bid only. The approximate cost of wall sawing is \$22.00/ft^2 of cutting surface for reinforced concrete up to a 7/8 inch-diameter reinforcing rod. Heavily reinforced concrete is priced per bid only. The saw is operated by one operator with no helper.

7.3.9 Core Stitch Drilling

1. Description of Process

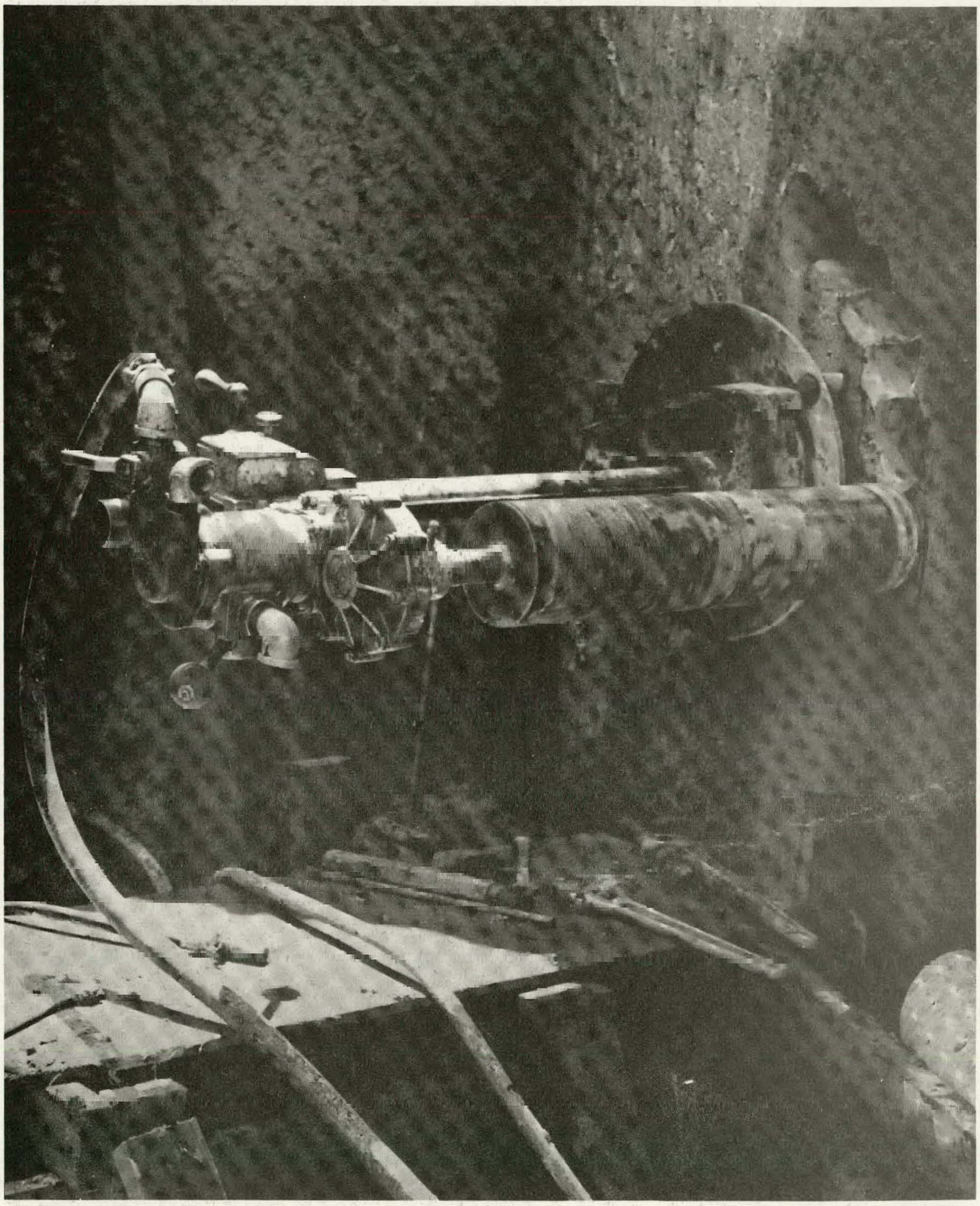
Core stitch drilling consists of close-pitched drilling of holes in concrete using a diamond or carbide-tipped drill bit in an electric or fluid-driven rotary drill. The center lines of the holes are located to correspond to the desired breaking plane in the concrete. The hole pitch is such that there is very little concrete left between adjoining holes (less than 1/2 the radius of the holes). When a line of holes has been drilled along the breaking plane, bars are inserted into the holes and force is applied to the free end of the bars in a line perpendicular to the breaking plane to shear the remaining concrete. Alternatively, a wrecking ball may be dropped onto the piece to be removed to shear the remaining concrete. Figure 7.14 shows a typical diamond bit core drill and motor.

2. Applications

Core stitch drilling produces no gases or smoke, thereby facilitating contamination control. The dust produced by the drilling is controlled by a water spray that is also used to cool the drill bit. Core stitch drilling is used where surrounding material must not be

FIGURE 7.14

DIAMOND CORE STITCH DRILLING



disturbed, or where accessibility is limited. However, the slab to be removed must be accessible to the method of shearing the concrete (bar, slab or wrecking ball).

The method is not recommended for reinforced concrete because the remaining reinforcing rod inhibits shearing.

Concrete drills can cut a 4-inch diameter hole through 4 feet of concrete in 60 minutes. The pitch between holes is recommended to be no greater than 1/2 inch for 4-inch diameter drills. Accordingly, this process is very slow and costly for large volumes of massive concrete removal.

3. Cost Information

Table 7.16 summarizes the costs for core drilling.[13] This cost includes labor, drill bits, and drill motor costs.

7.3.10 Explosive Cutting

1. Description of Process

An explosive cutter consists of an explosive core such as RDX or PETN, surrounded by a casing of lead, aluminum, copper or silver. Cutting is accomplished by a high explosive jet of detonation products of combustion and deformed casing metal. The jet forms a directed shock wave that severs the target material. The cutter is chevron-shaped with the apex pointing away from the material to be cut. When detonated, the explosive core generates a shock wave that fractures the casing inside the chevron and propels the casing into the material to be cut. Figure 7.15 shows various charge thicknesses and Figure 7.16 shows the detonation sequence during a cut.[15]

The target material is cut, not fractured or snapped. In concrete, there would be some local fracturing and pulverizing of the

TABLE 7.16

CORE DRILLING - COST PER FOOT

Unit Prices Per Foot Per Hole Including Reinforcing To 5/8 Inch Diameter

Diameter,in	Cost, $/Ft	Diameter,in	Cost, $/Ft
1 - 1-1/2	17.00	8	48.00
2	21.00	9	52.00
2-1/2	23.00	10	60.00
3	25.00	12	94.00
3-1/2	29.00	14	120.00
4	31.00	16	185.00
4-1/2	34.00	18	260.00
5	38.00	20	400.00
6	42.00	22	475.00
7	44.00	24	550.00

Special Conditions

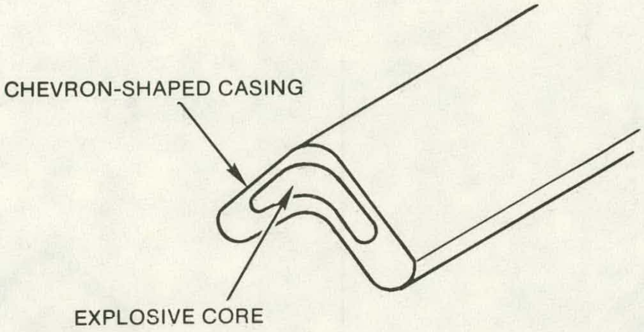
Deep Drilling:	13 to 18-1/2 inches = 1-1/2 x Listed Price Per Foot 19 to 24-1/2 inches = 2 x Listed Price Per Foot 25 to 36 inches = 3 x Listed Price Per Foot
Angle Drilling:	1-1/2 x Listed Price Per Foot
Inverted Drilling:	3 x Listed Price Per Foot
Reinforcing Steel over 5/8 inch:	1-1/2 x Listed Price Per Foot

Prices on the following are per Bid only:

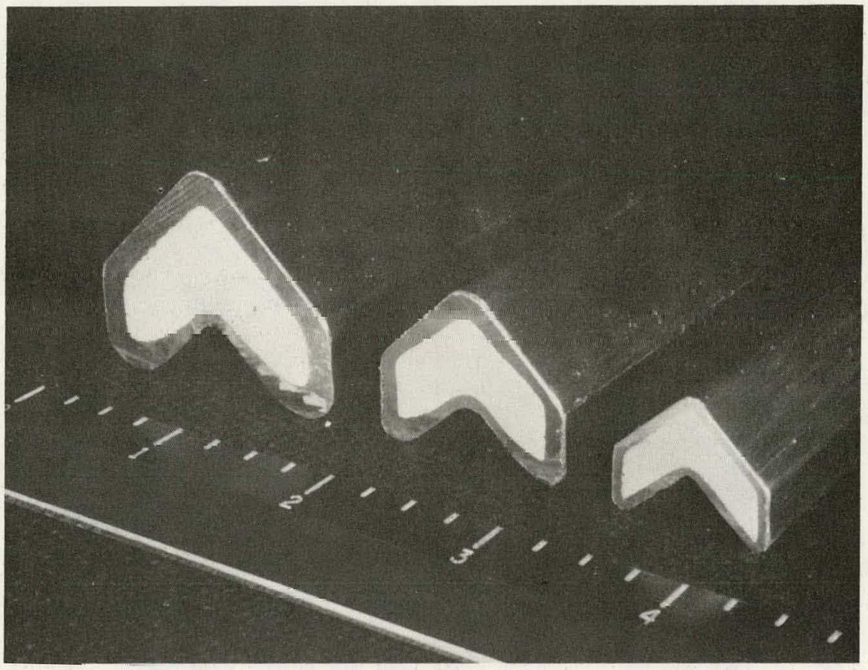
Roto Hammer and Dry Drilling
Work over a 10 ft height from a ladder
Work off a scaffold

FIGURE 7.15

LINEAR SHAPED EXPLOSIVE CUTTERS



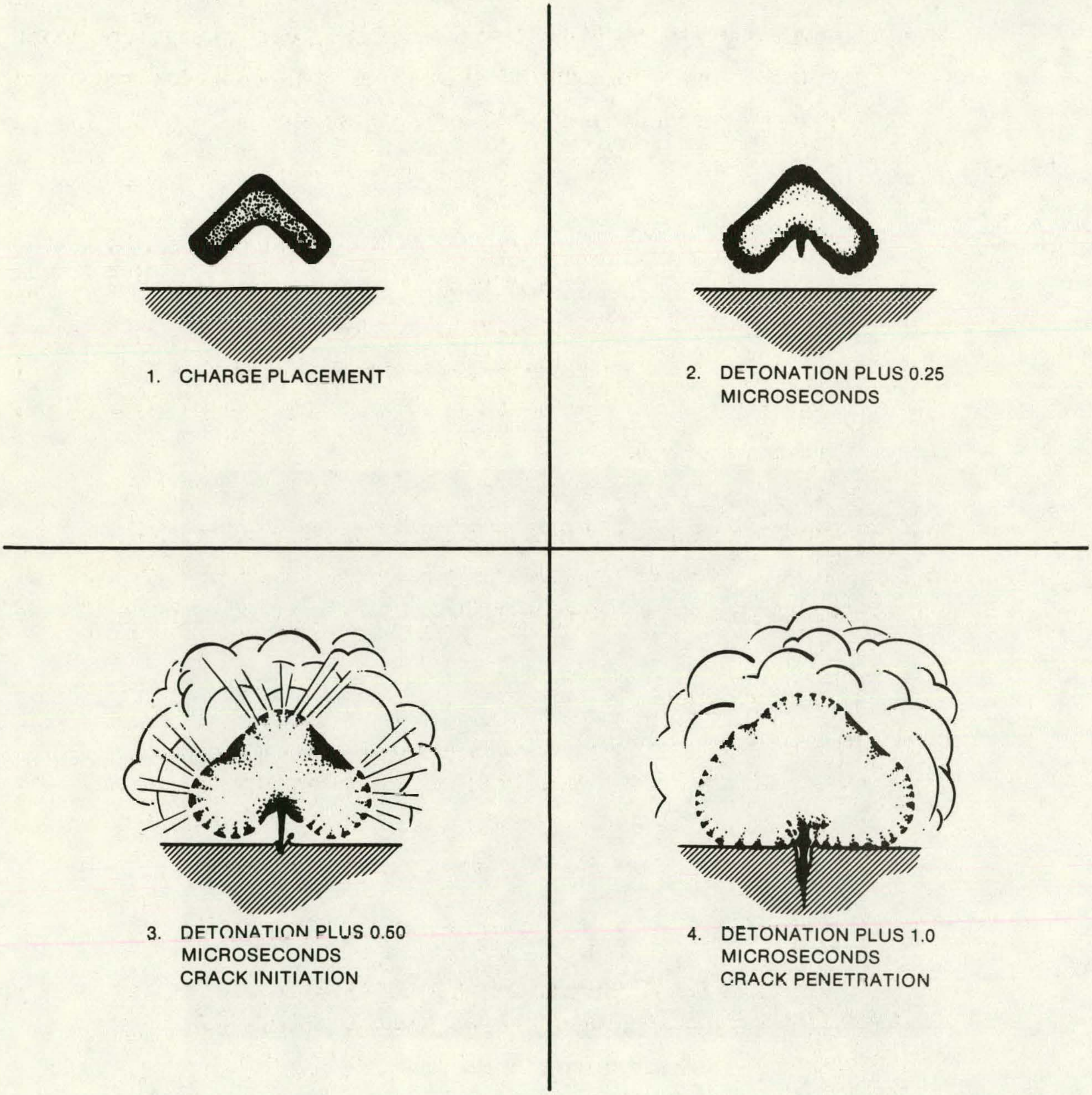
CUTTER COMPOSITION



SAMPLE CHARGE THICKNESSES

FIGURE 7.16

DETONATION SEQUENCE
Source: Explosive Technology



1. CHARGE PLACEMENT

2. DETONATION PLUS 0.25
MICROSECONDS

3. DETONATION PLUS 0.50
MICROSECONDS
CRACK INITIATION

4. DETONATION PLUS 1.0
MICROSECONDS
CRACK PENETRATION

surrounding area. In reinforced concrete, some of the deeper reinforcing rods will not be cut. In this case, either a reinforcing rod cutter or oxyacetylene torch can be used.

Other explosive types are available such as HNS, DIPAM, HMX, CH-6, HNAB, DATB, TATB, KHND and NONA, to accommodate higher temperature (up to 600° F) applications. Lead casings are most frequently used for the smaller sizes and core loadings, and aluminum, copper or silver used for larger sizes.

2. Applications

Explosive cutting is normally used either when the geometry of the object being cut is too complex to employ other methods, or when several cuts must be made simultaneously (e.g. removal of a large prestressed beam where it is impractical to shore up the ends for temporary support).

Explosive cutters are used for precision cutting rather than massive heaving or demolishing. Cutters have been used on concrete for removing buildings, salvaging bridges, and felling smokestacks.

3. Cost Information

Table 7.17 presents typical prices of explosive cutters. These prices may be used as input for cost estimating purposes, but actual demolition should be estimated and directed by a demolition expert.

TABLE 7.17

COST OF EXPLOSIVE CUTTERS

Size	Cost, $/ft *
RDX Lead Sheath: 300 grains/ft	14
RDX Lead Sheath: 2200 grains/ft	64
RDX Copper Sheath: 2000 grains/ft	94
RDX Copper Sheath: 4000 grains/ft	145

* Reference 14 - Up to 100 ft in length of explosive.

7.3.11 Paving Breakers and Chipping Hammers

1. Description of Process

Paving breakers and chipping hammers remove concrete (and asphalt) by mechanically fracturing localized sections of the surface. Fracturing is caused by the impact of a hardened tool steel bit of either a chisel or moil point shape. The bit is driven in a reciprocating motion by either a compressed air or hydraulic fluid pressure source.

Paving breakers (also called "jackhammer" and "pneumatic drill") weigh approximately 35 to 100 pounds and are intended for use on floors. Paving breakers deliver about 1500 blows per minute at up to 95 foot-pounds of energy per blow, depending on the size of the unit. Typical sizes and capacities of paving breakers (pneumatic and hydraulic) are shown in Table 7.18.

TABLE 7.18

PAVING BREAKER - SIZE AND CAPACITY

Unit Weight, lbs	35	65	90
Moil Point diameter, in	7/8	1-1/4	1-1/4
Blows/Minute	1600	1400	1300
Energy/Blow, ft lbs	34	80	95
Air Compressor Size, cfm @100 psi or	40 - 150	40 - 150	40 - 150
Hydraulic System, gpm @ 2000 psi	7 - 9	7 - 9	7 - 9
Removal rate yd^3/day (Non-reinforced concrete)	Not available	Not available	20

The chipping hammer is similar in concept to the paving breaker but is light enough (15-35 lbs.) to be hand-held for use on walls or ceilings. Chipping hammers deliver about 2000 blows per minute. Typical sizes and capacities of units are shown in Table 7.19. Figure 7.17 shows photos of pneumatic and hydraulic paving breakers, respectively. Figure 7.18 shows photos of pneumatic and hydraulic chipping hammers respectively.

TABLE 7.19

CHIPPING HAMMER - SIZE AND CAPACITY

Unit Weight, lbs	24
Moil Point diameter, in	5/8
Blows/Minute	2000
Air Compressor Size, cfm or	50 @ 100 psi
Hydraulic System	7 - 9 gpm @ 2000 psi
Removal rate ft^3/day (Non-reinforced concrete)	27

2. Applications

Paving breakers are recommended for use on floors to remove small areas that are inaccessible for heavy equipment. They may also be used to expose reinforcing rods after controlled blasting to permit cutting of the rods. The chisel point may be used to scarify surface areas of concrete floors where contamination may have penetrated several inches deep in localized areas. Contamination control may be accomplished using water or fog sprays. Chipping hammers are recommended for use on walls to scarify small areas where contamination may have penetrated several inches deep over localized areas. However, the limited removal capacity and significant weight (up to 35 pounds) make it impractical for use on large areas. Other techniques are better suited for this purpose.

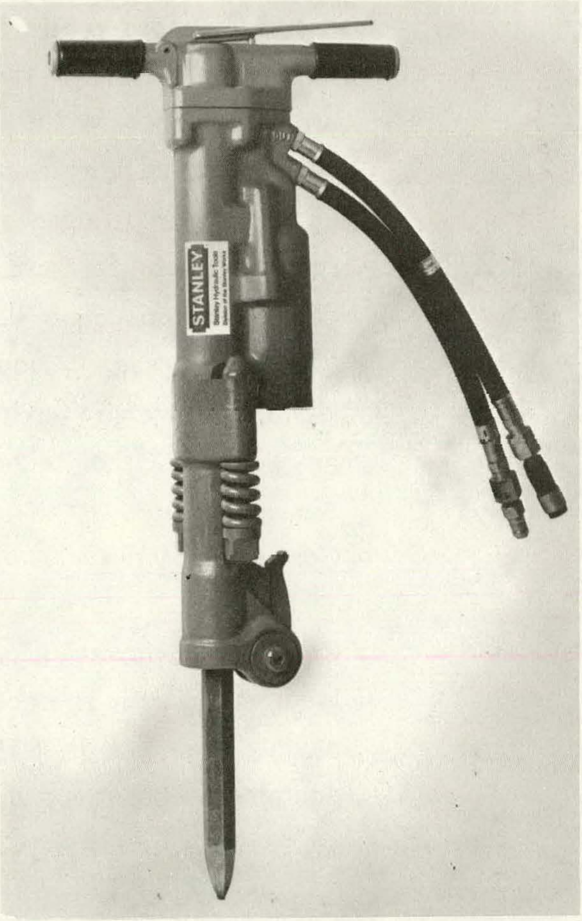
3. Cost Information

Concrete removal using paving breakers or chipping hammers is labor-intensive. The cost for removal of non-reinforced concrete by paving breakers is \$32.00/yd^3. The crew consists of one light equipment operator and two laborers. The crew has an output of 20 yd^3/day.

FIGURE 7.17

PAVING BREAKERS

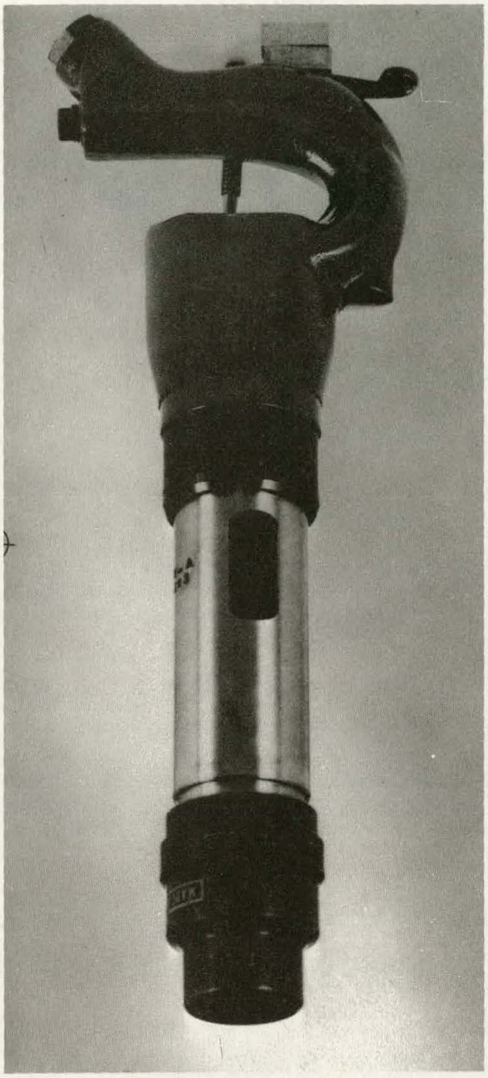
PNEUMATIC



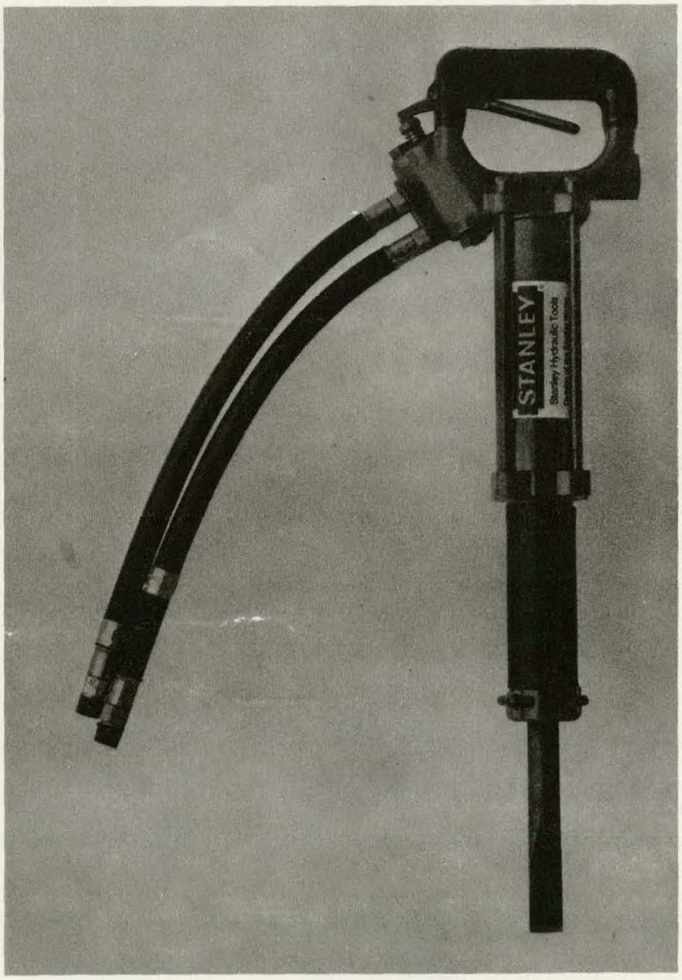
HYDRAULIC

FIGURE 7.18

CHIPPING HAMMERS



PNEUMATIC



HYDRAULIC

For reinforced concrete, the crew consists of one light equipment operator, two laborers and one ironworker. The crew output is 12 yd^3/day at a cost of \$62.00/yd^3.

Chipping hammer costs are essentially those of the hammer operator's hourly rate since the consumption of materials and power requirements is insignificant.

7.3.12 Drill and Spall

1. Description of Process

The drill and spall technique was developed for the removal of contaminated surfaces of concrete without demolishing the entire structure. The technique consists of drilling 1 to 1-1/2 inch diameter holes approximately 3 inches deep into which is inserted a hydraulically operated spalling tool. The spalling tool bit is an expandable tube of the same diameter as the hole. A tapered mandrel is hydraulically forced into the hole to spread the fingers and spall off the concrete. The holes are drilled on approximately 12 inch centers such that the spalled area from each hole overlaps the next.

Battelle Pacific Northwest Laboratories[15] is developing the process with an aim to speed the removal rate of concrete surfaces. Photos of the system in use are shown in Figures 7.19 and Figure 7.20. A shematic of the concrete spaller is shown in Figure 7.21.

2. Applications

The drill and spall technique is recommended for removing surface contamination that penetrates one to two inches into the surface. Removal of the surface radioactivity in this manner eliminates the need to dispose of large quantities of non-radioactive concrete as with other volume removal techniques. Contamination control while

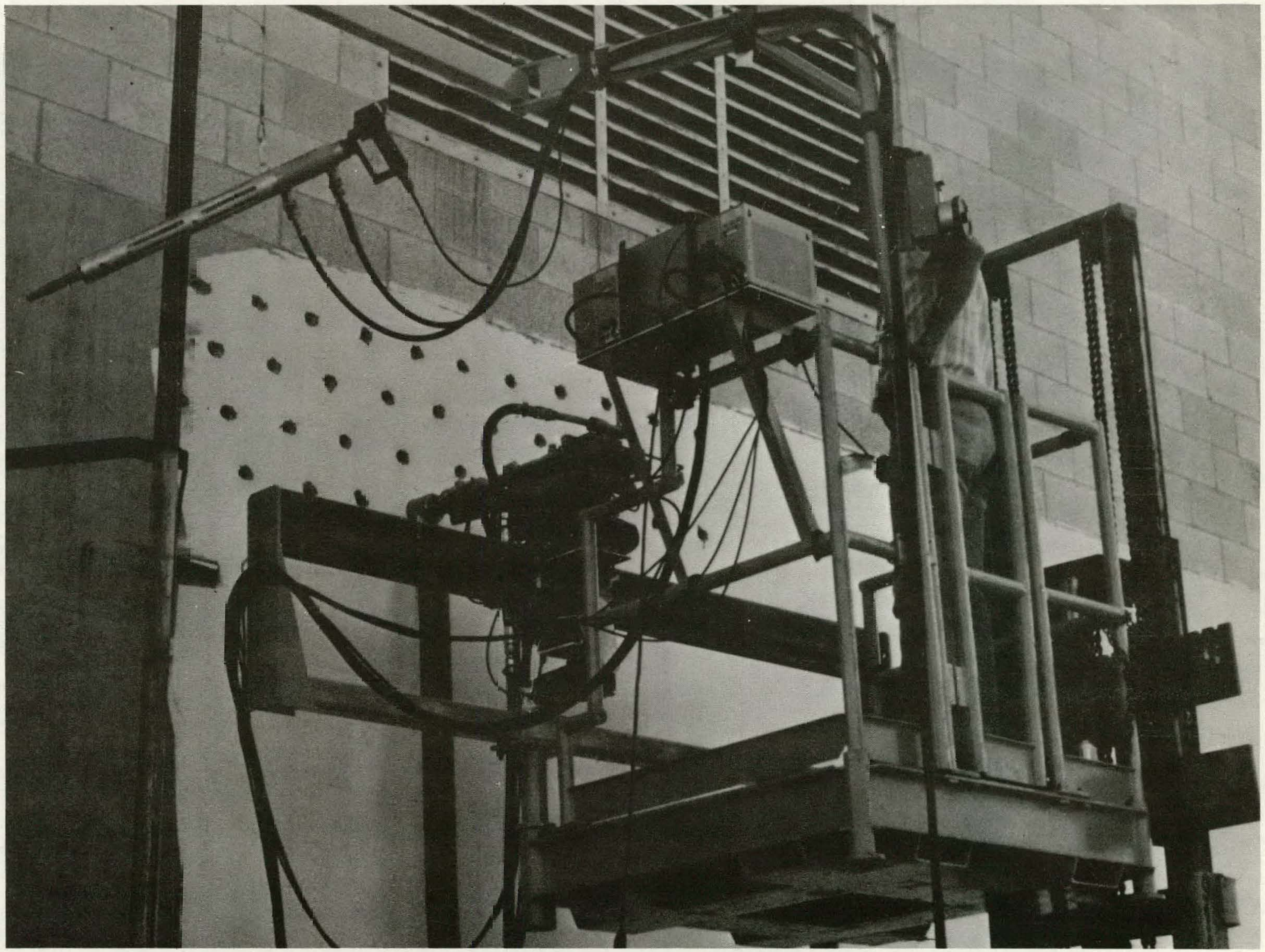
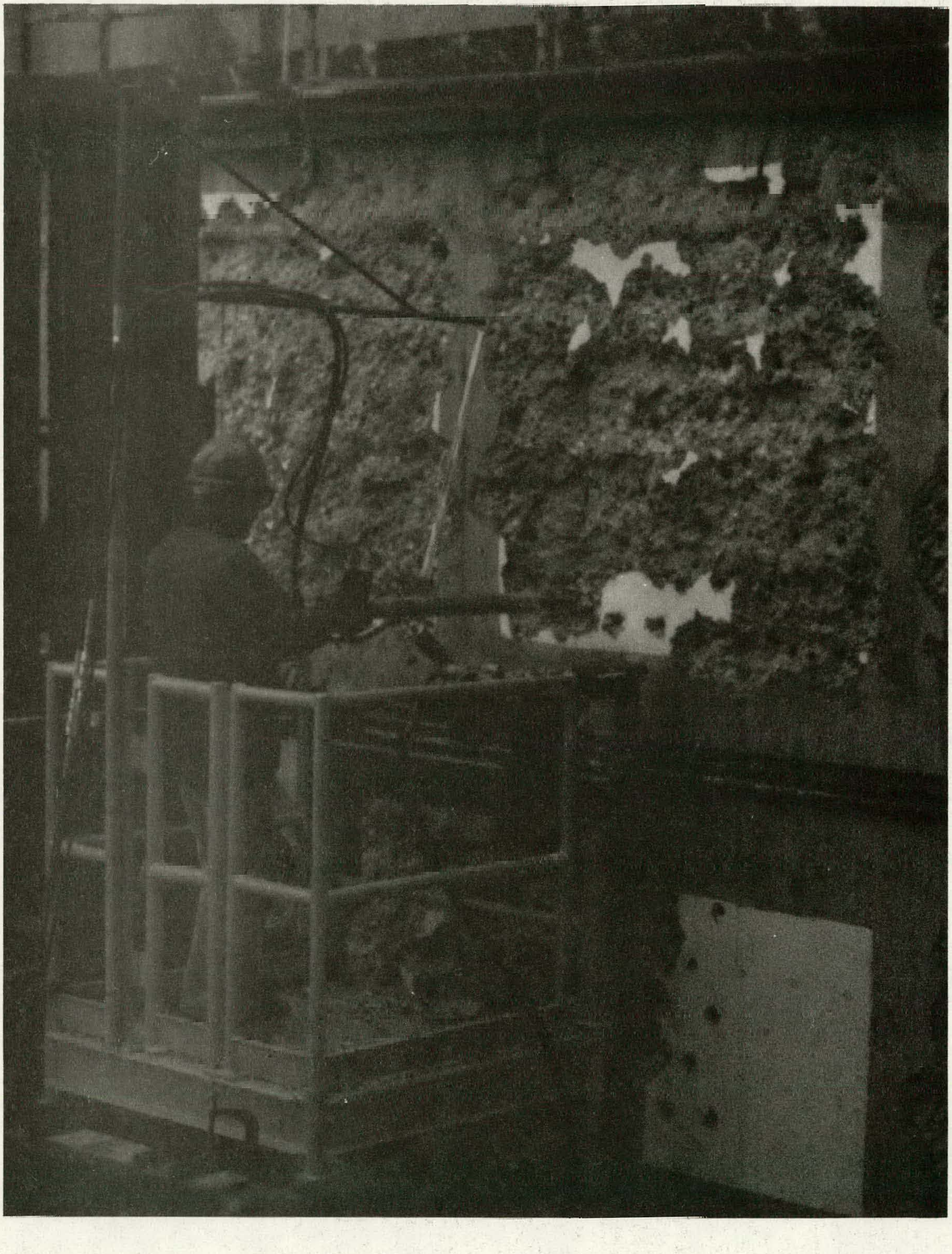


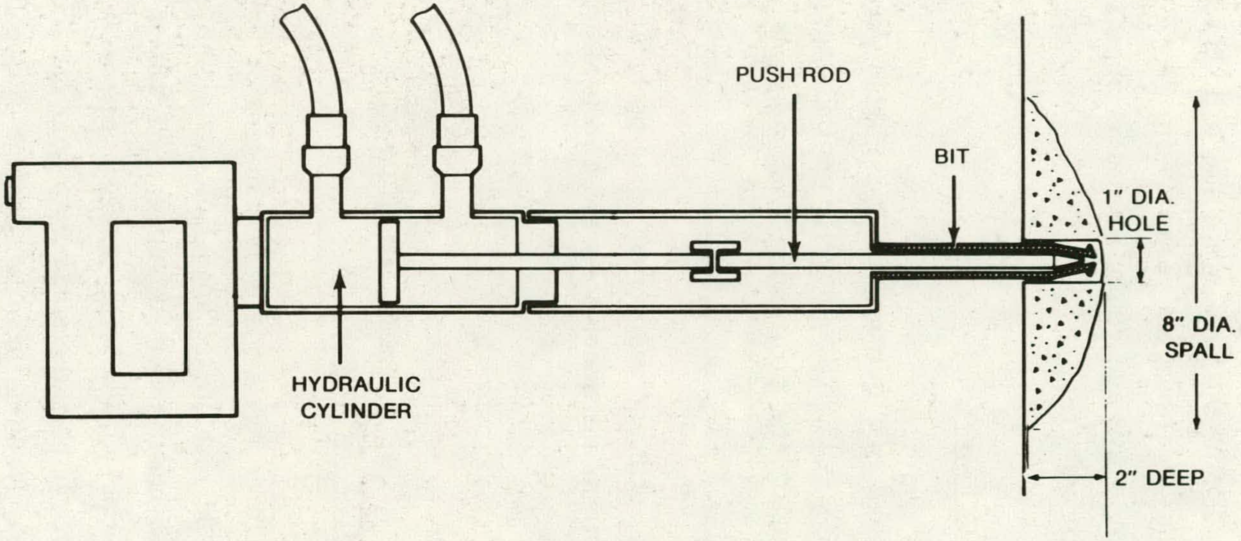
FIGURE 7.19

DRILL AND SPALL RIG

FIGURE 7.20

DRILL AND SPALL SYSTEM





CONCRETE SPALLER

FIGURE 7.21

drilling is accomplished with a filtered vacuum system. Fog sprays may be used to wet the surface and reduce contamination and dust levels.

The system is being developed at the Hanford Reservation in the Battelle Northwest 3000 Area, and will be tested in various Hanford 100 Area locations and possibly in the 233-S Building. Battelle reports the average removal rate is approximately 7.5 yd^2/hr for standard concrete.

3. Cost Information

No detailed cost information is available yet on removal costs since the tool is still in the developmental stage. The equipment cost, exclusive of the positioning equipment, is estimated to be about $10,000.

A typical drill and spall crew would probably consist of one operator, one platform positioner operator, two laborers and a front-end loader operator.

7.3.13 Scarifier

1. Description of Process

The scarifier technique is best suited for the removal of thin layers (up to one inch in thickness) of contaminated concrete. The tool, marketed under the trade name of "Scabbler" by the MacDonald Air Tool Company, New Jersey, consists of pneumatically operated piston heads that strike the surface to chip off the concrete. The piston heads are available in either 5-point or 9-point tungsten carbide bit sizes depending on the degree of surface roughness allowable. The 5-point bit has 1/4 inch high points and the 9-point bit has 1/8 inch high points.

The pistons are mounted in a wheeled-floor chasis that is available in 5, 7 and 9 piston sizes. The chasis is pushed along the floor to remove the surface layer. The chasis can be modified to include a HEPA filtered vacuum exhaust system to capture contaminated dust. Other tool models include a 3-piston wall scabbler that may be spring counter-balanced to relieve the tool weight. Smaller hand-held units are available but are not intended for large surface area removal. Figure 7.22 shows the scabbler floor and wall tools and typical 5-point and 9-point bits.

2. Applications

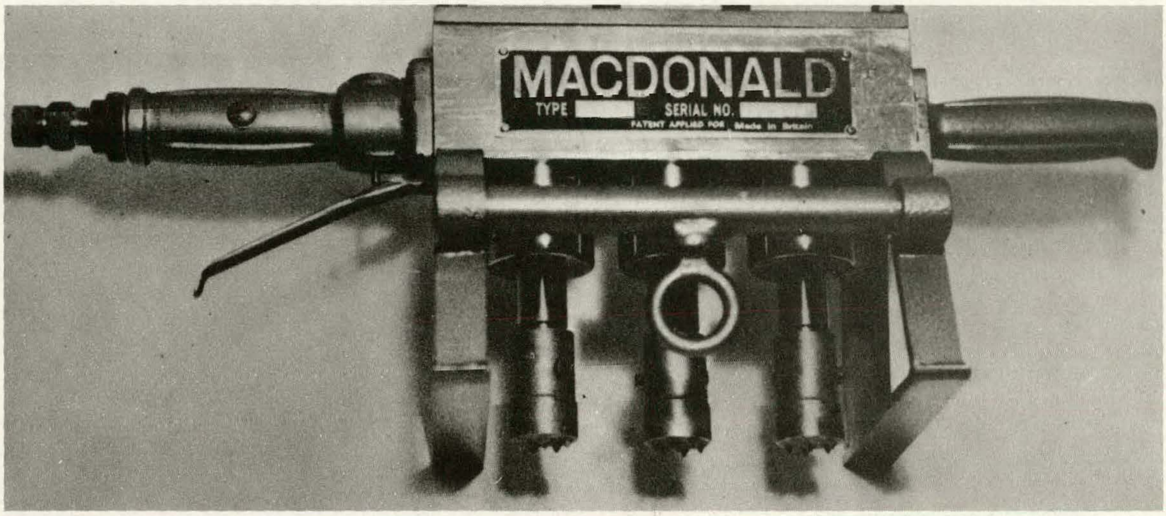
The scabbler tool is recommended for applications where the concrete surface is to be reused after decontamination. The scarified surface is generally level with coarse finish (1/4 to 1/2 inch peak-to-valley height) resulting from the 9-point bit. The coarse surface is suitable for bonding to a concrete finish cap, and the smoother surface suitable for epoxy, polymer and similar finishes.

A 7-piston floor model scabbler was used at the SRE decommissioning program to scarify slightly contaminated floors. An HEPA filtered vacuum exhaust system was fitted to the floor scabbler to control the release of contaminated dust.

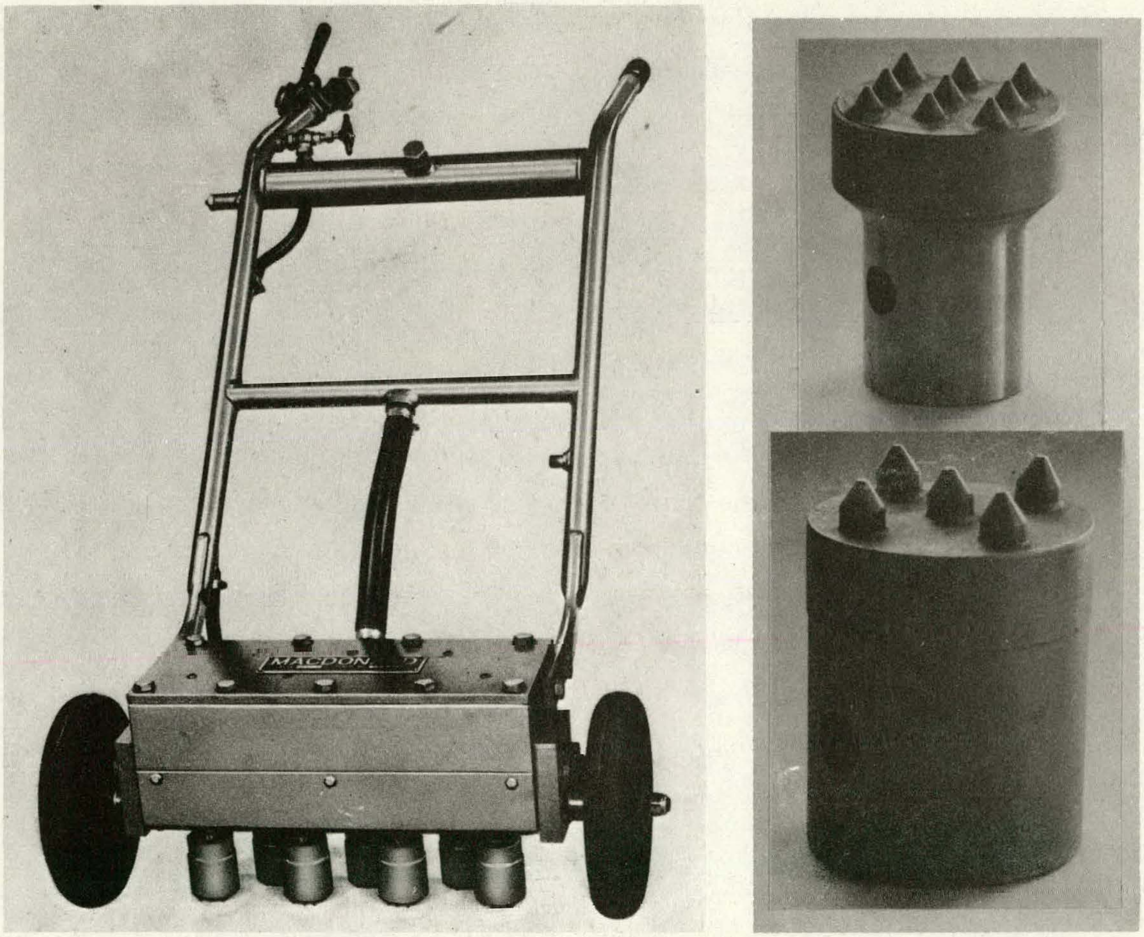
The concrete surface removal rate is 5 square yards per hour per bit[16] for the floor scabbler, which represents 35 square yards per hour for a 7-piston unit. The three-piston wall scabbler will remove 8-12 square yards of surface per hour. The tungsten-carbide tool bits have an average working life of 80 hours under normal use. Additional bit types are available that are designed to be resharpened.

FIGURE 7.22

FLOOR AND WALL SCABBLERS



WALL MODEL



FLOOR MODEL

SCABBLER BITS

3. Cost Information

The approximate unit cost in 1980 dollars for floor and wall scarifying is shown in Table 7.20. The unit cost includes operator cost, air consumption cost, dust and chip removal, subcontractor overhead, and profit.

A typical crew consists of the tool operator and one laborer for chip removal.

TABLE 7.20

CONCRETE SURFACE REMOVAL COST USING FLOOR AND WALL SCABBLERS

Tool Type	Removal Cost, $/yd^2
7 - Piston Floor Model	$ 1.50
11 - Piston Floor Model	$ 2.35
3 - Piston Wall Model	$ 6.70

7.3.14 Water Cannon

1. Description of Process

Two types of high-pressure jet spalling devices have been developed under the common name of water cannon[15]: Type 1, the Glycerine Gun, fires solidified glycerine capsules in a modified 458 magnum rifle through a nozzle. Type 2, the Water Cannon, uses compressed gas to drive a piston that forces water through a small diameter nozzle.

A. Glycerine Gun

The glycerine gun uses a 458 magnum rifle with a short smooth bore barrel. A nozzle is threaded onto the end of the barrel to reduce the diameter from 0.45 inches to 0.17 inches. A 9-inch diameter funnel-shaped shield is placed around the nozzle to protect the operator and collect chips and dust through a vacuum exhaust system. Rubble pieces are 0.5 inches to 0.75 inches in diameter, and are covered with glycerine that contains the dust. The shield extends one inch beyond the nozzle to provide the necessary standoff from the workspace. Figure 7.23 shows the glycerine gun in use and Figure 7.24 is a schematic of the glycerine gun components.

The glycerine gun fires solidified glycerine capsules 2 inches long by a 0.45 inch diameter. The capsules are propelled by gun powder loaded into conventional cartridge cases. The glycerine is accelerated by the propellant, and is extruded through the nozzle at very high velocity. Wax is placed in the cartridge case to hold in the powder, and to create a moving seal around the glycerine to prevent combustion gases from bypassing the glycerine.

B. Water Cannon

The water cannon uses compressed gas to drive a piston and force a small quantity of water through a nozzle. Figure 7.25 shows a schematic of the water cannon components. A funnel-shaped shield is placed over the nozzle to protect the operators and collect debris through a vacuum system. The gas that propels the piston is compressed by a hydraulic impactor. Firing rates of up to 5 shots per second are possible. Water is injected into the chamber in front of the piston after each shot.

The unit is usually mounted on a back hoe or excavator and may be articulated to spall concrete walls, floors or ceilings.

2. Applications

The glycerine gun has been extensively tested, and has been shown to create spall craters 3 to 4 inches in diameter and 0.75 inches deep.

FIGURE 7.23

458 MAGNUM GLYCERINE GUN BEING FIRED

FIGURE 7.24

458 MAGNUM GLYCERINE GUN COMPONENTS

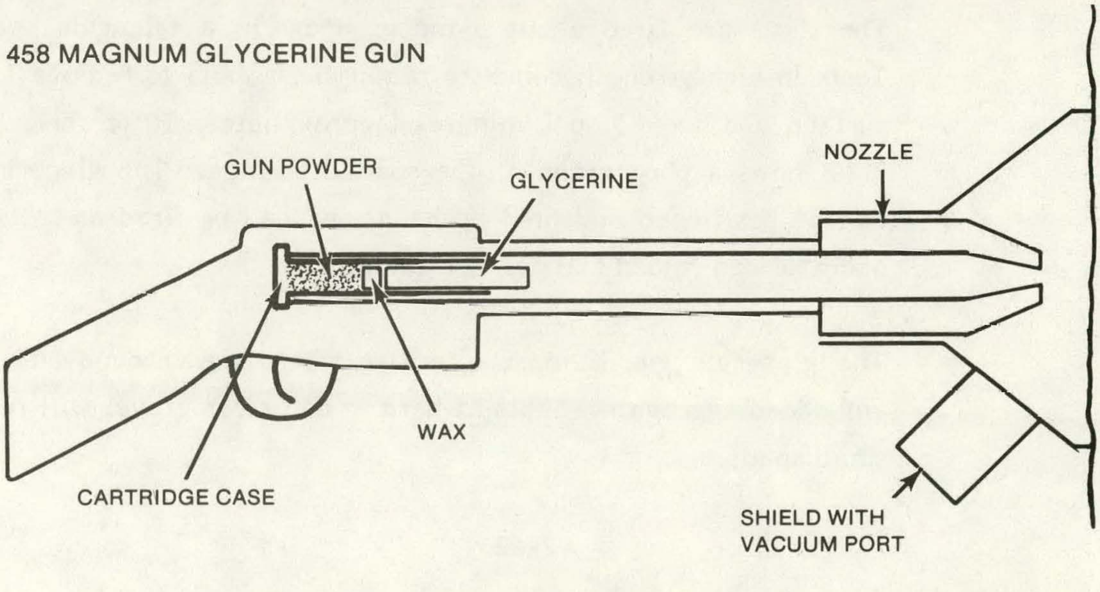
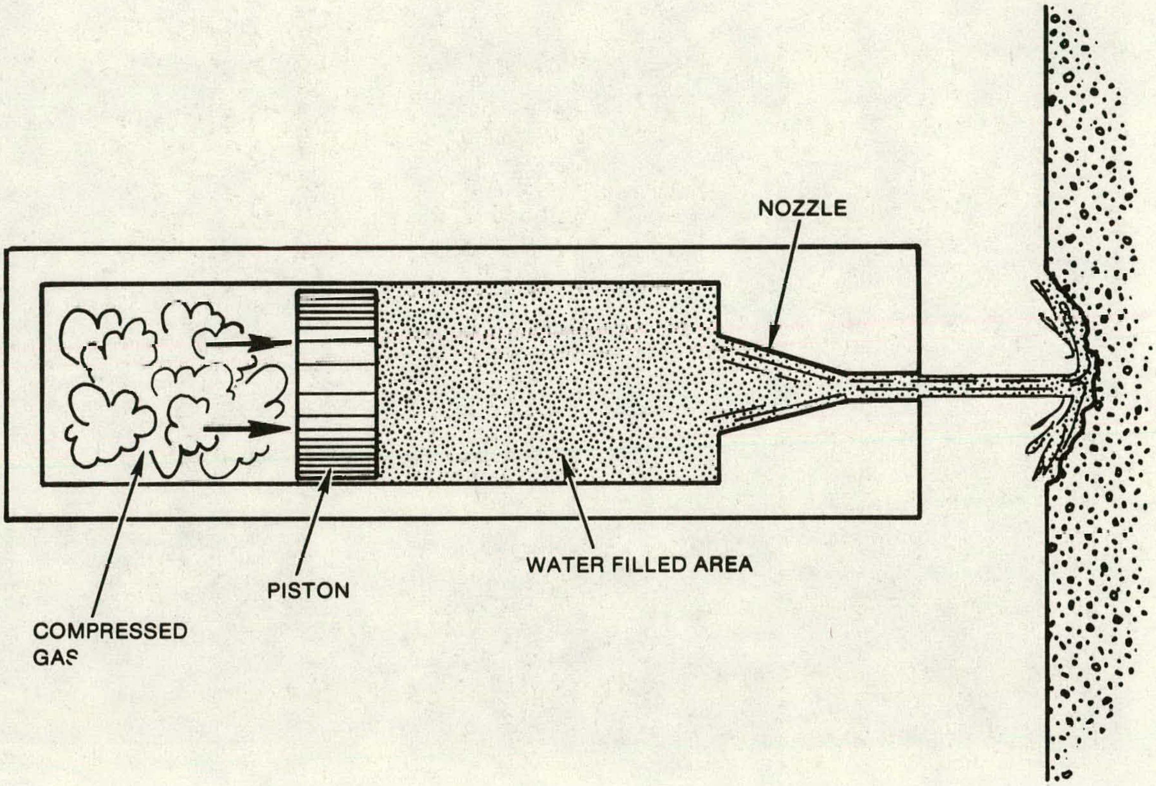


FIGURE 7.25

SCHEMATIC OF A WATER CANNON BASIC COMPONENTS

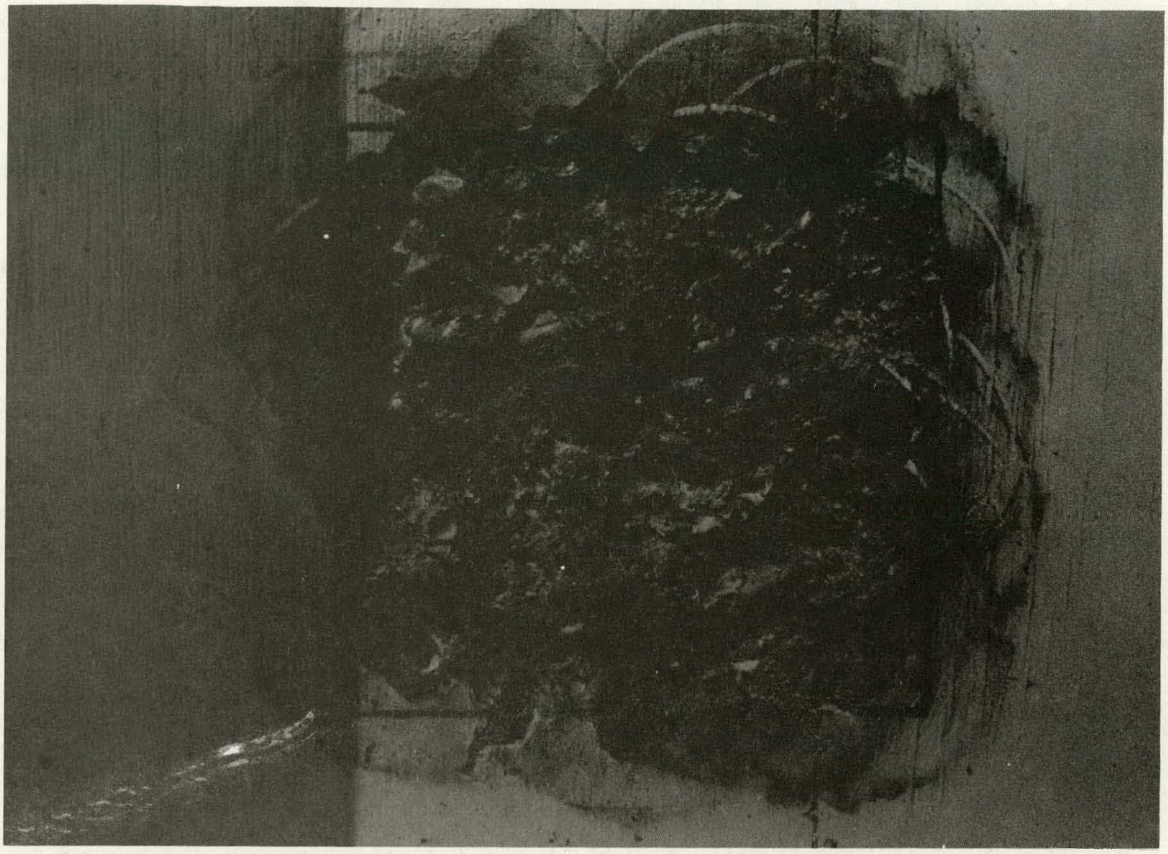


The shots are fired about 3 inches apart in a triangular pattern. Tests in high-strength concrete required 24 shots to remove 1 ft^2 of surface and took 5 to 6 minutes (approximately 10 ft^2/hr). Figure 7.26 shows a photograph of the spalled surface. The glycerine gun can be positioned and held by hand, and can be fired as fast as the operator can reload and position the gun.

The glycerine gun is most effective when fired around and behind embedded aggregate. Shots at hard, round river gravel will result in small spalls.

FIGURE 7.26

458 MAGNUM GLYCERINE GUN SPALLED SURFACE



The water cannon generally exhibits slower rates of removal than the glycerine gun. Typical rates of 1 ft^2 in 15 minutes (4 ft^2/hr) have been demonstrated. The water jet serves to coat the rubble particles and thus helps to reduce the spread of contamination.

3. <u>Cost Information</u>

No detailed cost information is available yet on removal costs since these tools are still in the developmental stages at Battelle Pacific Northwest Laboratory.

A typical crew would consist of the gun operator and one laborer.

7.3.15 Grinding

1. Description of Process

The grinding process includes a large number of similar tools for the removal of thin layers of surface contamination from concrete. In many cases the contamination is limited to the paint coating or concrete sealer finish. The technique consists of abrading the surface using coarse-grained abrasives in the form of water-cooled diamond grinding wheels or multiple tungsten-carbide surfacing discs. Machines to power these abrasives are of the circular floor grinding type where the grinding head rotates parallel to the floor. Water required for cooling is injected into the center of the grinding head eliminating any possibility of dust. Supplementary contamination control can be accomplished through the use of HEPA filtered vacuum systems attached to or held near the machine. The surface may be moistened before and during grinding to hold down dust levels. Figures 7.27 and 7.28 show examples of heavy duty floor and hand-held grinders.

2. Applications

Grinding is recommended primarily for thin layers of contamination because of the rapid disintegration of the abrasives when in contact with concrete.

Typical diamond grinding removal rates with disc type rotary floor grinders are capable of removing several thousand square feet (per day) of surface approximately 1/2 inch deep, and lesser areas to as much as 1 inch deep. The machine may be operated by one operator.

Floor and hand-held grinding machines have been successfully used at the San Onofre Unit 1 Nuclear Plant to remove surface contamination.

FIGURE 7.27

HEAVY DUTY FLOOR GRINDER

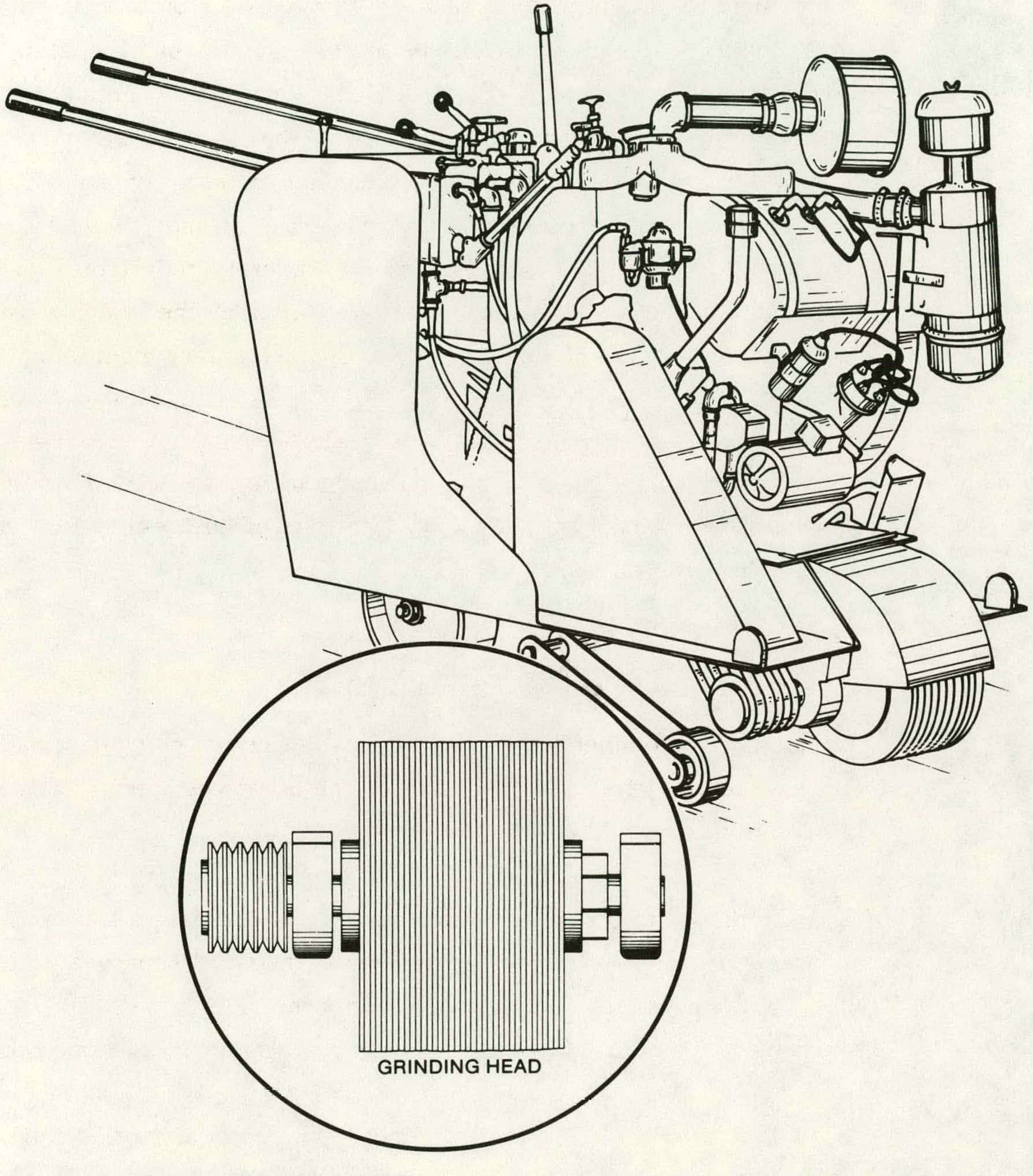


FIGURE 7.28

HAND-HELD FLOOR GRINDER

3. Cost Information

The approximate unit cost in 1980 dollars for concrete floor grinding is $40.00/yd^2.[13] The approximate unit cost includes operator cost, grinding wheels and discs, electricity, dust removal and packaging, and subcontractor overhead and profit.

A typical crew consists of the machine operator and one laborer for dust removal and packaging.

7.4 REFERENCES

1. Havers and Stubbs: "Handbook of Heavy Construction," Second Edition, McGraw Hill, New York, N.Y. (1971)

2. E.I. DuPont de Nemours & Co. (Inc.): "Blasters Handbook" (1977)

3. Levesque, R.G. and Holman, E.C.: Radiological Protection Problems Associated with Removal of Biological Shields, ANS Winter Meeting in Washington, D.C. (Nov. 14, 1978)

4. Personal Communication with Mr. J. Mark Lorzeaux, Vice President, Controlled Demolition, Inc. (Oct. 12, 1979)

5. Dodge Building Cost Services: "1978 Dodge Guide for Estimating Public Works Construction Costs," Annual Edition No. 10, McGraw Hill, New York, N.Y. (1977)

6. United Power Association: Final Elk River Reactor Program Report, COO-651-93, prepared under USAEC Contract No. AT(11-1)-651 (September, 1974)

7. Personal communication with Mr. Will Megin of Meticulous Wrecking, Brookfield, Connecticut, August 1979.

8. R.I. Smith, et al.: Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station, NUREG/CR-0130, Appendix G (June 1978)

9. Personal communication with Mr. Ben Ureda of Atomics International, Rockwell Division, Canoga Park, California, September 1979.

10. Personal communication with Mr. Edward Dempsey, Concrete Coring Company, Hawthorne, California, July 1978.

11. Watanabe, Y., General Manager, Development Department, Onoda Cement Co., Ltd.: 1-1-7 Toyosu Koto-ku, Tokyo, Japan. Cable Address: ONOSEME TOKYO; Telex No.: 2523945 ONOCEM-J.

12. Personal communication with Mr. Larry Martin, Sales Manager, Concrete Coring Company, 12900 S. Prairie Avenue, Hawthorne, California, October 1979.

13. Personal Communication with Mr. Walt Johannes, Explosive Technology, Fairfield, California, November 1979.

14. Personal communication with Mr. J.M. Halter, Battelle Pacific Northwest Laboratory, October 1979.

15. Personal communication with Mr. Len Hendri, MacDonald Air Tool Company, South Hackensack, New Jersey, September 1979.

CHAPTER 8

SEGMENTING PROCESSES FOR CONTAMINATED PIPING, TANKS, AND COMPONENTS

8.1 INTRODUCTION

The removal of piping, tanks, and ancillary components constitutes a major activity in any dismantling program, particularly when radioactive contamination or activation is present. Removal of these radioactive systems must be accomplished in a controlled manner to contain radioactivity and to prevent local recontamination. Removal may be done manually if no significant direct radiation hazards are present or if local shielding can be used effectively. Remote removal may be necessary when highly contaminated or activated systems preclude direct worker access. In the latter case remote cutting would be required to accomplish the segmenting activity.

Typically, system piping in a 1100 MWe light water reactor consists of carbon steel, with diameters as great as 72 inches and wall thicknesses up to 6 inches, and stainless steel piping, but generally of smaller diameter and wall thickness. Tanks are fabricated of either stainless steel or carbon steel. Tank diameters vary from several feet to 50 feet, with wall thicknesses comensurate with the tank's pressure rating. Ancillary components such as pipe hangers and supporting beams are fabricated largely of carbon steel.

This chapter deals with the segmenting processes appropriate for activated and contaminated piping, tanks, and components. Specifically, the chapter includes information pertinent to the selection of cutting methods for various metals and presents detailed descriptions of each method. The data presented are keyed to metal type and section thickness in a manner to be of general use in the area of metal cutting.

8.2 PROCESS SELECTION

It is expected that a user of this handbook who has need for information concerning the segmenting of piping, tanks, and miscellaneous components will have a specific application in mind. Therefore, Tables 8.1, 8.2, and 8.3 present tabulations of useful processes as a function of material, material thickness, and cutting environment (in-air or underwater). This permits the user to make preliminary selection of a process or processes. The detailed information pertinent to the selection of the optimum process may be found in Section 8.3.

8.3 DETAILED DESCRIPTION OF PROCESSES

The segmenting processes in this chapter include:

1. Plasma Arc
2. Oxygen Burner
3. Thermite Reaction Lance
4. Explosive Cutting
5. Hacksaws and Guillotine Saws
6. Circular Cutters
7. Abrasive Cutters
8. Arc Saw
9. Mechanical Nibbler and Shears

A summary of the application characteristics of each process is presented in Table 8.4.

8.3.1 Plasma Arc Cutting

1. Description of Process

The plasma arc cutting process is described in detail in Section 6.3.2(1). That discussion is completely applicable to the cutting of piping and components and is not included in this chapter.

TABLE 8.1

SEGMENTING METHODS APPLICABLE TO PIPING

Wall Thickness (inches)	Applicability	Process	Note
	Pipe Diameter (inches): ≤ 72		
All thicknesses	Carbon steel	Oxygen Burner	1
All thicknesses	All metals Pipe diameter limited to 1/3 dia of saw blade	Arc Saw (stationary)	
> 3	All metals	Thermite Reaction Lance	2
≤ 6	All metals	Explosive Cutting	3
≤ 3-1/2	All metals	Plasma Arc	
≤ 3	All metals All piping > 6" dia	Circular Cutter	
	Pipe Diameter (inches): ≤ 36		
All thicknesses	Carbon steel	Oxygen Burner	1
≤ 6	All metals	Explosive Cutting	3
≤ 3-1/2	All metals	Plasma Arc	
≤ 3	All metals All piping > 6" dia	Circular Cutter	
	Pipe Diameter (inches): ≤ 18		
All thicknesses	Carbon steel	Oxygen Burner	1
All thicknesses	All metals All piping 2" to 18" dia	Guillotine Saw	
All thicknesses	All metals All piping up to 14" dia	Power Hacksaw	
≤ 6	All metals	Explosive Cutting	3
≤ 3-1/2	All metals	Plasma Arc	
≤ 3	All metals All piping > 6" dia	Circular Cutter	

TABLE 8.1
(Continued)

Wall Thickness (inches)	Applicability	Process	Note
	Pipe Diameter (inches): ≤ 6		
All thicknesses	Carbon steel	Oxygen Burner	1
All thicknesses	All metals All piping ≥ 2" dia	Guillotine Saw	
All thicknesses	All metals All piping ≥ 2" dia	Power Hacksaw	
≤ 6	All metals	Explosive Cutting	3
≤ 3-1/2	All metals	Plasma Arc	
≤ 3	All metals Minimum pipe dia is 6"	Circular Cutter	
	Pipe Diameter (inches): ≤ 2-1/2		
All thicknesses	All metals	Plasma Arc	
All thicknesses	Carbon steel	Oxygen Burner	1
All thicknesses	All metals	Guillotine Saw	
All thicknesses	All metals	Power Hacksaw	
All thicknesses	All metals	Large Bolt Cutter	
All thicknesses	All metals	Portable Abrasive Cutter	
≤ 1/4	All metals	Mechanical Shear	

NOTES:

1. Underwater cutting is limited to a depth of 35 feet (15 psig) when using oxyacetylene fuel because of the explosive instability of acetylene under pressure.
2. May be used in limited applications for very thick pipe walls or special pipe construction, or access limitations such as reactor nozzels.
3. Limited access or other circumstances may dictate application of explosive cutting. The effect of detonation shockwave must be considered.

TABLE 8.2

SEGMENTING METHODS APPLICABLE TO TANKS AND PRESSURE VESSELS

Wall Thickness (inches)	Process	Applicability	Note
≤ 6	Plasma Arc	All metals	1
	Oxygen Burner	Carbon steel	2
	Thermite Reaction Lance	All metals	3
	Explosive Cutting	All metals	4
≤ 2-1/2	Plasma Arc	All metals	
	Oxygen Burner	Carbon steel	2
	Thermite Reaction Lance	All metals	3
	Explosive Cutting	All metals	4
	Circular Cutter	All metals; limited to vessels of circular cross-section	
	Mechanical Nibbler/Shear	Carbon steel; wall thickness limited to 1/4"	

NOTES:

1. Underwater applications limited to thicknesses less than 4 inches.
2. Underwater cutting is limited to a depth of 35 feet (15 psig) when using oxyacetylene fuel because of the explosive instability of acetylene under pressure.
3. Suitable for very thick walls or special construction, or access limitations.
4. Limited access or other circumstances may dictate application of explosive cutting. The effect of detonation shockwave must be considered.

TABLE 8.3

SEGMENTING METHODS FOR MISCELLANEOUS COMPONENTS

Material Form	Process	Applicability
Bar Stock Angle Iron	Plasma Arc	Generally suited for cutting large quantities of materials and for stainless steel
Channel Iron	Oxygen Burner	Carbon steels only
"I" Beams Flat Stock	Thermite Reaction Lance	Gross cutting technique especially suited for cutting reinforcing rods
	Explosive Cutting	An expensive technique to be used selectively when other techniques are not feasible
	Abrasive Saw	Slow process, used for cutting carbon and stainless steel in small applications
	Guillotine Saw	Can be adapted for bar, angle, or channel cutting
	Power Hacksaw	Can be adapted for bar, angle, or channel cutting
	Mechanical Nibbler/ Shear	Limited to 1/4" thick carbon steel; thinner stainless steel

TABLE 8.4

APPLICATION CHARACTERISTICS OF SEGMENTING PROCESSES

Process	Application	Relative Cost	Note
Plasma Arc	All metals ≤ 6"	High	P, R, S
Oxygen Burner	Mild steels, all thicknesses	Low	P, R, S
Thermite Reaction Lance	All metals, all thicknesses	Low	P
Explosive Cutting	All metals ≤ 6" in thickness	High to Very High	R
Hacksaws and Guillotine Saws	All metals Piping ≤ 18" in diameter	Low	P, R
	All metals Piping or Stock ≤ 24"	Low	S
Circular Cutter	All metals Piping ≥ 6" diameter with wall thickness ≤ 3"	Low	P, R
Abrasive Cutter	All metals Piping and stock ≤ 2" chord length	Low	P
	All metals Piping and stock ≤ 8" chord length	Low	S
Arc Saw	All metals ≤ 36" chord length	High	S
Mechanical Nibbler	All metals ≤ 1/4" in thickness	Low	P or R
Mechanical and Hydraulic Shears	All metals Piping ≤ 2" in diameter	Low	P or R

NOTE:

Recommended operating modes for the cutting processes include:

(P) Portable application where personnel bring the process equipment to components being disassembled.

(R) Remote application where remotely operated mechanisms are required to segment components.

(S) Stationary application where material is brought to a permanently established work station for segmenting.

2. Applications

Applications of plasma arc cutting are described in Section 6.3.2(2) and are applicable to the cutting of piping and components with the following additions:

Track systems are available for use with small plasma torches. In most cases, commercially available off-the-shelf tracks will meet the required geometric constraints; however, in some cases specially fabricated designs may be required. These tracks have various methods of being fastened to the workpiece, including magnetic and strap fasteners. The torch is advanced and guided on the tracks by a motor that is remotely controlled by an operator. This minimizes the contamination control requirements and reduces personnel exposures.

Hand-held plasma torches can be used to segment contaminated components if attention is paid to contamination control. Filter masks for torch operators are required as well as high volume ventilation systems that draw the contaminated fumes through HEPA filters. Another method of control is a fabricated non-flammable contamination control envelope, similar to a glove box, in which the cutting is performed. Ventilation of the control envelope must allow for in-leakage of air and filtration of contaminated fumes.

Manual (hand-held) torch operation cannot be used for materials greater than 1-1/2 inches due to the reaction force of the gas flow and the plasma jet.

Plasma arc cutting of reactor coolant piping was performed when replacing the steam generators at Virginia Electric Power Company's Surry Unit 2. It proved to be an effective, rapid separation technique. Since the separated pipes were eventually to be rewelded, weld surface preparation of the plasma-cut pipe was required. For this reason, alternative cutting machines that leave the pipe cut in condition for welding are being evaluated by VEPCO for similar tasks on Unit 1.[1]

3. Cost Information

The approximate cost in 1980 dollars of the plasma arc cutting system capable of cutting three-inch thick stainless steel in air, is $15,000. A similar system for cutting four-inch thick stainless steel in air costs approximately $25,000. Each system includes the torch assembly, power supply, control console, and cooling water system. A manually operated torch for cutting steel up to 1-1/2 inches costs approximately $500.00. Track mounting of the plasma arc system would result in higher costs associated with torch positioning, cutting speed control, and automatic arc control.

The operation of a manual plasma torch at a decommissioning site would probably require a three-man team, for handling of the torch itself and the workpiece segments.

Gas consumption is about 300 ft^3/hr for in-air cutting. Considering the life expectancy of the torch components, the total consumables cost for a 40-hour per week in-air cutting program would be approximately $1600.00. This includes the following:

gas	$300.00
electric power	$ 60.00
electrodes	$ 40.00
nozzle tip and nut	$400.00

Operating costs of a manual or track mounted torch for underwater cutting would be approximately twice as much as in-air cutting.

8.3.2 Oxygen Burning

1. Description of Process

The oxygen burning process, sometimes referred to as oxyacetylene cutting, is described in detail in Section 6.3.3(1). That discussion is completely applicable to the cutting of piping and components and is not included in this chapter.

2. Applications

Applications of oxygen burning are described in Section 6.3.3(2) and are applicable to the cutting of piping and components with the following additions:

Only in rare instances, such as PWR hot and cold leg piping, will thicknesses ever exceed 3 inches. Therefore, most oxygen burning during a decommissioning will be through piping with wall thicknesses of 3 inches or less.

When cutting pipe, cutting speed is determined by the pipe wall thickness. As in the case of plasma arc cutting (see Section 8.3.1(2)) attention must be paid to contamination control of the potentially radioactive fumes of the cutting process. The control methods described in 8.3.1(2) are also applicable to oxygen burning.

3. Cost Information

The cost information presented in Section 6.3.3(3) is applicable for oxygen burning of piping and components. Note however, that the thickness of pipe to be cut will be less than 6 inches.

8.3.3 Thermite Reaction Lance

1. Description of Process

The thermite reaction lance process is described in detail in Section 6.3.4(1). That discussion is applicable to the cutting of selected components during decommissioning and is not included in this chapter.

2. Applications

Applications of the thermite reaction lance are described in Section 6.3.4(2); however, the lance is not intended for general use in pipe cutting. Its application in pipe cutting is limited to very thick walls, or in cases where access is limited. It is effective in the cutting of reinforcing rods and other ancillary components with irregular surfaces. It should be considered only as a gross manual cutting technique.

3. Cost Information

The cost information presented in Section 6.3.4(3) is applicable to the uses discussed herein.

8.3.4 Explosive Cutting

1. Description of Process

Explosive cutting is a method of segmenting metal via the use of an explosive that is formed in a geometric shape specially designed and sized to produce the desired separation of the workpiece. It is based upon a phenomenon known as the Munroe Effect and uses directed shock waves, together with the products of explosive decomposition and the metal fragments from the explosive's sheathing material, to form the primary jet-like cutting action.[2] RDX is normally used as the explosive. It is a potentially dangerous process and the application should be left to experts who specialize in that field.

Pieces of explosive, slightly longer than the target, are taped or wired to the target with standoff blocks under the explosive. Standoff is the recommended distance between the target and the explosive to allow the cutting jet to form properly before reaching the target. Low density polystyrene ($\sim$ 1 lb/ft^3) makes a good standoff block. The extra length of explosive should be at the initiating end to allow the explosive column to reach full cutting performance before it hits the target area. No foreign debris or water should be present in the standoff area or in the apex of the explosive.

Explosives are initiated by non-electric or electric blasting caps. The caps are attached to the end of the explosive with tape or a holder. The exposed end of the explosive must be clean and free of debris. The caps are centered on the explosive column. Detonating cord pigtails or electric leads are run from the caps to the initiation source. Delays can be built in by using two or more initiators attached to separate trunk lines or by using delay caps at the appropriate explosive interfaces.

The detonation front progresses along the length of the explosive at approximately five miles per second (25,400 ft/sec); consequently, severance of the target is essentially instantaneous. The specific application must be evaluated in actual use for material type and condition, as well as the type of loading on the structure to be severed (compression, tension, etc.).

2. Application

Explosive cutting can be used on any material and is not configuration limited. This technique was successfully used for underwater segmenting of a 3/4 inch thick stainless steel, core tank liner attachment in the reactor vessel of the Sodium Reactor Experiment. It has been reported that explosive cutters have been used for materials greater than six inches in thickness and also used in-air or underwater.[3] Obviously, the technique is limited by the effect of the blast on mechanical integrity of the surrounding structures and ability to preclude the uncontrolled spread of radioactive material. It is envisioned that explosive cutting of metals will find limited use in a decommissioning program and then only where other techniques are simply not feasible nor practical.

Explosive cutting of contaminated components and systems may be used for the following unique applications:

1. Where simultaneous cuts must be made
2. Where cutting techniques do not have sufficient access
3. In high radiation zones where long handled tools are used to position the explosive cutters.

The ease with which charges can be placed is an important feature of explosive cutting. Charges are designed with spring clamps or other mechanical fasteners for ease of fastening either manually or with long handled tools.

3. Cost Information

The highly specialized nature of explosive cutting makes it a costly process used in selective circumstances. The actual costs of the explosives vary from $4.00 to $20.00 per foot of explosive, depending on the amount of explosive and the sheathing material. Complex cutting geometries require additional costs for the design and fabrication of unique charge configurations and loading densities. In general, however, the cost of explosives is small compared to the fees charged by firms specializing in this technique. The total cost for explosive cutting varies widely depending upon application.

8.3.5 Hacksaws and Guillotine Saws

1. Description of Process

Hacksaws and guillotine saws are relatively common industrial tools used for cutting all metals with a reciprocating-action, hardened steel saw blade. These saws use mechanical methods for segmentation, rather than the previously discussed thermal methods. This offers two distinct advantages: fire hazards are reduced and radioactive contamination control is simpler because there are no fumes or gases. Hacksaws and guillotine saws are the tools frequently selected for cutting piping systems because of their low operating cost, high cutting speed and ease of contamination control. They can be applied in either portable or stationary modes.

Portable power hacksaws are clamped with a chain to a pipe in a position such that the blade contacts the underside of the pipe. This allows the weight of the motor to advance the blade into the workpiece about the chain mounted pivot point. An operator may increase the feed pressure manually by applying downward force on the motor body or by suspending weights from the body. In general, blade lubrication is not necessary. Figure 8.1 shows a typical portable air powered hacksaw in use.[4]

A portable guillotine saw also clamps by chain to a pipe but the saw and motor are mounted above the cut allowing the weight of the unit to advance the saw into the workpiece. In general, blade lubrication is not necessary. Figure 8.2 shows a typical, air powered guillotine saw. Motors for either type portable saw may use air or electricity for motive power.[5]

The light weight and compact size of either saw and the ease with which either straps around piping reduces set up time for cutting. Furthermore, once positioned, either saw will operate without operator assistance. These features make both saws ideal for reducing operator exposures when cutting in high radiation zones.

Hacksaws may also be used in stationary applications with a large rigid bed to hold the workpiece and a reciprocating bow holding the saw blade that cuts the work from above. These saws are larger, more powerful, and faster than the portable saws. Their blades are provided with a lubricating spray that must be recycled or filtered to remove radioactive contamination.[6]

FIGURE 8.1

PORTABLE AIR POWERED HACKSAW

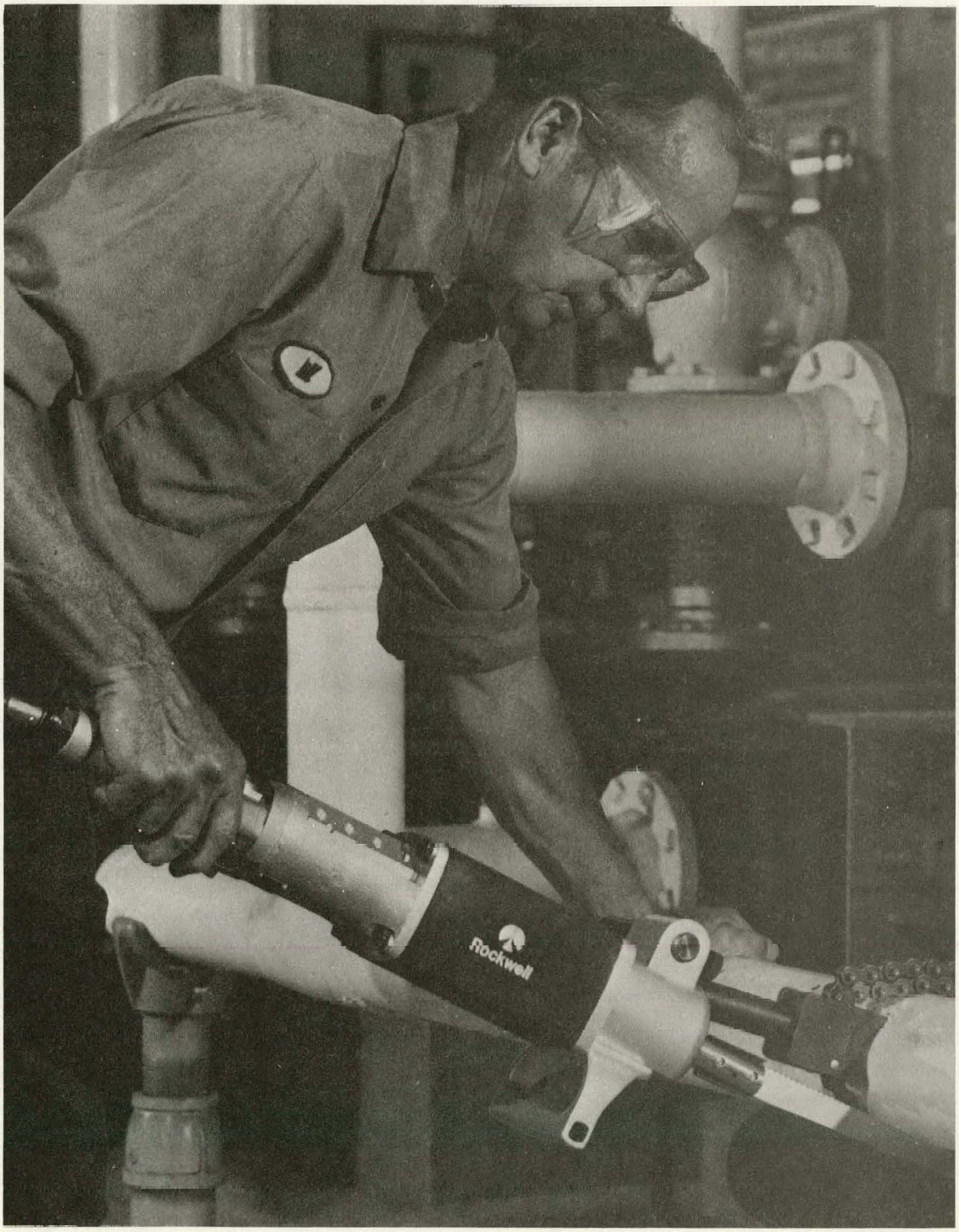
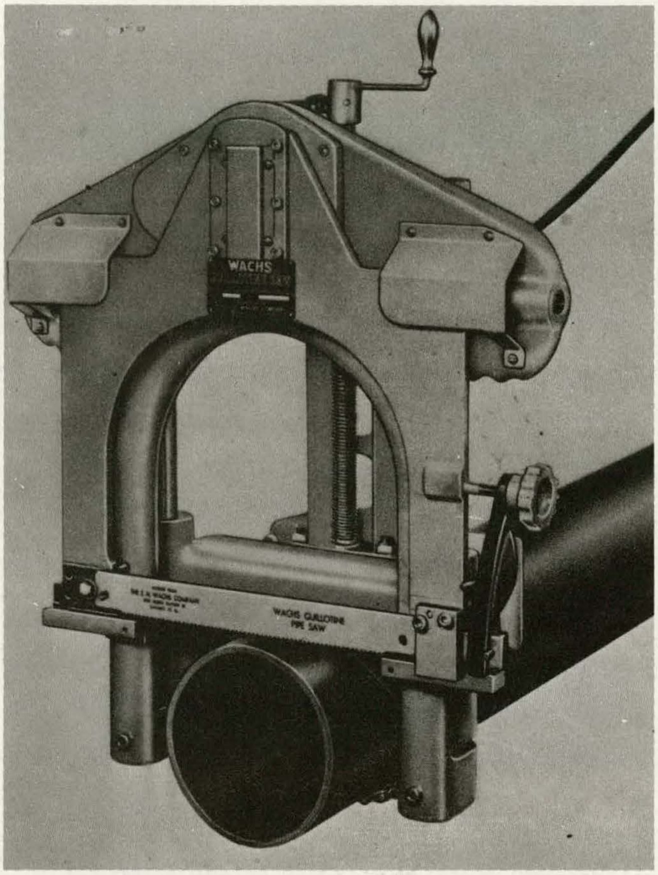


FIGURE 8.2

PORTABLE AIR POWERED GUILLOTINE SAW



2. Applications - Portable

Portable power hacksaws can cut piping up to 14 inches in diameter. Cutting time varies with the material being cut, use of lubricant, if any, and the force applied to the blade. As a general rule, an 8 inch diameter Schedule 40 pipe can be cut in 6 to 10 minutes by a power hacksaw.

Hacksaws weigh approximately 15 pounds and therefore are easily positioned by one operator. With a blade length of 8 to 24 inches plus the 24 inch length of the power unit, they are relatively small and fit easily into constricted areas. Pneumatic models consume 30 to 50 SCFM of air at 90 psig while electric models require 750 watts.

Guillotine saws are capable of cutting pipe from 2 to 18 inches in diameter. Cutting speed is approximately 1 minute for each inch of pipe diameter, based upon Schedule 40 pipe. Guillotine saws may weigh as much as 120 pounds and should be positioned by two operators.

3. Applications - Stationary

Large stationary hacksaws can be effectively used in decommissioning activities if a central cutting station is established. The station would be used to finish cut long lengths of pipe into shorter pieces for packaging and shipping. The determination of the effectiveness of a stationary hacksaw depends upon numerous site-specific variables. Included among these are the cost of labor, the quantity of material to be cut, the radiation levels of the material, and the worth of a person-rem. Locating the cutting station near the decommissioning activities will reduce the costs and exposures associated with rigging and moving long sections of pipe.

Large stationary hacksaws can weigh up to five tons and are not easily moved once installed. Cutting speeds of 14 in^2/minute in mild steel stock and 17 in^2/minute in pipe make them ideal for cutting large quantities of material. The saws have three phase electric motors of up to 40 horsepower. They can cut material as thick as 25 inches.

4. Cost Information - Portable Hacksaws

Pneumatic portable hacksaws cost approximately \$1500.00 for the basic unit with an additional \$250.00 for pipe clamps. Blade cost varies between \$7.00 and \$20.00, depending upon length and thickness. Blade lifetime varies depending upon the material being cut, use of a lubricant, and the cutting force on the blade. In general, one unlubricated blade will have an 8 hour lifetime cutting carbon steel and 3.5 hours for stainless steel, based upon a 50% duty cycle.

5. Cost Information - Guillotine Saws

Pneumatic guillotine saws cost from approximately $2500.00, for models that can cut 8 inch pipe, to $4400.00 for those that cut 24 inch pipe. Comparable costs for electrical units are $2000.00 to $3700.00. Blades cost from $5.00 to $15.00 and have a lifetime of 2 to 30 cuts, depending upon the material being cut and the cutting speed.

6. Cost Information - Stationary Hacksaws

Small manually operated units for cutting pipe of less than 8 inch diameter cost $15,000.00, while automated units that can cut up to 30 inch diameters cost $60,000.00. Blades cost from $30.00 to $175.00, depending on size.

8.3.6 Circular Cutting Machines

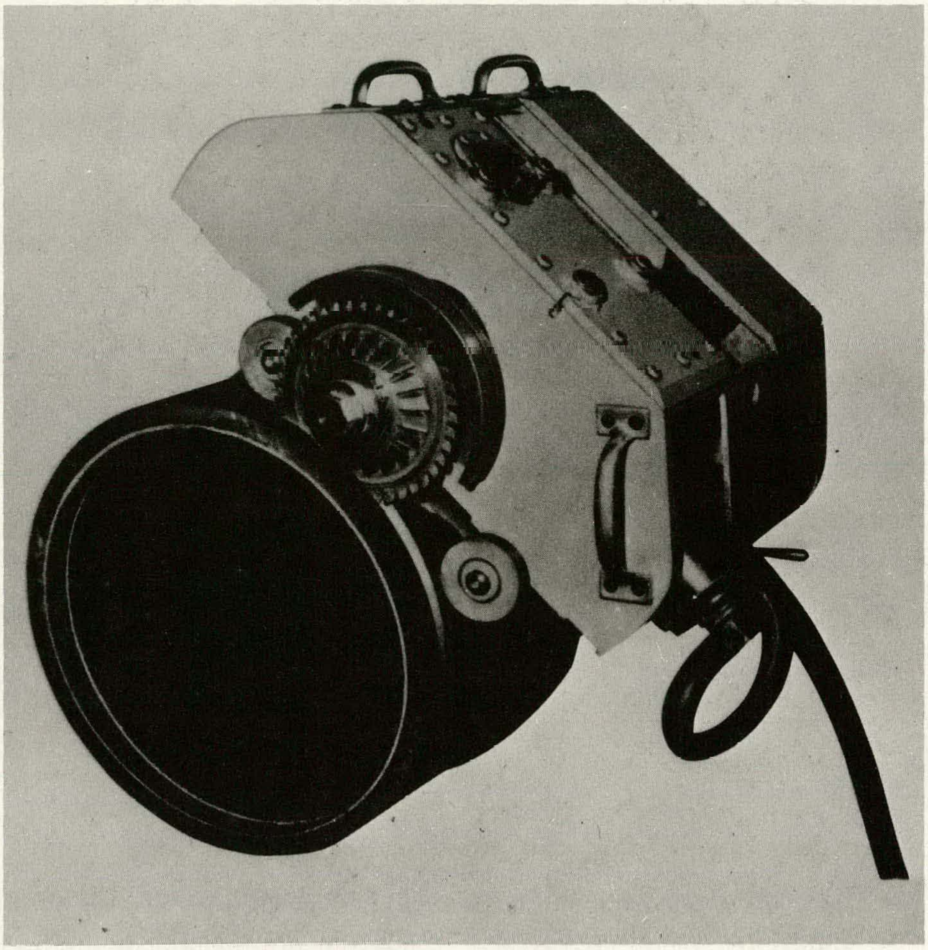
1. Description of Process

A circular cutting machine is a self-propelled circular saw that cuts as it moves around the outside circumference of a pipe on a track. The machine may be powered either pneumatically, hydraulically, or electrically and is held to the outside of the pipe or component by a guide chain that is sized to fit the outside diameter. A guide ring is available if very precise cuts are necessary.

The saw blades are made of hardened steel and their number may be varied to change the thickness of the cut. If a beveled cut is required, special cutters are available. Wall thickness of up to 3 inches may be cut on pipes with outside diameters ranging from 6 inches to 20 feet. Figure 8.3 shows a typical circular cutting machine in use.[6]

FIGURE 8.3

CIRCULAR CUTTING MACHINE



2. Applications

Historically, circular cutting machines have been used primarily for pipe weld preparation but they are an effective decommissioning tool for segmentation of pipe and round vessels. After positioning by one or two operators, they can be operated remotely to reduce exposure to personnel.

The maximum cutting depth in carbon steel is limited to 3/4 inch per pass. Multiple passes are necessary for thicker pipe wall thicknesses.

One unique advantage of circular cutting machines is their ability to reduce a pipe wall thickness to a minimum without cutting completely through. This allows final breaking of the pipe with a cold chisel and hammer, minimizing the intrusion of foreign matter into the pipe and reducing the spread of contamination.

Contamination control is maintained by vacuuming the chips from the cut, if required, and by collecting, filtrating and recycling cutting lubricants, if they are used. Since the cutting is by mechanical methods, there is little fire hazard.

Portable cutting machines require approximately 12 inches of radial clearance and 21 inches of lateral clearance. Weight is approximately 200 pounds.

For the steam generator replacement at Surry Unit 1, Virginia Electric Power Company is considering using circular cutters for cutting hot and cold leg reactor coolant piping. Since these pipes are eventually to be rewelded, the clean, straight cuts produced by the circular cutter are highly desirable.[1]

At the Garigliano BWR in Italy, a remotely controlled circular cutting machine was used in a 2.5 Rem/hr radiation field to make four cuts in two 24-inch-diameter, 3-inch-thick recirculation line safe ends. A similar machine had previously been used to cut out nine safe ends at the Gundremmingen Nuclear Power Station in the Federal Republic of Germany. The basic device consists of a split ring that is mounted on a pipe and located by four shoes that are clamped to the pipe by jack screws on the ring housing. Two cutting tools are carried on a rotating ring that is held in the main stationary ring by a split roller bearing. The motor is mounted separately and drives through a reduction gear box and a universal shaft to a stub shaft on the side of the ring housing.

Prior to its actual installation at Garigliano, the machine and cutting tools were tested on a full size mock-up at the site. Installation and cutting techniques were then determined in this non-radiactive environment in accordance with ALARA principles. During the work, the machine was controlled from a room where the radiation level was negligible. The work was monitored by two remote controlled TV cameras and an acoustic ultrasonic device. Total exposure was 9 man-Rem. A time summary for the actual cutting effort is as follows:

Installation time (machine on floor nearby and motor already mounted, crew of 4)	30 min
24 inch pipe cutting time	1 hour
Average cutting time to go through nozzle wall and thermal sleeve	6 hours
Machine removal time to adjacent floor (crew of 4)	20 min

The only difficulties experienced were in cutting the internal monel cladding in the nozzle (see Figure 8.4 and Reference 7).

3. Cost Information

The base cost for a circular cutting machine varies between $6,000 and $7,000, depending on whether it is electrically, pneumatically, or hydraulically operated. This includes enough chain for a 6 inch diameter pipe. Extra chain is approximately $4.00 per inch. Cutters for steel pipe range from $90.00 to $200.00 each, depending on the diameter and thickness of the cutter.

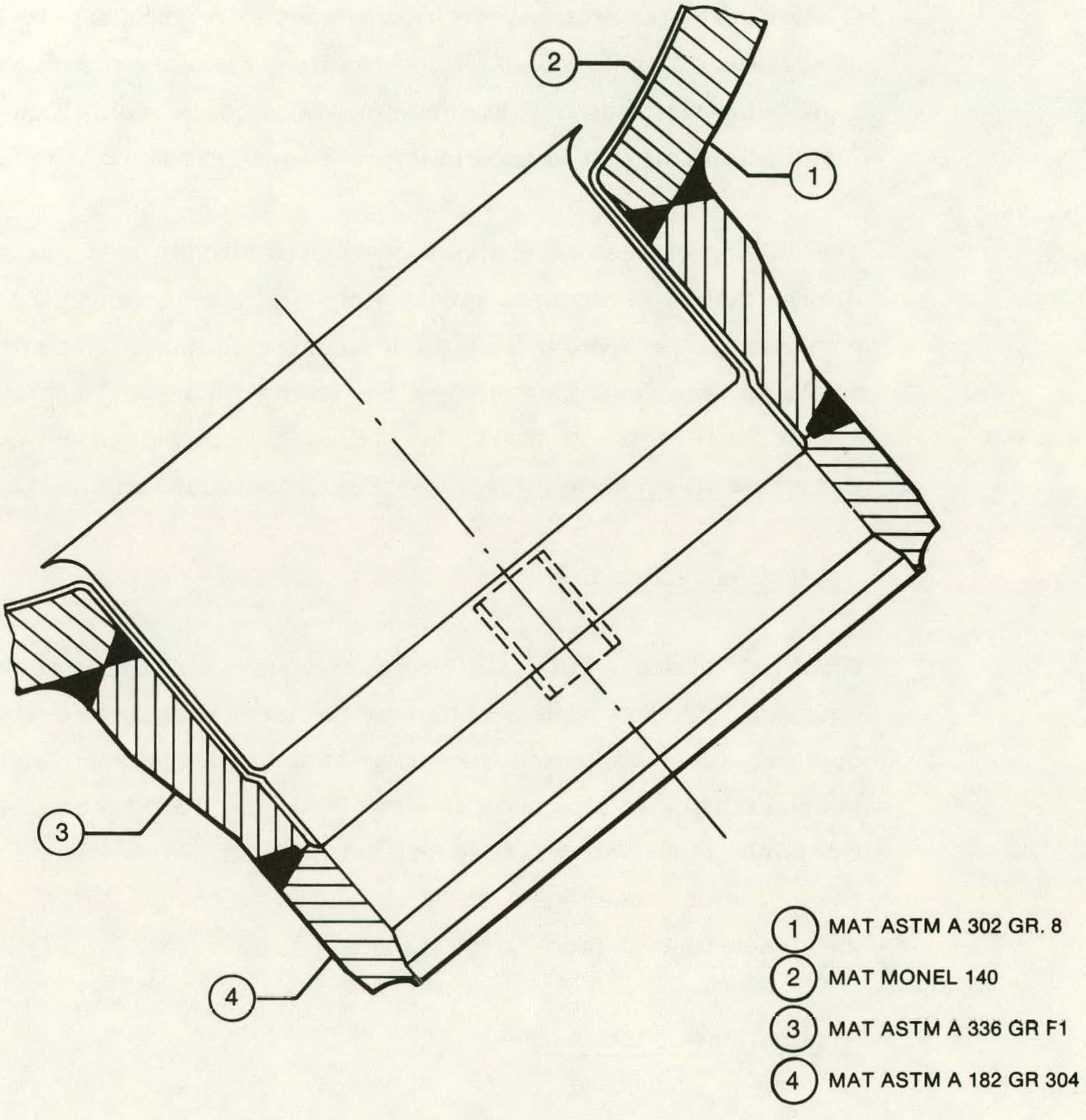
8.3.7 Abrasive Cutters

1. Description of Process

An abrasive cutter is an electrically, hydraulically, or pneumatically powered wheel formed of resin-bonded particles of aluminum oxide or

FIGURE 8.4

GARIGLIANO RECIRCULATION NOZZLE AND SAFE END



silicon carbide. Usually the wheel is reinforced with fiberglass matting for strength. It cuts through the workpiece by grinding the metal away, leaving a clear kerf.

Cutting rates for stationary abrasive wheels are approximately 1 in^2 of cut area every 7 seconds. Reported wear rates for wheels average 1 in^2 of surface area consumed for each square inch of cut area. Water lubricants can be used to improve wear resistance by 50%.

The cutting process generates a continuous stream of sparks making it unsuitable for use near combustible materials. Since the swarf particles are removed in very small pieces, contamination control is a significant problem. Cutters may be fitted with a swarf containment system that acts to limit the spread of contamination. Water lubricants also tend to limit the spread of contamination.

2. Applications - Portable

Hand-held abrasive cutters are relatively slow and require continuous operator attention. The reaction force of the workpiece against the operator for long periods is tiring and limits the applicability of manual cutting to pipe and components of less than 2 inch diameter. Contamination control is a significant problem. In most applications the operator would have to work within a contamination control envelope and wear protective clothing and respiratory protection.

3. Applications - Stationary

Abrasive cutters can be used in a stationary central work station concept. Here faster and more powerful machines can segment long sections of pipe into lengths suitable for packaging and shipping. A 30 horsepower unit is capable of cutting 6 inches of solid stock in two minutes. The spread of contamination is reduced in this more controlled environment by fitting the machine with a swarf containment hood and by using water as a lubricant.

As compared to the stationary hacksaw, abrasive cutters have similar cutting speeds and are approximately six times less expensive to purchase. When contamination control envelopes are used, the abrasive cutter's only disadvantage is that it can only cut through materials thinner than 8 inches.

4. Cost Information

The base cost for a 3 horsepower portable dry abrasive cutting unit is \$350.00; when equipped with water lubrication, the cost rises to \$725.00. The 10 inch diameter abrasive wheels cost \$5.00 each, when purchased in lots of 100.

The base cost for a 30 horsepower stationary, wet lubricated unit with a swarf containment system and dust collector is approximately \$10,000.00. The 26 inch abrasive wheels cost \$27.00 each when purchased in lots of 100.

8.3.8 Arc Saw Cutting

1. Description of Process

The arc saw cutting process is described in detail in Section 6.3.1(1). That discussion is completely applicable to the cutting of piping and components and is not included in this chapter.

2. Applications

Use of the arc saw cutting process as described in Section 6.3.1(2) is applicable to the cutting of piping and components with the following modifications:

- It is not practical to use an arc saw for in-situ segmenting of installed piping. However, a central cutting station system using an arc saw to segment long lengths of pipe and stock into shippable lengths may be a practical application.

The arc saw is ideally suited for the mass cutting of large quantities of pipe; a cost/benefit analysis must be performed to consider if the quantity of large diameter pipe to be segmented can justify the large initial capital investment of the system.

Determining if an arc saw is cost beneficial depends upon numerous site-specific variables. Included among these are the cost of labor, the quantity of material to be cut, the radiation levels of the material, and the worth of a man-rem. Locating the cutting station near the decommissioning activities will reduce the costs and exposures associated with rigging and moving long sections of pipe.

Since airborne contaminants will be produced by vaporization of the material being cut, it is recommended that arc saw cutting be performed within a contamination control envelope similar to that shown in Figure 6.3.

3. Cost Information

The cost information presented in Section 6.3.1(3) is applicable to the uses discussed herein.

8.3.9 Cutting with Power Nibbler and Shears

1. Description of Process

Nibbling and shearing processes are described in Section 6.3.7(1). That discussion is completely applicable to the cutting of piping and components and is not included in this chapter.

2. Applications

Uses of nibblers and shears are described in Section 6.3.7(2) and are applicable to the cutting of piping and components with the following addition:

In addition to the cutting of thin sheets of steel, the hydraulic shear has been modified by the Savannah River Laboratory for the cutting of small diameter piping underwater in high level waste storage tanks. While pipe outside diameters are limited to less than 2 inches, the device was effective in remotely shearing process piping.[8] In a similar application in Europe, a shear was modified to cut in-core instrumentation in a BWR.[9]

3. Cost Information

The cost information presented in Section 6.3.7(3) is applicable to the cutting of piping and components as described herein.

8.4 REFERENCES

1. Proceedings of a meeting between the Advisory Committee on Reactor Safeguards Subcommittee and Virginia Electric Power Company (January 23, 1980)

2. Product Information Bulletin, Explosive Technology, Fairfield, California.

3. Supplied by P. DeFranic of Jet Research, Arlington, Texas in a communication with F. Seymore of Nuclear Energy Services, Inc., Danbury, Connecticut (May, 1980)

4. Supplied by J. Whelan of Rockwell International Industrial Tool Division in a communication with F. Seymore of Nuclear Energy Services, Inc., Danbury, Connecticut (November, 1979)

5. Supplied by E.D. McGarthy of The F. Hallock Company, Derby, Connecticut in a communication with F. Seymore of Nuclear Energy Services, Inc., Danbury, Connecticut (January, 1980)

6. Product Information Bulletin, E.H. Wachs Company, Wheeling, Illinois.

7. Supplied by C. D'Anna of Ente Nationale per L'Energia Electrica, Rome, Italy in a communication with W.J. Manion of Nuclear Energy Services, Inc., Danbury, Connecticut (April, 1980)

8. Supplied by S.W. O'Rear of E.I. DuPont DeNemours & Company, Aiken, South Carolina in a communication with R. Bauer of Nuclear Energy Services, Inc., Danbury, Connecticut (February, 1980)

9. Supplied by I.G. Servol of Fiat TTC, S.P.A., Torino, Italy in a communication with W.J. Manion of Nuclear Energy Services, Inc., Danbury, Connecticut (April, 1980)

CHAPTER 9

DISPOSITION OF WASTES

9.1 INTRODUCTION

Large quantities of waste materials will be generated from the decommissioning of nuclear reactors, reprocessing plants and other contaminated facilities. Because the waste materials will exist in a variety of forms and contain varying levels of radioactivity, a detailed waste disposition program must be developed to ensure their safe, efficient, and economical handling and disposition.

This chapter has been prepared to provide information essential to the planning of a waste disposition program that meets the above criteria (safety, efficiency and economy). Planning a waste disposition program requires knowledge about the types of waste that exist in the facility, the mass/volume inventory of the waste that exists and will be generated by the decommissioning activities, suitable methods of processing and packaging both solid and liquid waste materials, and the appropriate disposal methods for each waste type. The topics covered in the chapter include:

1. Types of Waste, their Sources and Content
2. Classification and Estimation of Wastes
3. Methods of Processing Wastes
4. Packaging Requirements
5. Transportation/Disposal Requirements.

Where appropriate, the guides for classification, estimation and processing of wastes are presented in the form of procedures that identify the principal steps to be taken and analytical methods to be employed.

The packaging and transportation of radioactive materials are subject to issuance of appropriate licenses. Applicants for such licenses must demonstrate that the proposed packaging or modes of transport satisfy the requirements set forth in the Code of Federal Regulations. The packaging and shipping procedures outlined in this chapter encompass the requirements of 10 CFR 71 and 49 CFR 172 thru 178. *

These regulations prescribe allowable packaging and dictate shipping and labeling requirements for the waste based on form, quantity, radionuclide content, activity levels and surface dose rates. Estimates of the radioactivity content parameters are determined using the methods outlined in Chapter 4. These estimates are then categorized by form and quantity, using the procedures presented herein, to establish the overall waste packaging and disposal scheme.

9.2 TYPES OF WASTE, THEIR SOURCES AND CONTENT

Three types of waste material will be encountered in decommissioning activities: activated, contaminated, and non-contaminated waste material. The emphasis in this chapter is placed on the activated and contaminated materials since they present more significant handling, packaging and shipping problems.

9.2.1 Activated Waste Materials

For nuclear power or research reactor facilities, activated waste results from the direct neutron bombardment of materials in close proximity to the nuclear chain reaction. Essentially, all of the activated waste material in reactor facilities is contained within the reactor vessel itself, the internal structures of the vessel, and in the biological shielding that surrounds the vessel. Typically, these components contain the following materials:

1. Structural Materials

   Carbon steel, stainless steel, aluminum, reinforced concrete

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* There is a proposed revision to 49 CFR pending that will incorporate several changes to the noted parts, and introduces a new Part 127. Where applicable, the procedures account for the possibility that the changes will be adopted.

2. Shielding Materials

   Lead, heavy/light concrete

3. Internals Materials (other than structural)

   Zirconium, silver, cadmium, graphite, boron

A detailed listing of the individual radionuclides associated with the activated waste material is obtained by the radionuclide inventory analysis presented in Chapter 4.

9.2.2 Contaminated Waste Materials

For nuclear facilities such as nuclear power plants, fuel processing plants, fuel reprocessing plants, and research centers, contaminated waste material results from the disposition of radioactive material in or on the surfaces of facility components or structures. For example, the fluid systems in nuclear power plants directly or indirectly associated with the high temperature reactor coolant become contaminated when suspended corrosion products or dissolved particles, activated by the reactor core neutron flux, are deposited on the surfaces of the systems. Additional examples of facility components and materials that can become contaminated include:

1. Filter media, such as HEPA filter cartridges
2. Pool or cavity liners
3. Ventilation/electrical duct work
4. Surfaces of buildings and structure
5. Surfaces of concrete walls or slabs
   (up to several inches in depth)
6. Soil regions
7. Miscellaneous items such as rags, plastic sheeting and clothing.

Contaminated liquid wastes in nuclear power and fuel reprocessing plants usually result from activated materials being suspended and/or dissolved in the liquids. For example, in nuclear power plants the liquids associated with the high temperature reactor coolants can contain corrosion products that produce radionuclides such as ^{58}Co, ^{60}Co, ^{54}Mn, ^{51}Cr, ^{58}Ni, ^{65}Zn and ^{59}Fe. They also may contain fission products due to defective fuel that contributes radionuclides such as ^{90}Sr, ^{137}Cs, ^{131}I and ^{85}Kr. In general, approximately one-fourth of the activated corrosion products, especially iron and nickel, tend to be present in the liquid as suspended solids. The fission products tend to be present as dissolved solids.[1]

The presence of other contaminants in liquid waste is dependent on the type of facility and the source of the waste. Examples of the contaminants present in a fuel reprocessing plant are given in the Batelle study on the decommissioning of this type of facility.[2] The sources of liquid waste include system/equipment drains, system tank residuals, building and floor drain sumps, decontamination/flushing fluids, resin flushes, regeneration solutions, laundering activities and sludges from evaporator bottoms, spent resins and filters.

A detailed listing of the radionuclides associated with contaminated solid and liquid waste materials is obtained during the radionuclide inventory analyses as described in Chapter 4.

9.2.3 Non-Contaminated Waste Materials

Decommissioning also involves the handling and disposition of solid and liquid waste materials that do not contain radioactivity or contamination. Typically, the non-contaminated solid waste materials can include:

1. System piping and components
   (pumps, valves, tanks, heat exchangers, etc.)
2. Duct work and associated equipment

3. Cable trays and associated wiring
4. Electrical equipment
   (motors, generators, switchboards, panels, etc.)
5. Building and structure materials
   (concrete, beams, columns, siding, etc.)

The non-contaminated liquid waste materials can include:

1. Residuals from non-contaminated systems
   (condensate, potable water, service water, cooling water from auxiliaries, etc.)
2. Residuals from decommissioning activities
   (system flushes, chemical solutions, detergent solutions, etc.)

Both non-contaminated solid and liquid waste materials can be disposed of with conventional methods. The liquid wastes may, however, require pretreatment prior to disposal, particularly if the liquids contain significant chemical and/or detergent concentrations.

9.3 ESTIMATION OF WASTE MATERIAL

A major consideration in planning the decommissioning waste handling program for a nuclear facility is the quantity of waste requiring processing and disposal that will result from the decommissioning activities. Consequently, an accurate volume estimation of the waste material by type (activated, contaminated, non-contaminated) and by physical characteristics (compactible solid, non-compactible solid, liquid) is of major importance to the planning activity.

This section presents a general approach that can be employed to develop an accurate volume estimate of waste materials. This approach consists of the following activities:

1. Classifying facility systems and structures with respect to waste type (activated, contaminated, non-contaminated)

2. Developing a detailed mass/volume inventory of facility systems (equipment, piping, etc.) and structures
3. Determining the quantities and volumes of compactible solid wastes
4. Determining the quantities and volumes of non-compactible solid wastes
5. Determining the volume of liquid wastes.

The following sections present the principal steps to be taken for each of these activities. While certain steps might be considered obvious, all are included as a comprehensive overview.

9.3.1 Classification of Facility Systems/Structures

It is necessary to classify facility systems and structures by their radioactive status: activated, contaminated, or non-contaminated. This status characterizes the type of waste that will be generated as well as the treatment, handling, packaging and disposal requirements. The principal steps in a systematic classification of facility systems and structures are as follows:

1. Prepare detailed listing of facility systems and develop initial classification for each system.
2. Prepare detailed listing of facility structures and constituent structural elements (pool walls, foundation mat, turbine pedestals, etc.) and develop initial classification for each structure/structural element.
3. Assemble and review facility radiation survey data (area, surface and component contamination and dose levels) and radionuclide inventory data. This information is obtained using the methods and procedures outlined in Chapter 4.
4. Review operating history of facility (with operators, if possible or available) to determine if equipment failure, accidental spills or releases may have contaminated areas, surfaces and equipment.

5. Revise initial classification of structures and systems to reflect results of reviews performed in Steps (3) and (4).

9.3.2 Development of Facility Systems/Structures Inventory

A detailed mass/volume inventory of the facility systems and structures is a prerequisite to determining an accurate estimation of waste materials and their subsequent handling, packaging and disposal. The principal steps in performing a systematic mass/volume inventory of facility systems and structures are as follows:

1. For each facility system identified in the classification activity, list the system components (including piping) and obtain the data presented in Table 9.1 from facility documents and drawings. Table 9.1 lists the major components present in a typical nuclear power reactor system and identifies the principal data that should be obtained for each.
2. If weight information is not available for any system component, the weight can be estimated using the data in Table 9.2.
3. For each facility structure identified in the classification activity, list the structural elements by classification.
4. Develop dimensions/weights for structural elements using the information presented in facility documents and drawings.

9.3.3 Estimation of Compactible Waste Volume

Compactible solid wastes generally consist of items of a trash nature, such as rags, clothing, sheeting, etc., that are expended during the decommissioning activities. The volume of this type of waste can vary greatly depending on the type of facility being decommissioned, the extent of the decontamination effort, the size of the work force, etc.

TABLE 9.1

TYPICAL DATA REQUIRED FOR SYSTEM COMPONENT MASS/VOLUME INVENTORY

Components	Required Data
Piping	Pipe size and schedule Total length (by size/schedule) Material of construction
Valves	Valve size and schedule (pressure rating) Total number of valves (by size/schedule) Valve dimensions/weight Material of construction
Pumps	Type of pump Pump speed/flow rate Pump dimensions/weight Material of construction
Tanks/Ion Exchangers	Tank dimensions (inside diameter, length, wall thickness) Tank weight Material of construction
Heat Exchangers Steam Generators Evaporators	Type of exchanger Heat transfer area Pressure rating (both sides) Exchanger dimensions/weight Material of construction
Filters Miscellaneous Equipment	Type of filter/miscellaneous unit Filter (unit) dimensions/weight Material of construction

TABLE 9.2

INFORMATION FOR DEVELOPING PIPING AND COMPONENT WEIGHT ESTIMATES

1. PIPING

Information Required

1. Pipe sizes and schedules
2. Pipe lengths

Weight Data

Nominal Size OD, In.	Schedule No.	Approx. Weight, (lb/linear ft)
0-1	80	2
	160	3
2	40	4
	80	5
	160	8
3	40	10
	80	12
	160	15
4	40	12
	80	15
	160	25
6	40	20
	80	30
	160	50
8	40	30
	80	45
	160	75
10	40	50
	80	70
	160	120
12	40	55
	80	90
	140	140
	160	170
14	40	65
	80	110
	140	170
	160	190
16	40	95
	80	140
	140	225
	160	250
18	40	105
	80	175
	140	280
	160	310
20	40	125
	80	225
	140	350
	160	400
24	140	500
	80	300
	140	500
	160	550
large reactor coolant piping		900

TABLE 9.2
(Continued)

2. PUMPS

Information Required

1. Type of pump
2. Speed of pump motor
3. Pump flow rate

Weight Data

1. Vertical Single Step Centrifugal

	Up to 1000 gpm	1500 gpm	2000 gpm	3000 gpm
3350 RPM	350 lb	-	-	-
1750 RPM	540 lb	1000 lb	1300 lb	1500 lb

2. Single Stage Horizontal Centrifugal

	Up to 500 gpm	500-1800 gpm	2000-5000 gpm
3550 RPM	500 lb	750 lb	-
1750 RPM	800 lb	1000 lb	2000 lb

3. Two Stage Horizontal Centrifugal

	Up to 300 gpm	350-700 gpm	800-1100 gpm
3550 RPM	1100 lb	1500 lb	2300 lb

	500 gpm	750-1000 gpm	1500 gpm
1760 RPM	2300 lb	3900 lb	5000 lb

4. Multistage Horizontal Centrifugal

	Up to 300 gpm	300-600 gpm	700-900 gpm	1000-1500 gpm
3550 RPM	3500 lb	3800 lb	5100 lb	6500 lb

5. Vertical In-line Centrifugal (includes motor)

	Up to 200 gpm	200-500 gpm	600-800 gpm
3550 RPM	1000 lb	1650 lb	2200 lb

TABLE 9.2
(Continued)

6. Vertical Turbine Pumps (single or multi-stage)

	Up to 500 gpm	750-1500 gpm	2000-3000 gpm	4000-5000 gpm
1750 RPM	800 lb	1400 lb	1700 lb	2100 lb

	6000 gpm	7000 gpm	8000-10,000 gpm
1750 RPM	2800 lb	3000 lb	5600 lb

7. Reactor Coolant Pump

88,500 gpm
190,000 lb

3. TANKS

Information Required

1. Tanks inside diameter, tank length
2. Wall thickness

Tank Weight

Weight = (length of shell section) x (lb/ft factor for ID) + weight of 2 heads

NOTE: Weight is given in data table for a wall thickness of 0.5 inches. For thicker wall proportion factor/head weights accordingly.

Weight Data

ID, in	lb/linear ft	Weight, 2 heads	ID, in	lb/linear ft	Weight, 2 heads
24	165	350	90	585	4010
30	200	495	96	625	4550
36	240	705	102	660	5100
42	280	930	108	700	5725
48	315	1200	114	740	6360
54	355	1500	120	775	6950
60	390	1830	126	820	8500
66	435	2200	132	855	11170
72	470	2610	138	890	12200
78	505	3025	144	930	13270
84	550	3500			

TABLE 9.2
(Continued)

4. HEAT EXCHANGERS

Information Required

1. Exchanger surface, ft^2
2. Pressure rating of higher side

Weight Data

Exchanger Area, ft^2	Rating of Higher Side of Exchanger 150 psi	300 psi	450 psi
25	21 lb/ft^2	25	28
50	15	18	20
100	14	17	19
200	12	15	16
500	9	12	14
750	8	10	11
1000	7	9	10

5. ION EXCHANGERS
(Demineralizers)

If documented weight is not available, use TANK calculation method (see item 3) and add approximate weight of skid.

6. STEAM GENERATORS

Information Required

Heat transfer area (HTA)

Weight Estimation

S.G. Weight = (HTA)(20 lb/ft^2)

7. EVAPORATORS

Information Required

Heating surface area

TABLE 9.2
(Continued)

Weight Data

Heating Surface, ft^2	Weight, lb	Heating Surface, ft^2	Weight, lb
4	3000	100	20000
10	5000	140	24000
35	7000	180	36000
70	15000	225	50000

8. FILTERS

Information Required

Dimensions needed to calculate volume (e.g. Diameter, Height)

Weight Estimation

Filter Weight = (Filter Volume, ft^3)(180 lb/ft^3)

9. MISCELLANEOUS EQUIPMENT

Information Required

Dimensions needed to calculate volume

Weight Estimation

Equipment Weight = (Equipment Volume)(200 lb/ft^3)

10. COMPACTIBLE WASTE

Information Required

Uncompacted waste volume

Weight Estimation

1. Determine the compacted volume of contaminated compactible waste:

   $$\text{(compacted volume)} = V_{trash} \div \text{reduction factor}$$

   A reduction factor of 5 is typical for the conventional compaction equipment. The factor should be adjusted as required to reflect the efficiency of the actual compaction process. A reduction factor of 10 is typical for the incineration process (see Section 9.4).

TABLE 9.2
(Continued)

2. Determine the number of 55-gallon drums required for the compacted volume:

   (number of drums) = (compacted volume) ÷ (7.3 ft^3 per drum)

   It is assumed that the total compacted volume can be distributed evenly among the drums. If this is not possible, a suitable adjustment must be made. Each drum will weigh about 220 lbs (based on an average compaction density of 30 lbs/ft^3).

9.3.4 Estimation of Non-Compactible Solid Waste Volumes

Most of the solid wastes resulting from decommissioning activities are comprised of materials that cannot be readily compacted. These materials consist primarily of structural concrete, structural metals, equipment, and components. The purpose of the section is to provide guidance for estimating the volumes of these items.

1. Volume of Concrete/Metal Structural Elements

   The following steps can be used to estimate the structural concrete and metals that will result from facility decommissioning:

   A. Using the inventory information developed for the facility structures (see Section 9.3.2), list the concrete structural elements that have been classified as activated and the associated dimensions and weight data. Repeat this step for the concrete structural elements classified as contaminated and non-contaminated.

B. Estimate the volume for each concrete structural element classified as activated using the information from Step A. Sum the individual concrete structural element volumes to obtain the total activated concrete volume.

C. Estimate the surface area of each concrete structural element classified as contaminated using the information from Step A. Sum the individual areas and use an assumed 2 inch depth to obtain a conservative estimate of the total concrete volume classified as contaminated.

D. Estimate the volume of each concrete structural element classified as non-contaminated using the information from Step A. Add to the sum of these individual volumes, the concrete volume of the subsurface sections identified in Step C which are not contaminated.

E. Repeat Steps A through D, as applicable, to obtain the volumes/weights of other activated, contaminated and non-contaminated structural members.

2. <u>Volume of Piping</u>

The following steps can be used to estimate the volume of contaminated piping that will be dismantled during facility decommissioning:

A. Using the inventory information developed for the facility systems (see Section 9.3.2), tabulate the total length of each piping size in each contaminated system.

B. Calculate the total volume (by piping size) of the contaminated piping by multiplying the total lengths by the appropriate cross-sectional area as designated in Table 9.3.

C. Calculate the approximate packing volume by multiplying the total volume for each pipe size by the appropriate packing efficiency factor as designated in Table 9.3. The total volume and packing volume for non-contaminated piping can be obtained in the same manner.

TABLE 9.3
PACKING VOLUME OF PIPING

Size, OD (in)	Cross-Section Area, ft^2	Packing Efficiency Factor
0 - 2	0.031	1.4
4	0.110	1.5
6	0.240	1.5
8	0.406	1.6
10	0.630	1.6
12	0.887	1.8
14	1.07	1.8
16	1.40	2.0
18	1.77	2.0
20	2.18	2.0
24	3.16	2.0

The packing efficiency factors are used to reflect the fact that not all the useable container space can be occupied by piping; thus, the actual burial volumes may be somewhat larger than volumes of piping.

For example, 100 feet of 6-inch OD pipe would result in a volume of $24ft^3$, but this would result in a packing volume of 36 ft^3 (i.e., 24 ft^3 x 1.5). In reality, however, it may be possible to reduce the total packing volume by nesting smaller piping within larger piping.

3. Volume of Components and Equipment

The volumes of components and equipment will vary greatly depending on the physical characteristics of the objects and whether the objects are segmented. The following general procedure should be followed in arriving at an estimate of the volumes of facility components and equipment:

A. Using the inventory information developed for the facility systems/structures, list the facility components and equipment that have been classified as activated. Repeat this step for components/equipment classified as contaminated and non-contaminated.

B. Evaluate each component or equipment item to determine if it can be segmented (see Chapter 6 for cutting methods) and if its contamination status indicates it should be segmented to simplify handling, packaging and disposal. Segmenting may not be applicable to many non-contaminated components or equipment since they may be reused, converted or sold for salvage.

C. If applicable, estimate volume of component after it has been segmented.

9.3.5 Volumes of Liquid Waste Materials

The following general procedure can be used to arrive at an estimate of the volumes of liquid wastes that will require processing or treatment:

1. Determine the volume of residual liquids in all tanks and piping. Include the residuals in contaminated systems and those in non-contaminated systems, if they cannot be directly released to the environment. Residual liquids should be classified according to the categories identified in Section 9.5.1 of this chapter (e.g. high purity, low purity, chemicals, detergents, sludges) in order to establish required treatment.
2. Calculate the total volume of decontamination and rinse/flush fluids for each system. Depending on the process, this may vary from 1 to 5 system volumes.[3]
3. Sum volumes of liquids obtained in Steps 1 and 2 above to establish the liquid waste volume prior to treatment.
4. Classify the decontamination, rinse and flush liquids for each system in accordance with the categories identified in Section 9.5.1. If decontamination involves chemical solutions (e.g. HCl), the resulting fluids would form chemical wastes. If the decontamination process involves simple flushing, the resulting fluids would form high or low purity wastes. If a detergent is used, the waste fluid would also be classified as a detergent.

5. Select treatment method for each residual, decontamination, rinse and flush liquid. Estimate volume of residue following treatment of each liquid. Sum volumes of residues to establish total liquid waste volume needs.

9.4 TREATMENT OF SOLID WASTES

9.4.1 Compactible Solid Wastes

Compactible solid wastes are primarily processed by either of two methods: compaction or incineration. Incineration is a viable process since up to 90% of the compactible wastes are also combustible. Brief descriptions of each process are presented in the following sections.

1. Compaction Process

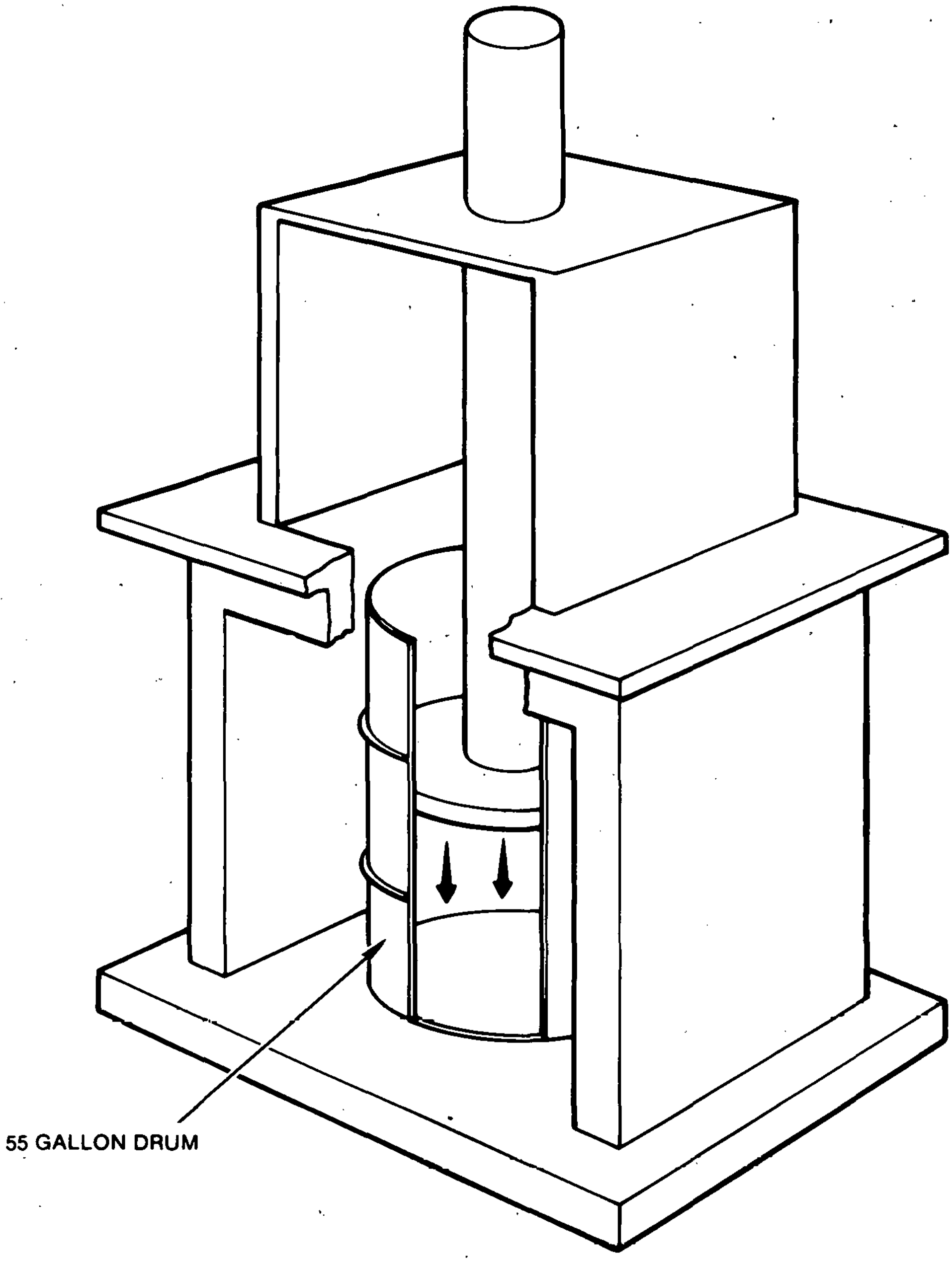
The compaction process is generally accomplished with a drum compactor of the type shown in Figure 9.1. A steel shipping drum (typically the standard 55 gallon drum) filled with compactible solid waste is placed on the compactor platform and the compactor disc is hydraulically rammed into the drum. The process is repeated until the drum is filled. These compactors operate on hydraulic pressures ranging from 10,000 to 30,000 psi and can achieve a volume reduction factor of about 5. At that volume reduction, each drum will contain approximately 220 lb of waste material.

2. Incineration Process

Incineration is essentially the controlled burning of combustible solid waste. In this process, air (usually preheated) is fed into a combustion chamber where the combustible waste is burned. The ash that results from the burning is kept in the chamber by the low flow rate of heated air. This ash retains up to 99% of the original radioactivity in the combustible waste while at the same time presents a volume that is only 1/10th of the original combustible waste volume. A typical incineration system is shown in Figure 9.2.

FIGURE 9.1

TYPICAL WASTE COMPACTOR (SIMPLIFIED)



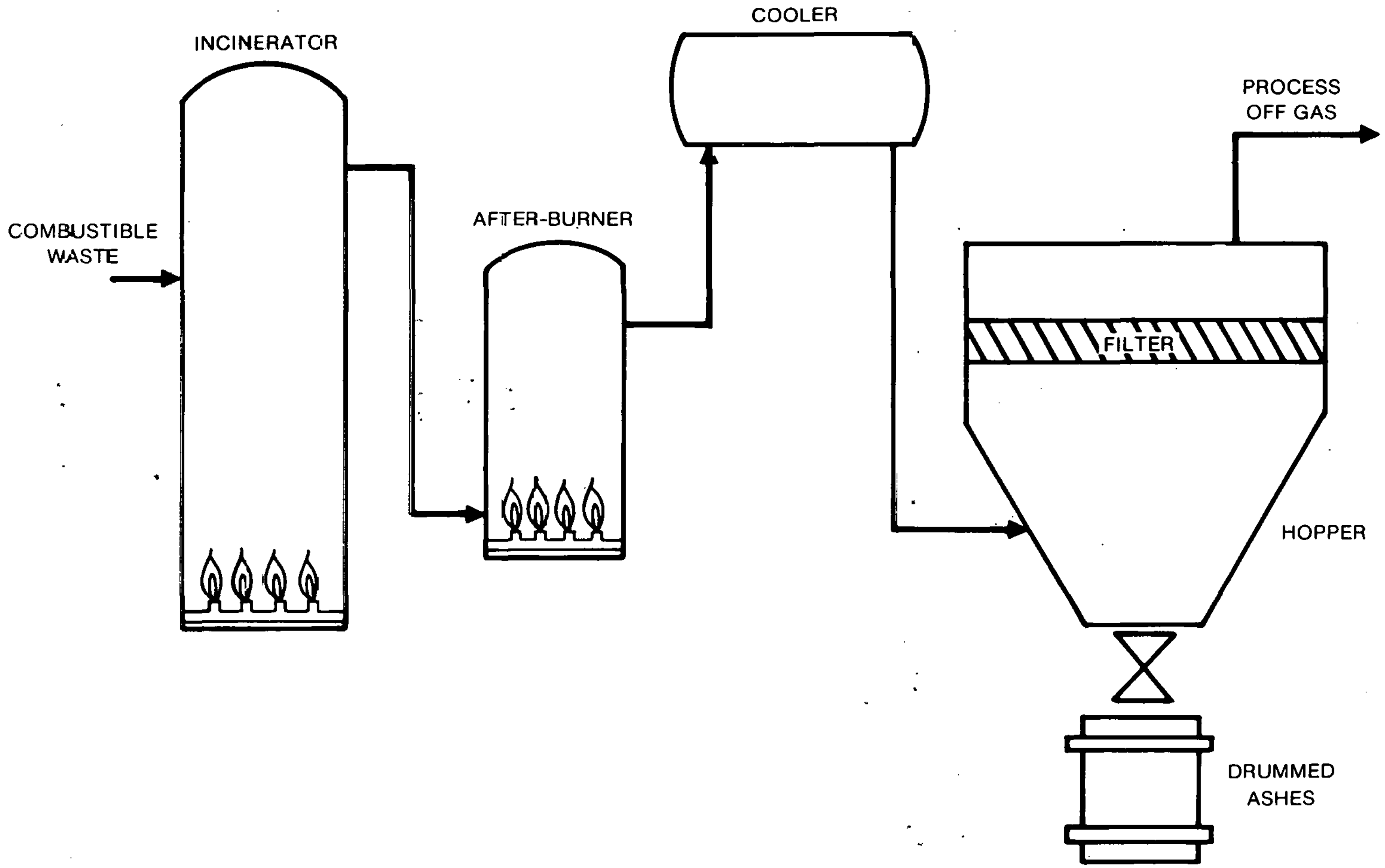


FIGURE 9.2

INCINERATOR

An additional consideration with the use of incineration is the treatment of the gaseous effluent produced by the burning process. Effective treatment of this effluent is achieved by the use of HEPA filters to remove any particulate activity. After filtration, the gas must be sampled and analyzed to determine if the activity levels are below the maximum allowed for release.

9.4.2 Non-Compactible Solid Wastes

A variety of non-compactible solid wastes will be generated during decommissioning. These non-compactible solids have been divided into the following representative groups to illustrate the principal methods of treatment and packaging:

1. Building concrete
2. System piping and components
3. Reactor vessel and internals

1. Concrete Solid Waste

During the course of decommissioning, several activities will result in the generation of large volumes of contaminated and non-contaminated concrete solid waste or rubble.

Because washing techniques are generally not effective in removing concrete contamination (particularly when the contamination has penetrated to a depth of several inches) a surface layer of the concrete itself must be removed by scarifying. Several methods used to scarify concrete surfaces are presented in Chapter 7.

The complete removal of concrete structures creates the second major source of concrete waste. Basically the concrete is fractured into rubble by one or more of the methods described in Chapter 7, and the exposed reinforcing bar, if any, is cut.

In general, concrete waste material requires no further processing and can be disposed of by one or a combination of the following methods:

A. Packaged and shipped for burial at a low-level radioactive waste disposal site, if the concrete is contaminated or activated.
B. Transported to a nearby landfill site, if the concrete is not contaminated.
C. Used as backfill during site reclamation, if the concrete is not contaminated.

The sequence of activities required for disposition of concrete solid wastes is presented below:

A. Prepare the volume estimates of activated, contaminated and non-contaminated concrete using the guidance presented in Section 9.3.4(1).
B. Using the methods presented in Chapter 4, establish the radioactivity level of the activated concrete. In classifying the facility structures, activation analyses were performed to establish the activated regions of the facility structures and the radioactive inventory in these regions (see Chapter 4). These analyses are used to determine the radioactive level of the activated concrete.
C. Estimate the packaging volume required for the activated concrete waste using the following formula:

Volume of packaging required
for activated concrete rubble   Volume of Concrete * x 1.67

Because concrete demolition generally results in a <u>less</u> compact volume, the volume of packing required will be greater than the

---

* From Step A * above.

original volume of concrete. A factor of 1.67 provides a reasonable and conservative estimate of the generated concrete rubble volume.[4]

D. Using the methods and guidance presented in Section 9.6 of this chapter, choose an appropriate package based on radionuclide inventory, activity level, etc. Typically, activated (and contaminated) concrete is packaged in steel boxes/drums because of weight considerations. Packages of the type are illustrated in Section 9.6 and Appendix A.

E. Determine if the chosen package satisfies external dose limitations using the methods presented in Section 9.6 and Appendices A and B. If the dose rate exceeds limitations, consideration should be given to the use of shipping casks, overpacks, etc.

F. Determine the number of packages required to ship the activated concrete.

G. Ship packages to disposal sites using the guidance presented in Section 9.7.

H. Repeat Steps B through G for the disposal of contaminated concrete waste.

I. Repeat Step C to determine the disposal volume for non-contaminated concrete. Generally, this material is simply trucked to backfill and/or landfill sites.

2. Piping and Components

To facilitate packaging and shipping, facility piping and large components classified as contaminated are usually segmented. Methods to physically perform the cutting employ mechanical, flame, arc and explosive techniques that are discussed in detail in Chapters 6 and 8. Usually more than one technique must be employed to obtain the component segments and sizes compatible with shipping and handling restrictions. The sequence of activities required for the disposal of facility piping and components is presented below.

A. Prepare the inventory of activated, contaminated and non-contaminated piping using the guidance in Section 9.3.4(2).

B. Using the methods presented in Chapter 4, establish the radioactive level of the activated piping.

C. Select the segmenting scheme for the activated facility system piping using the following guidelines in conjunction with the segmenting techniques presented in Chapters 6 and 8. The selection of segment size to facilitate the packaging and shipping of activated piping to a waste burial site is governed by three general constraints:

(1) Curie Content

The regulations at the available waste burial sites place limits upon the total curies per shipment arriving for burial (among other things). A typical value for this limit is 50,000 curies, but each location must be consulted for the exact value. This limit must be taken into consideration when choosing a segment size, especially for highly activated material, so that the total number of curies in one package will be in compliance with the limitation. The curies present in the activated items are determined according to the methods described in Chapter 4.

(2) Package Size

When activity levels are sufficiently low, the size of the piping segment will not be limited by the number of curies contained. Consequently, the segment size should be chosen so that it will "fit" suitably into available containers or packages. A segment length of ten feet has been found to be convenient for piping that is not curie-content-limited.

(3) Weight of Package

The total weight of segmented piping to be placed in a package should be appropriate for the package chosen. Specific information on weight limitations can usually be obtained from the package or container manufacturer. However, Table 9.4 presents guidelines that can be used to select segment sizes.

TABLE 9.4

APPROXIMATE WEIGHT OF CONTENTS FOR USE IN SEGMENT SIZE DETERMINATION

LSA materials less than Type A curie quantities:	
Steel boxes	10,000 lb
Wooden boxes (steel-strapped)	3,000 lb
Materials of Type A quantities:	
Disposable cask liners	10,000 lb
Steel boxes	5,000 lb
Wooden boxes	400 lb

D. Determine that the packaging chosen for compatibility with the segmentation scheme satisfies external dose limitations using the guidance/methods presented in Section 9.6 and the associated Appendices. If the dose rates exceed limitations, considerations should be given to changing the size/content of package to the use of overpacks, etc.

E. Determine the total packaging requirements for the activated piping (number and weight of packages required to dispose of all activated piping).

F. Ship packages to waste burial sites using the guidance presented in Section 9.7.

G. Repeat Steps B through F for the disposal of contaminated piping. Additional considerations apply to contaminated piping.

TABLE 9.4
(Continued)

(1) Generally contamination within a facility system is distributed over the internal surfaces of the system. It is, therefore, reasonable to assume that equal area piping segments contain equal activity unless otherwise indicated by the radiological survey.

(2) For typical nuclear facilities, the contaminated piping does not contain activity levels high enough to be the limiting concern in packaging unless otherwise indicated by the radiological survey. Consequently the segmentation scheme would be selected by package size/weight limitations.

H. Repeat steps B through F for the disposal of activated and/or contaminated facility components (see Section 9.4.2(3) for disposal of reactor vessel and internals). While it is expected that most facility components will require segmentation to facilitate packaging and disposal, it is evident that smaller components such as valves and pumps may be packaged together or singly without segmenting.

3. Reactor Vessel/Internals Solid Waste

The radiation exposure levels of the reactor, vessel and internal components are significant and require the use of remotely operated cutting tools to segment the vessel and internals either under water or with the use of temporary shielding. Several segmenting techniques have been developed, including the plasma arc torch and the arc saw. A complete description of each technique is presented in Chapter 6.

While the sequence of activities required to dispose of the reactor vessel and internals solid waste material is similar to that presented for the disposal of activated/contaminated piping and components, the high curie content of the activated reactor vessel and its internals impact the disposal activities as follows:

A. A more detailed and accurate analysis of the activation history and component composition and weight is required. This analysis is performed as part of the radionuclide inventory determination described in Chapter 4.

B. The cutting/segmenting of the vessel and its internals require the use of remotely positioned and operated cutting tools as well as the use of shielding mediums.

C. Remote and shielded handling of segments is required.

D. Shipping casks may be required for segment shipment. Cask liners are used to facilitate handling of the segment(s) including transfer into and out of the cask and as the burial container.

E. Significant external radiation dose levels for casks may require the use of supplementary shielding.

F. Burial ground and transportation restrictions are stringent.

The sequence of activities required to dispose of the reactor vessel and internals solid waste is as follows:

A. Identify activated regions of reactor vessel and internals.

B. Determine vessel/internals composition and weights by individual structures or regions.

C. Determine radionuclide inventories of vessel/internals by individual structures or regions.

Note: Items A through C are described in detail as part of the analysis in Chapter 4. The completed analysis will provide the composition, weight and curie count for each component, and these can be applied directly in the determination of segment size, packaging, etc.

D. Establish segmenting schemes. The segmenting schemes must be defined to satisfy the individual cask or box loading requirements. These loading requirements are subject to the following constraints:

(1) Curie Content

Regulations at the avaiable waste burial sites place limits upon (among other things) the total curies per shipment arriving for burial. (A typical value for this limit is 50,000 curies, but each site should be consulted for the exact value.) This limit must be taken into consideration when choosing a segment size, especially for highly activated components or structures, so that the total number of curies in one package will be in compliance with the limitation. The curies present in the activated components are determined according to the methods described in Chapter 4.

(2) Package Size

When activity levels are sufficiently low, the size of the component or segment will not be limited by the number of curies contained. Consequently, the segment size should be chosen so that it will "fit" suitably into available containers or packages. Thus, segments can be as large as available packaging as long as they do not exceed curie or weight limits.

(3) Weight of Package

The total weight of components or segment to be placed in a package should be appropriate for the package chosen. Specific information on weight limitations can usually be obtained from the package or container manufacturer. However, Table 9.4 presents guidelines that can be used to select segment sizes.

(4) Total Weight of Shipment

The typical total load limit per shipment (including the vehicle) is 73,800 pounds in most states. However, with the approval of the individual states, this can be extended to 105,000 pounds.

E. Choose appropriate casks, liners or other container. This step may require a reiteration of segment size.

F. Verify by using the methods and criteria of Appendix B, that the resultant dose rate from the container plus segment is within limits for transport (see Section 9.6).

G. Determine, based on the total number of components or segments, the total number of shipments required for disposal.

H. Ship to burial site.

9.5 TREATMENT OF LIQUID WASTES

Most of the liquid wastes resulting from decommissioning activities contain relatively small quantities of radioactive and/or chemical contaminants. The first objective of liquid radwaste treatment is to reduce the volume of liquid waste that must be disposed of as radioactive or toxic materials. This objective is achieved by using treatment methods that separate the waste liquids into two constituents: a minimum volume residue that contains essentially all of the radioactive and/or chemical contaminants, and the treatment effluent, which is essentially non-contaminated and non-toxic as defined by federal regulations.

The second objective of liquid waste treatment is to place the residue in a form suitable for shipment and acceptable for disposal at a commercial waste burial facility.

The treatment effluent can normally be released by conventional methods, e.g., dilution of effluent in water bodies at or near the decommissioning site, because the contaminant levels in the effluent are less than the maximum permissible concentrations established by federal and/or state regulations.

The degree of treatment and the associated methods required to reduce the liquid waste volume requiring special disposal depends on the quality of the untreated liquid waste material. Clean or high purity wastes may require only one treatment method (e.g., filtration) to produce a satisfactory effluent that can meet the requirements for release. Liquid waste materials or detergents may require a sequence of treatments to produce an effluent suitable for unrestricted release and a significant reduction in the waste volume requiring special disposal.

Because water-based liquids form the overwhelming percentage of liquid waste materials, the emphasis in this section is placed on water-based liquid materials and the most commonly applied treatment methods. The solidification methods most commonly used to place treatment residues into a form suitable for shipment and final disposal (as well as two recognized alternative methods) are also described in this section.

9.5.1 Classes of Water-Based Liquid Waste Materials

As stated previously, the degree of water treatment and the methods used depend upon the quality of the waste material and the type of contaminant (radioactive, chemical, dissolved/suspended). The following classification of liquid wastes is used to characterize the quality of the waste material and the type of contaminant:

1. Low Conductivity Liquids

   Water of generally high purity, with a relatively low activity content. These liquids are normally considered clean wastes and are obtained from known and controlled sources, such as equipment drains and tank residuals.

2. High Conductivity Liquids

   Water of generally low purity, with a high activity and/or a high dissolved or suspended solids count. These liquids are normally considered dirty wastes and are obtained from controlled or uncontrolled sources, such as building and floor drains.

3. <u>Chemical Liquids</u>

Liquids of low purity containing chemical solutions. The liquids are usually produced by laboratory analyses, decontamination activities, resin flushes and regeneration. These liquids are normally considered to be dirty.

4. <u>Detergents</u>

Liquids with generally low levels of activity that contain detergent solutions generated by decontamination flushing, laundering, handwashing, etc. These liquids are also classified as dirty.

5. <u>Sludges</u>

Concentrated wastes or waste slurries obtained from, for example, evaporator bottoms, spent resin sludges and filter sludges. Generally, these sludges are the results of previous liquid waste processing. They are solidified without further processing.

9.5.2 Methods of Liquid Waste Treatment

The principal methods used to treat the liquid waste materials resulting from decommissioning activities include the following:

1. Filtration
2. Neutralization
3. Evaporation
4. Ion Exchange

These methods are applied in various sequences and combinations to treat the different classes of liquid wastes. Figure 9.3 summarizes the primary and secondary methods of treatment that are suggested for each class of liquid waste. Figure 9.3 is based on methods recommended in References 5 and 6.

9.5.2.1 Filtration

Filtration is defined as the separation of undissolved, particulate, suspended solids from a fluid mixture by passage of the fluid through a septum or membrane that retains the solids on or within itself. The mixture to be separated is called the prefilt, the fluid that passes through the septum is called the filtrate, and the septum is called the filter medium. When the separated solids accumulate in amounts that cover the medium, they are called the filter cake.

Filtration is used first to remove undissolved solids (i.e., particulate radioactive matter) from liquid waste streams before further processing. By removing suspended solids prior to the evaporation and demineralization treatment methods, the evaporator will be less subject to fouling (by the formation of deposits), and the capacity of the demineralizer ion exchange resin will be extended.

1. Filter Media

The choice of filter medium is the most important consideration in ensuring efficient operation of a filter. The filter medium is selected primarily for its ability to retain the solids without plugging and without undue "leakage" of solid particles through the medium. The medium should also display, in varying degrees, the following additional characteristics:

A. Ability to bridge solids across its pores
B. Minimum resistance to flow

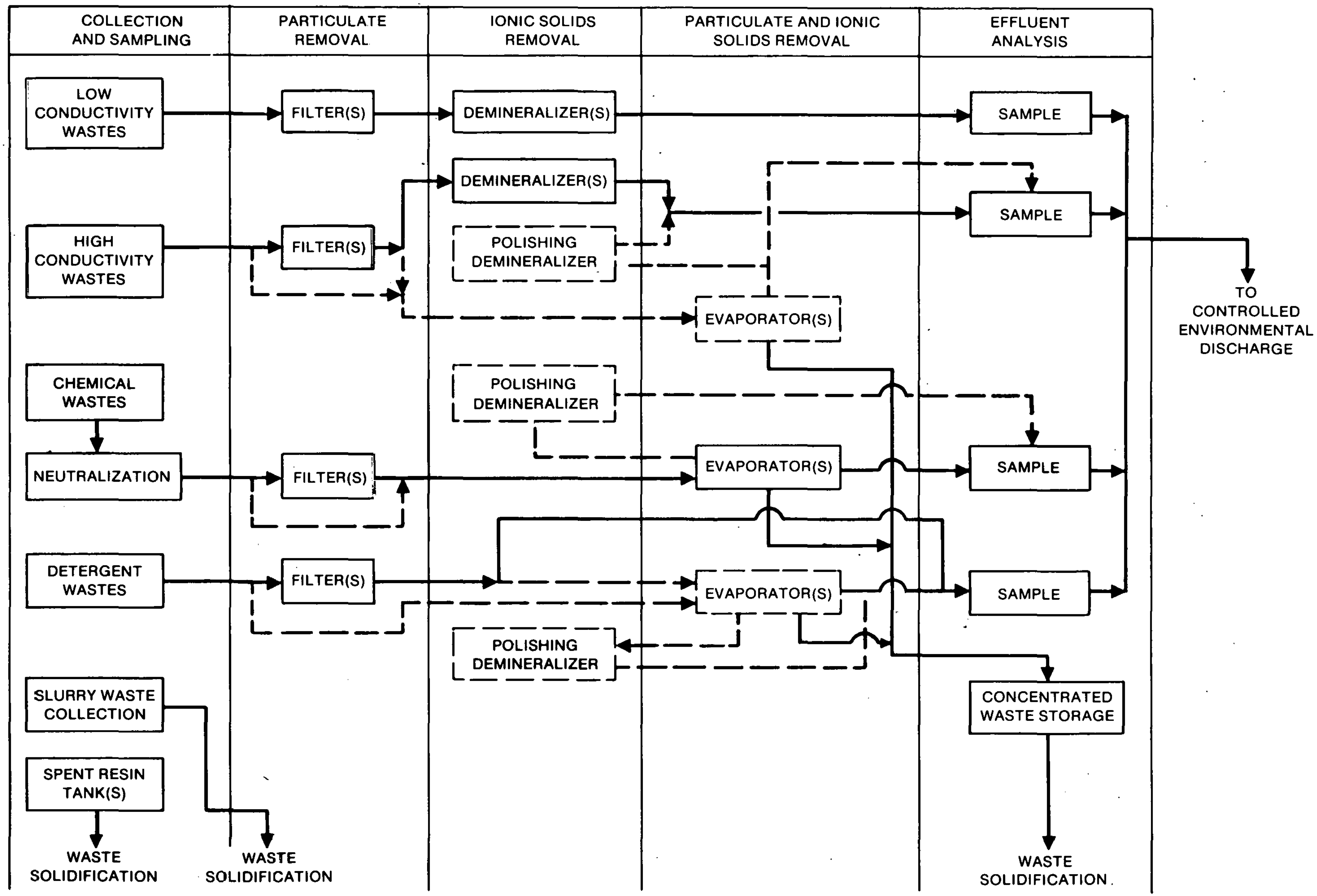


FIGURE 9.3

BASIC LIQUID RADIOACTIVE WASTE PROCESSING

C. Sufficient strength to withstand the filtering pressure and mechanical wear

D. Resistance to chemical attack

E. Smooth surface to facilitate discharge of cake if required.

Filter media are manufactured from cotton, wool, polyester, glass fiber, porous carbon, metals, and other miscellaneous materials. Filtration rates can be increased by precoating the filter media with a material containing large, non-compressible particles such as diatomaceous earth.

2. Filtration Equipment

Numerous types of filtration equipment exist, such as cake filters, vacuum filters and pressure filters. Pressure filters, however, are the most suitable type for this application and will be the only filters discussed here.

Pressure filters are those that operate at a pressure greater than atmospheric at the filtering surface. The advantages of this type of filter are: high filtration pressure permits rapid filtration and enables difficult separations; large filtration area relative to the space occupied by the filter; greater flexibility.

The filter medium is usually in the form of cartridges, tubes or wire elements, and is contained inside a pressure vessel. A typical filter of this type is illustrated in Figure 9.4.

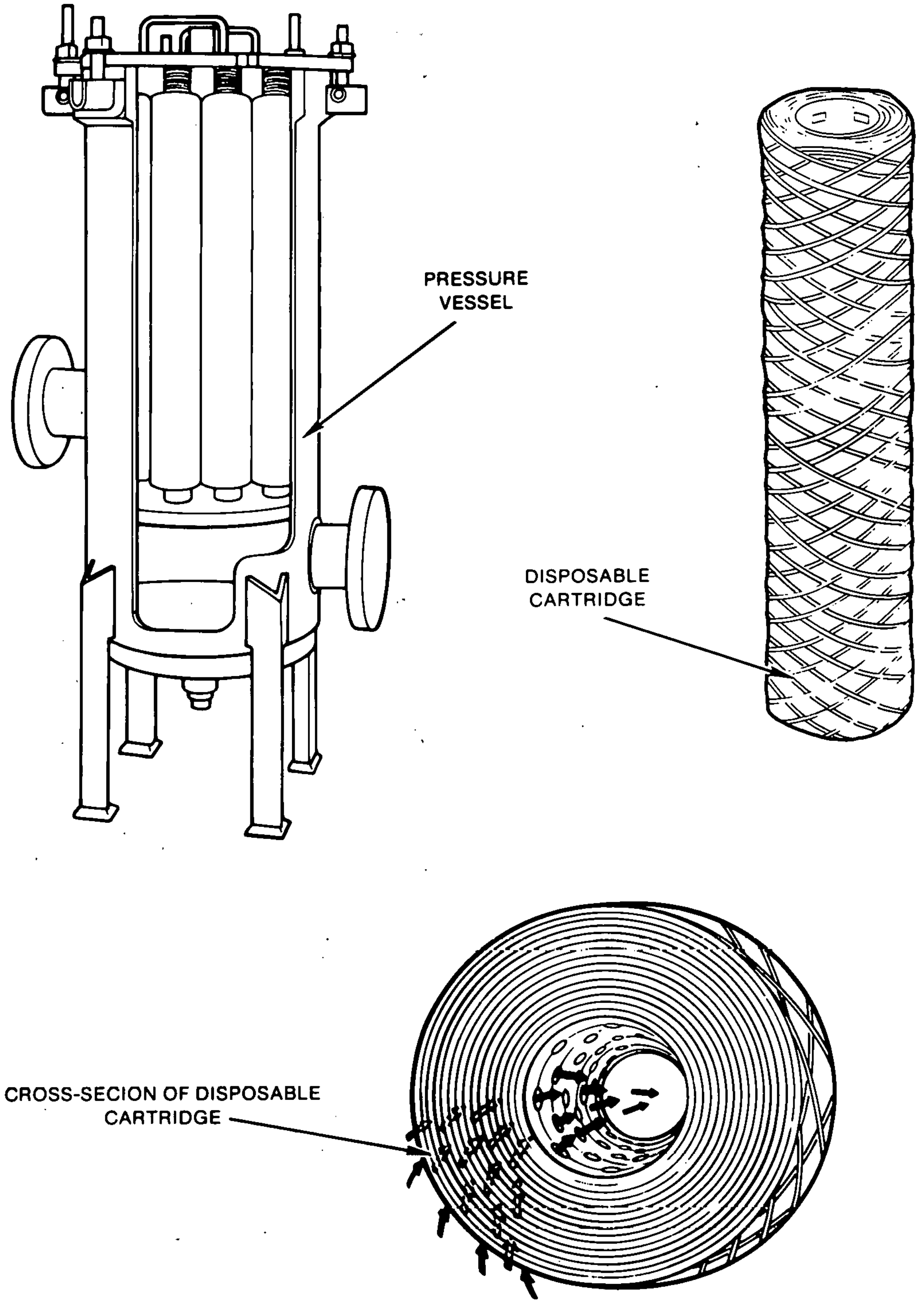
9.5.2.2 Neutralization

When chemical methods are employed for internal and external surface decontamination (see Chapter 5), the various chemical solutions and subsequent water flushes produce wastes that may require neutralization prior to subsequent treatments.

FIGURE 9.4

TYPICAL CARTRIDGE FILTER

Source: The Carborundum Company



Neutralization is accomplished by combining an acidic solution with a basic solution, which produces a salt plus water. A variety of acids and bases are suitable for decontamination, depending on the surface and its expected contaminants (see Chapter 5). Consequently, the neutralizing agent must be selected to match the decontamination agent. For example, if hydrochloric acid (HCl) is used in the decontamination process, the appropriate base neutralization agent is sodium hydroxide (NaOH). Methods of determining the requirements for neutralization are presented in standard chemistry handbooks.[7]

9.5.2.3 Evaporation

Evaporation is used in the removal of both dissolved and suspended solids over a wide range of concentrations. In the process, volatile and non-volatile components of a feed stream solution are separated by boiling away the volatile component, which is primarily water in water-based waste material. As the volatile component is vaporized, the liquid waste residue becomes more concentrated. Steam is usually used as the method of adding heat to the evaporator solution to vaporize the water. This steam is produced either electrically or by an oil-fired boiler. While evaporators generally treat liquid wastes in batch form, capacity is defined in terms of the volume of liquor evaporated per unit time. Typically, nuclear power plant radwaste evaporators have capacities ranging from 5 to 20 gpm.

1. Evaporator Effectiveness

The effectiveness of an evaporator is usually measured in terms of the decontamination factor for either gross activity or for a specific isotope. The decontamination factor, (DF) is the ratio of the activity concentration in the feed to the activity concentration in the condensed vapor. DF values for liquid radwaste evaporators at several PWR and BWR nuclear power plants have been reported to be 10^4 for nonvolatile fission and corrosion products and 10^3 for radionuclides such as iodine.[8]

Conditions that can adversely affect evaporator operation (by decreasing capacity or reducing the DF value) include fouling, scaling, corrosion and vapor entrainment. Fouling due to the presence of undissolved solids in the feed can be minimized by pretreatment using filtration. Scaling, which might result from the salts contained in decontamination solutions (e.g. NaCl), can be minimized by controlling the concentration of the thick liquor and by heat tracing the piping through which it flows. The corrosion of evaporator surfaces is minimized by fabricating with stainless steel or an equivalent corrosion resistant material. Vapor entrainment (the suspension of liquid in the vapor as droplets that are transported with the vapor stream) can be reduced in an evaporator by using wire mesh or tray type separators.

A major design objective for evaporators is to achieve a DF value large enough to reduce the radionuclide activities of the condensate to values below the limits specified in 10 CFR 20 Appendix B (Table II). Achieving this design objective should preclude the need to further process the condensate. Detailed information on the key parameters and equations which establish the design of the evaporator (e.g. required heat transfer area) are presented in Reference 9.

2. Types of Evaporators

There are several types of evaporators suitable for processing the liquid wastes resulting from decommissioning activities. These include the following:

1. Forced circulation evaporators that employ pumps to ensure the circulation of the liquid over the heating surfaces.

2. Long-tube vertical evaporators that consist of one pass shell and tube heat exchangers discharging into a relatively small vapor head. Depending on the design, the liquid may flow upward through the tubes (rising film type) or downward through the tubes (falling film). In either type, density variations and gravity are the principal mechanisms for vapor and liquid transport. Consequently these evaporators are classified as natural circulation units.

3. Horizontal-tube evaporators that consist of shell and tube heat exchangers in which the heating medium is inside the tubes and the liquor feed enters the shell.

The advantages, disadvantages, and best applications of each type of evaporator are presented in Table 9.5.[9]

9.5.2.4 Ion Exchange

Ion exchange involves a solid phase containing bound groups that carry an ionic charge (either positive or negative) in conjunction with free ions of opposite charge that can be displaced. Through the process of ion exchange, cations and anions are removed from water solutions.

Ion exchange is a chemically reversible reaction involving chemical equivalent quantities. For example, given a specific combination of resins for the demineralization of water, all the salts of calcium, magnesium, sodium and other metal cations are exchanged to their corresponding acids by the cation exchange resin; these acids are subsequently removed by the appropriate anion exchange resin. Using a calcium salt as an example, these reactions can be expressed by the following equations, where the resin is indicated by "R".

Type of Evaporator	Advantages	Disadvantages	Best Applications	Frequent Difficulties
Forced Circulation Evaporator	High heat transfer coefficients. Positive circulation. Relative freedom from fouling and scaling. High holdup time.	High cost.	Crystalline products. Corrosive solutions. Viscous solutions.	Plugging of tube inlets by salt deposits. Salting due to boiling in the tubes. Corrosion/ erosion.
Long-tube Vertical Evaporator	Low cost. Large heating surface in one unit. Small floor space requirements. Good heat transfer coefficients at reasonable temperature differences (rising film). Good heat transfer coefficients at all temperature differences (falling film).	High head room requirements. Generally unsuitable for severely scaling liquids. Poor heat transfer coefficients at low temperature differences (rising film). Recirculation usually required (falling film).	Clean liquids. Foaming liquids. Corrosive solutions. Large evaporation loads.	Sensitivity to changes in operating conditions (rising film) Poor feed distribution (falling film).
Horizontal Tube Evaporator	Low head room requirements. Large vapor-liquid disengaging area. Good heat transfer coefficients.	Not suitable for salting liquids. Not suitable for scaling liquids (straight tube type). High cost (bent-tube type).	Limited head room, small capacity requirements. Severely scaling liquids (bent-tube type).	

TABLE 9.5

ADVANTAGES/DISADVANTAGES OF EVAPORATOR TYPES

	Metallic Salt		Resin Groups		Exchanged Resin Groups		Acid
Cation Exchange:	$CaSO_4$	+	$2H^+R^-$	$\leftrightarrow$	$Ca^{+2}R^-_2$	+	H_2SO_4
Anion Exchange:	H_2SO_4	+	2R	$\leftrightarrow$	$R_2H_2SO_4$		

A water deionization system can consist of a number of individual ion exchange units or a single vessel containing a mixture of cation and anion resins. The types of resin are chosen based on the requirements for removal of specific ions. The following manufacturers can be consulted (among others):

1. Dow Chemical USA
2. Epicor
3. Graver
4. Rohm & Haas

9.5.3 Solidification of Liquid Waste Residue

Following the treatment of liquid waste materials, the radioactive and/or chemical contaminants are concentrated in the liquid waste treatment residue. This residue, depending on the liquid waste treatment methods, will consist of wet solids such as, spent filter cartridges and spent demineralizer resins (powdered or bead) and thick liquids such as filter sludges and evaporator concentrates. Federal regulations require that wet or liquid residues must be solidified in the form of a free-standing non-dispersible monolith containing no free liquid before the wastes can be shipped for final disposal (typically burial).

The ideal solidified waste monolith will possess characteristics that will preclude the release of the contained contaminants. The principal characteristics required by the monolith are as follows:

1. Low Leachability

   This characteristic minimizes the dispersion of the radioactive and/or chemical contaminants in the event that the solidified waste is exposed to air and/or water for long periods of time.

2. High Thermal Conductivity

This characteristic minimizes the possibility of deterioration of the monolith due to excessive internal temperatures and permits a high concentration of radioactive contaminants to be solidified without generating excessive internal temperatures.

3. High Radiation Resistance

This characteristic ensures that the monolith will not deteriorate as a result of the radiation dose levels produced by the radioactive wastes.

4. High Chemical Stability/Corrosion Resistance

This characteristic ensures that the monolith will not deteriorate as the result of chemical attack by environmental agents or by the contained radioactive and/or chemical waste materials.

5. High Mechanical Strength

This characteristic ensures the structural integrity of the monolith against chipping, cracking and/or shattering during handling, shipping and disposal activities.

There are three solidification agents in current use that produce solidification monoliths possessing acceptable characteristics: cement, urea-formaldehyde resin and polyester resin.

9.5.3.1 Cement

The type of cement best suited for waste solidification is Portland cement. The properties of Portland cement that are of importance to waste solidification (high strength, capacity to hold water, etc.) can be modified to some degree by the types/proportions of additives (such as tricalcium silicate, tricalcium aluminate, etc.). Since the liquids that comprise wet radwastes are not generally as pure as the water normally added to cement, the chemistry of cement solidification is not so easily definable. Some experimentation with the types/proportions of additives may be desirable to optimize the process for a given liquid waste. Generally, the liquid wastes in a waste-cement mixture are not permitted to exceed 15% by weight in order to minimize the effect of the waste material on the chemical process.

The volume occupied by the waste-cement mixture is always greater than the original volume of the liquid waste that is processed. While this means greater shipping and burial requirements it has the advantage of generally resulting in a lower activity density for shipping. A reasonable estimate of the waste-cement mixture volume can be obtained using the following relationship:

(volume of waste-cement mixture) = 1.67 (volume of liquid waste)

There are two basic methods of incorporating waste into cement:

1. <u>In-Drum Mixing</u>

   In systems employing this method, the waste and a predetermined quantity of cement are added to the shipping drum separately. Mixing can then be accomplished by employing a mechanical stirring device before the drum is capped or by simply vibrating or rotating the drum after it is capped. Figure 9.5 illustrates a system of the latter type, as described in Reference 1. For this particular system, mixing is performed by a weight, or "mixing bar" that agitates the mixture as the drum is rotated end-over-end.

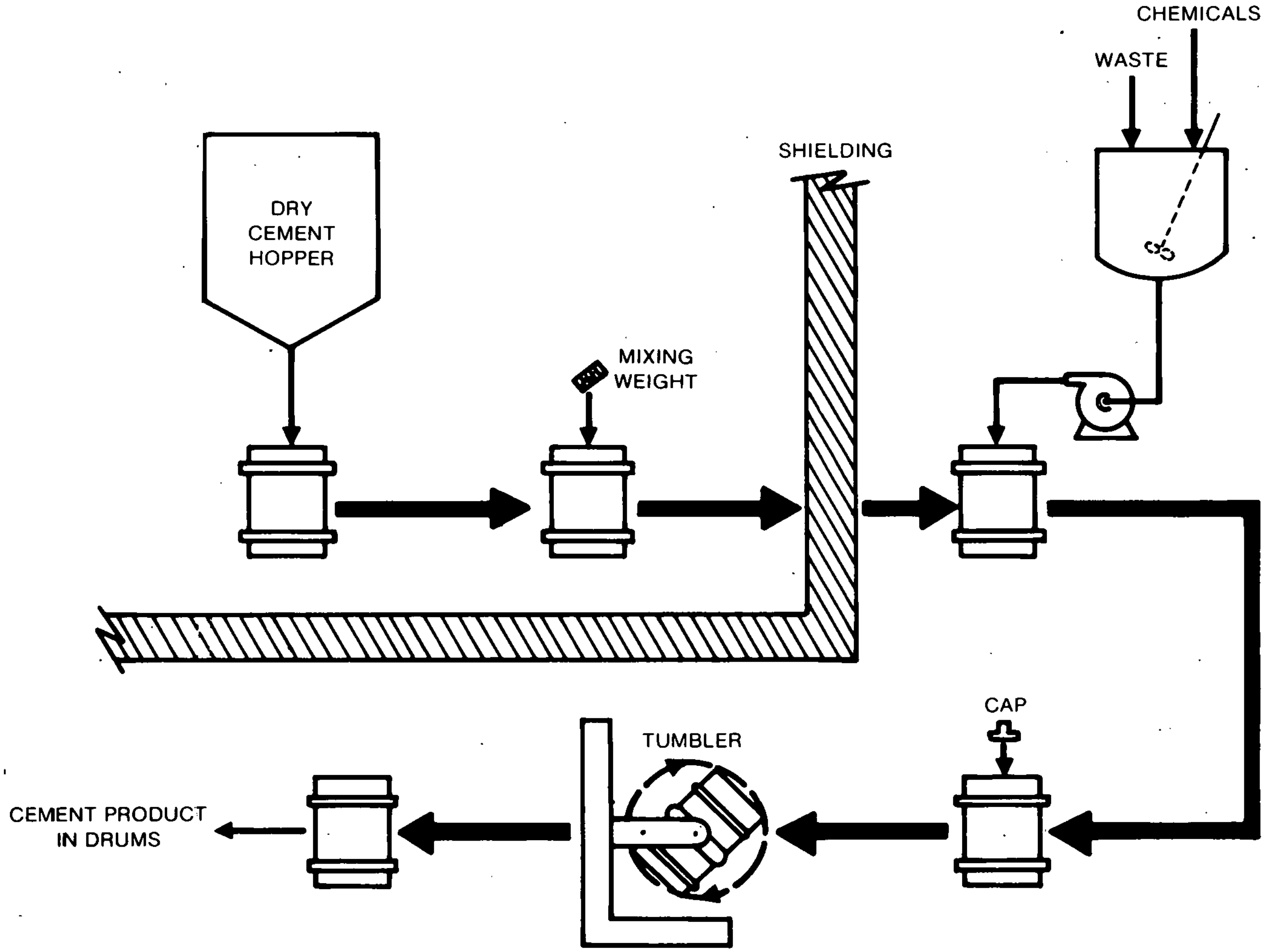


FIGURE 9.5

WASTE SOLIDIFICATION WITH CEMENT IN-DRUM MIXING SYSTEM

2. In-Line Mixing

In systems using this method, metered amounts of waste and cement are fed to an in-line mixer-feeder (usually screw-type). The mixture is then fed into the drum and allowed to solidify. Figure 9.6 illustrates a typical cement-radwaste system for in-line mixing.[1]

9.5.3.2 Urea-Formaldehyde Resin

Another agent used in the solidification of liquid wastes is urea-formaldehyde (UF) resin. For this process, solidification of the waste-UF resin mixture occurs after the addition of a catalyst, which causes a cross-linking polymerization-condensation reaction. The reaction is pH dependent, and two catalysts are generally used: sodium bisulfate ($NaHSO_4$), for wastes with pH in the range of 3 to 7, or phosphoric acid (H_3PO_4) for wastes with pH values up to 10. The amount of catalyst added controls the setting time.

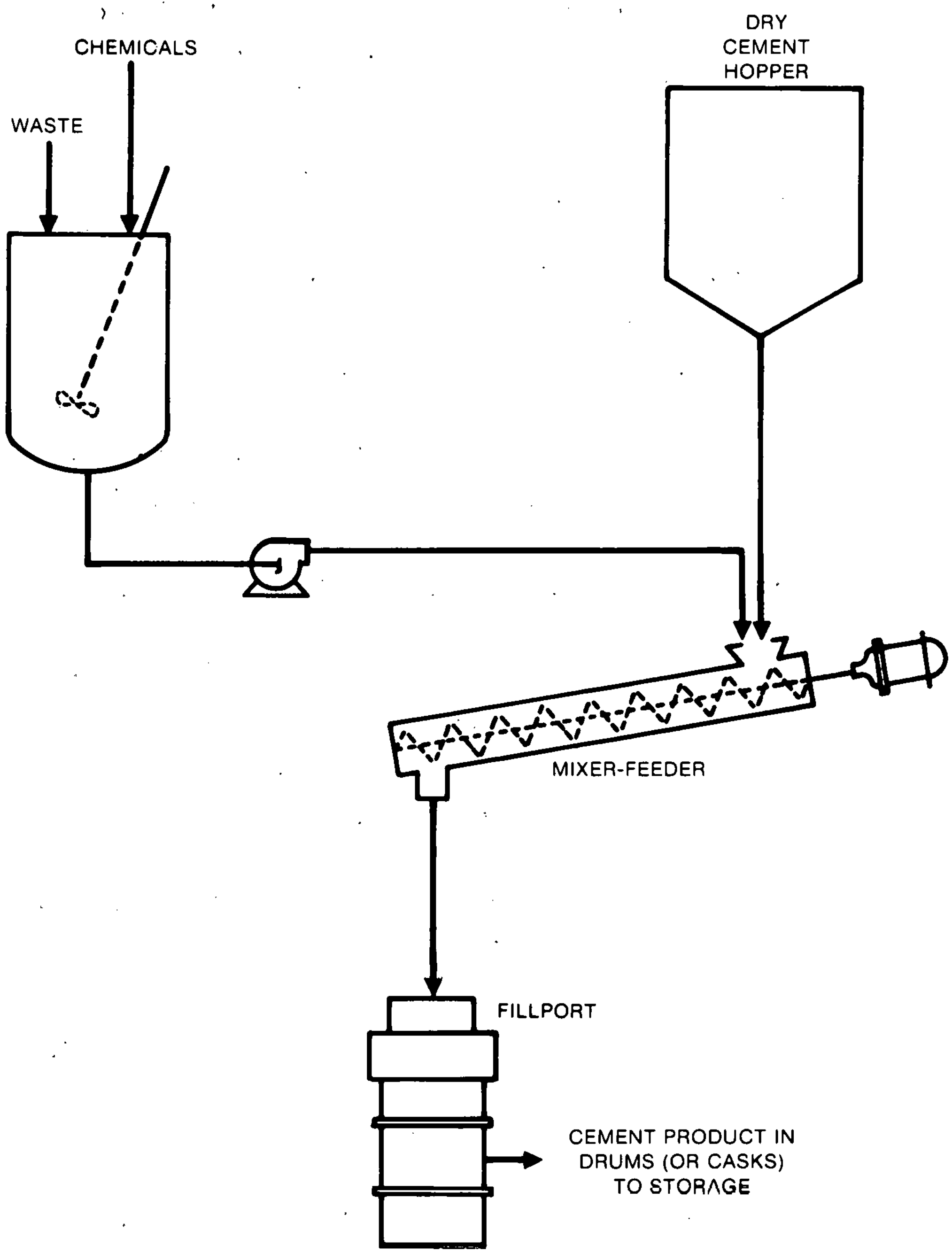
Since the reaction to solidification is pH (and temperature) dependent, the amount of acid catalyst required to adjust the pH of the waste-UF mixture to pH 1-2 must be determined for each waste type. After the initial setting, curing to a hard solid takes place over several hours. As a product of the solidification reaction, slightly acidic water is released. The quantity of water, which may or may not be visible in or on the solid, is dependent on the following:

1. Condition and quality of the resin
2. Temperature and composition of the waste
3. Proportion of waste and solidifying agent.

It should be noted that the acidic water is potentially corrosive to the container, and therefore appropriate steps to inhibit container corrosion, such as an acid-resistant coating, should be considered if the UF process is chosen.

FIGURE 9.6

WASTE SOLIDIFICATION WITH CEMENT IN-LINE MIXING SYSTEM



Because of the possible number of combinations of chemicals that might be present in different decommissioning wastes, prediction of components or chemical reactions that might interfere with the UF solidification process is difficult. Therefore, the design and operation of the system must be attentive to specific conditions. For example, sodium sulfate or soap solutions are difficult to entrap with UF without catalyst adjustments.

The most typical systems for the UF process utilize in-line mixing for combining the waste with the UF resin. A system of this type is illustrated in Figure 9.7 and is described in Reference 1.

9.5.3.3 Polyester Resin

Another type of organic polymer that is used as a medium for solidification of wastes is called modified vinyl ester resin. A system utilizing this agent is currently marketed by Dow Chemical U.S.A. This process, like the UF process, encapsulates the waste when it is combined with the resin and a catalyst is added. However, in the modified vinyl ester process, water is not produced as a by-product.

9.5.4 Alternative Methods of Liquid Waste Solidification

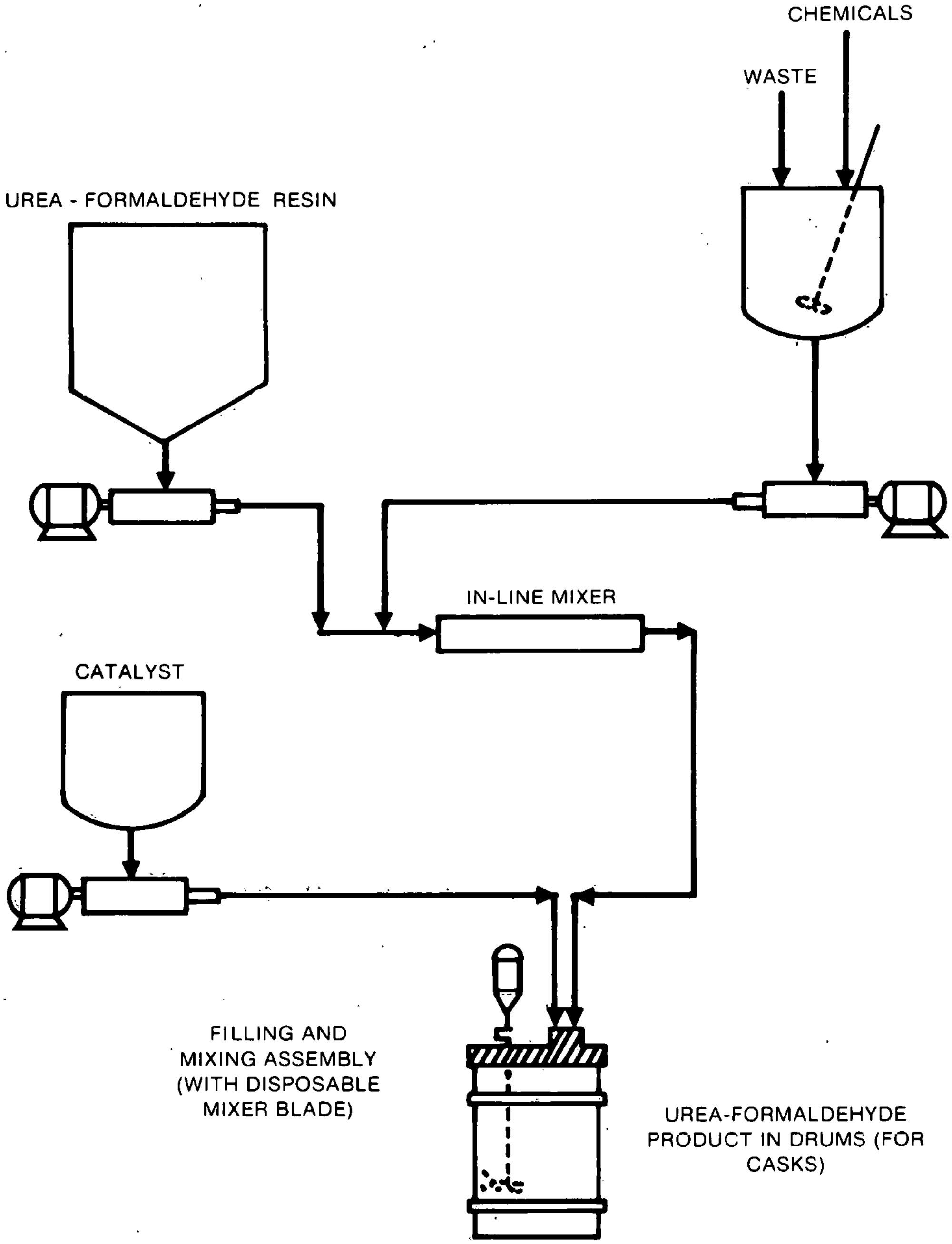
When cement is used as the solidification agent, the resulting volume of solidified waste will be on the order of 1.67 times the volume of the original liquid waste residue.[1] There are, however, several other waste treatment/solidification methods that provide greater volumetric efficiency than cement solidification. Two of these methods, the extruder-evaporator and the calciner process with vitrification, are described briefly in the following sections.

9.5.4.1 Extruder-Evaporator Solidification Method

An extruder-evaporator is a type of forced-circulation evaporator in which the feed is spread into a thin film over the heating surface by a

FIGURE 9.7

TYPICAL SYSTEM FOR SOLIDIFICATION



screw-type action. In liquid radwaste applications, the waste is fed to the evaporator along with asphalt (liquid bitumen), and they are mixed together by the motion of the spreader as the water is evaporated. The waste plus asphalt mixture is then discharged into shipping containers (i.e., drums).

The extruder can be used to solidify evaporator bottoms, spent resins and filter-demineralizer sludges. A volume reduction factor of approximately 8 can be achieved for evaporator bottoms, and possibly more for sludges, with water removal up to 99%.[10]

A system using an extruder-evaporator in conjunction with asphalt has been developed and is marketed by the Werner-Pfleiderer Corporation. A schematic of this system is shown in Figure 9.8.

9.5.4.2 Calciner Process with Vitrification

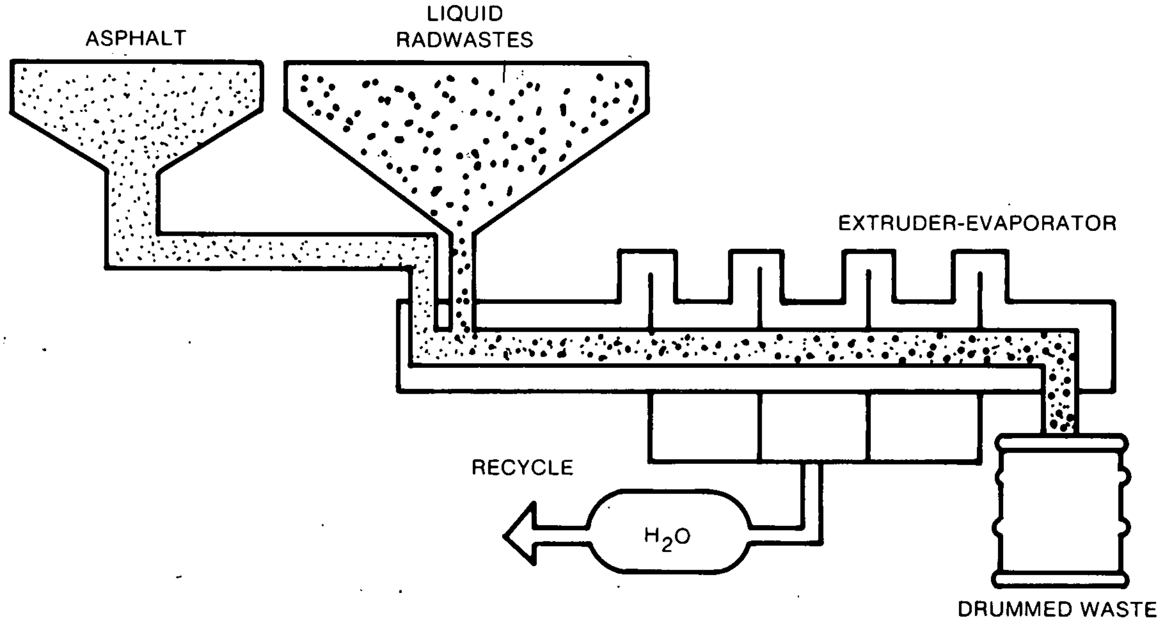
The calciner process is particularly suitable to process evaporator bottoms and demineralizer resin sludges. A volume reduction factor of approximately 8 can be realized for these waste materials.[10]

A schematic diagram of a calciner system developed by the Aerojet Energy Conversion Company is presented in Figure 9.9. In this system, pre-heated air is fed into the bottom of the calciner vessel producing a fluid bed of heated particles. (For this reason a calciner is also referred to as a fluid bed dryer.) The liquid waste residues are fed into the calciner bed, where the water is vaporized and the chemicals in the waste are decomposed into a calcine powder of metal oxides plus a process offgas. The calcine powder coats the bed and forms a new bed material (thus, large amounts of original bed material are not passed on for solidification). The dry residue from the calciner process is discharged from the bottom of the bed and must be solidified for disposal.

FIGURE 9.8

TYPICAL EXTRUDER-EVAPORATOR WITH ASPHALT

Source: Werner-Pfleiderer Corporation



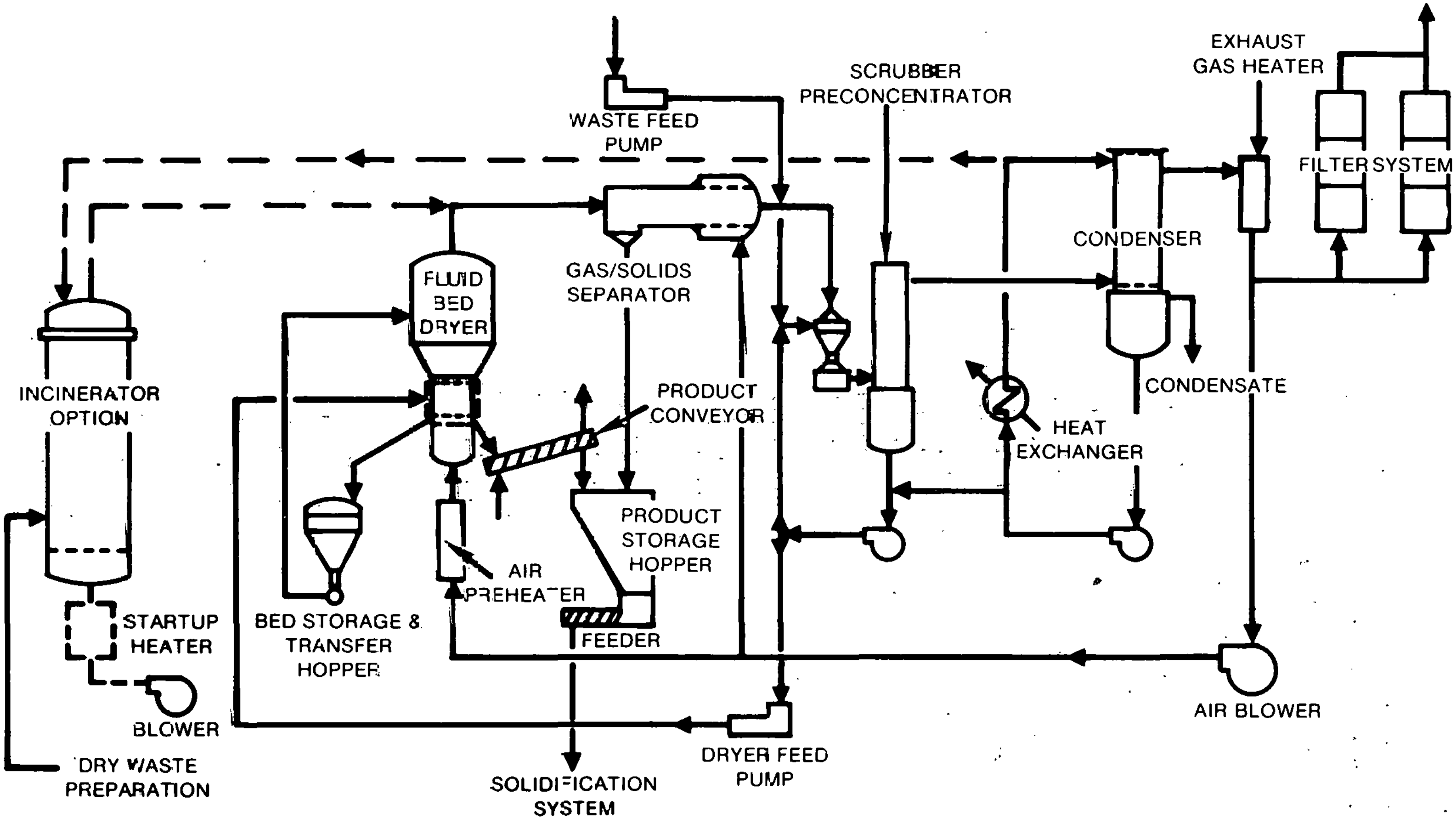


FIGURE 9.9

LIQUID WASTE CALCINER

Source: Aerojet Energy Conversion Company[1]

One solidification method that is very compatible with calcination is vitrification. In this process, granular glass frit is mixed with the dry residue from the calciner process using either batch or continuous feed methods. This mixture is then fed into steel canisters and heated to approximately 1100°C (~2000°F) for melting. Filled canisters are then cooled to solidify the waste-glass mixture.

9.6 PACKAGING WASTES

The purpose of this section is to summarize the basic requirements of the United States Department of Transportation (USDOT or DOT) regulations governing the packaging and shipment of radioactive materials and to provide an application of these rules in an action sequence. The action sequence follows the normal progression one goes through in establishing whether the rules apply to a particular situation and what steps must be taken to comply with the rules.

9.6.1 Data Required for Shipping

The basic data that must be available as a starting point are as follows:

1. Principal radioactive elements in the shipment, listed by isotope
2. Activity level, in curies, of each isotope
3. The physical form of the material, i.e., solid, liquid or gaseous and special form or normal form
4. The specific activity of the materials in the shipment:
    Microcuries/gram for solids
    Microcuries/milliliter for liquids, and
    Microcuries/cubic centimeter for gases.

NOTE: The above activity concentrations are determined using the methods of Chapter 4.

9.6.2 Action Sequence

1. Definition of Radioactive Material

   Determine if material is radioactive material as defined in the regulations (49 CFR 173.389(e)) *. Radioactive material is any material, or combination of materials, that spontaneously emits ionizing radiation. Materials in which the estimated specific activity is not greater than 0.002 microcurie per gram of material, and in which the radioactivity is essentially uniformly distributed, are not considered to be radioactive materials.

2. Classify Transport Group

   Classify the transportation group for shipment based on radionuclide determination (see Figure 9.10) (173.390).

3. Exemptions

   Determine if exemptions apply to this material as: (1) small amount per 173.391; or (2) low specific activity per 173.389.

4. Determine Quantity

   Determine the quantity type classification for the shipment: (1) Type A quantity, (2) Type B quantity, (3) Large quantity.

Transport Group	Type A Curies	Type B Curies
I	0.001	20
II	0.05	20
III	3	200
IV	20	200
V	20	5,000
VI, VII	1,000	50,000
Special Form Materials	20	5,000

NOTE: Quantities greater than Type B are large quantities. The numbers listed under each type are the upper limit for shipments in that category.

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* The referenced numbers indicate the paragraphs in 49 CFR.

FIGURE 9.10

TRANSPORT GROUP DETERMINATION FOR RADIONUCLIDES

ELEMENT	RADIONUCLIDE	GROUP
ACTINIUM (89)	Ac 277	I
	Ac 228	I
AMERICIUM (95)	Am 241	I
	Am 243	I
ANTIMONY (51)	Sb 122	IV
	Sb 124	III
	Sb 125	III
ARGON (18)	Ar 37	VI
	Ar 41	II
	Ar 41 (UNCOMPRESSED)	V
ARSENIC (33)	As 73	IV
	As 74	IV
	As 76	IV
	As 77	IV
ASTATINE (85)	At 211	III
BARIUM (56)	Ba 131	IV
	Ba 133	II
	Ba 140	III
BERKELIUM (97)	Bk 249	I
BERYLLIUM (4)	Be 7	IV
BISMUTH (83)	Bi 206	IV
	Bi 207	III
	Bi 210	II
	Bi 212	III
BROMINE (35)	Br 82	IV
CADMIUM (48)	Cd 109	IV
	Cd 115 m	III
	Cd 115	IV
CALCIUM (20)	Ca 45	IV
	Ca 47	IV
CALFORNIUM (98)	Cf 249	I
	Cf 250	I
	Cf 252	I
CARBON (6)	C 14	IV
CERIUM (58)	Ce 141	IV
	Ce 143	IV
	Ce 144	III
CESIUM (55)	Cs 131	IV
	Cs 134 m	III
	Cs 134	III
	Cs 135	IV
	Cs 136	IV
	Cs 137	III
CHLORINE (17)	Cl 36	III
	Cl 38	IV
CHROMIUM (24)	Cr 51	IV
COBALT (27)	Co 56	III
	Co 57	IV
	Co 58 m	IV
	Co 58	IV
	Co 60	III
COPPER (29)	Cu 64	IV
CURIUM (95)	Cm 242	I
	Cm 243	I
	Cm 244	I
	Cm 245	I
	Cm 246	I
DYSPROSIUM (66)	Dy 154	III
	Dy 165	IV
	Dy 166	IV
ERBIUM (68)	Er 169	IV
	Er 171	IV
EUROPIUM (63)	Eu 150	III
	Eu 152 m	IV
	Eu 152	III
	Eu 154	II
	Eu 155	IV
FLUORINE (9)	F 18	IV
GADOLINIUM (64)	Gd 153	IV
	Gd 159	IV
GALLIUM (31)	Ga 67	III
	Ga 72	IV
GERMANIUM (32)	Ge 71	IV
GOLD (79)	Au 193	III
	Au 194	III
	Au 195	III
	Au 196	IV
	Au 198	IV
	Au 199	IV
HAFNIUM (72)	Hf 181	IV
HOLMIUM (67)	Ho 166	IV
HYDROGEN (1)	H 3 (SEE TRITIUM)	
INDIUM (49)	In 113 m	IV
	In 114 m	III
	In 115 m	IV
	In 115	IV
IODINE (53)	I 124	III
	I 125	III
	I 126	III
	I 129	III
	I 131	III
	I 132	IV
	I 133	III
	I 134	IV
	I 135	IV
IRIDIUM (77)	Ir 190	IV
	Ir 192	III
	Ir 194	IV
IRON (26)	Fe 55	IV
	Fe 59	IV
KRYPTON (36)	Kr 85 m	III
	Kr 85 m (UNCOMPRESSED)	V
	Kr 85	III
	Kr 85 (UNCOMPRESSED)	VI
	Kr 87	II
	Kr 87 (UNCOMPRESSED)	V
LANTHANUM (57)	La 140	IV
LEAD (82)	Pb 203	IV
	Pb 210	II
	Pb 212	II
LUTECIUM (71)	Lu 172	III
	Lu 177	IV
MAGNESIUM (12)	Mg 28	III
MANGANESE (25)	Mn 52	IV
	Mn 54	IV
	Mn 56	IV
MERCURY (80)	Hg 197 m	IV
	Hg 197	IV
	Hg 203	IV
MIXED FISSION PRODUCTS M F P		II
MOLYBDENUM (42)	Mo 99	IV
NEODYMIUM (60)	Nd 147	IV
	Nd 149	IV
NEPTUNIUM (93)	Np 237	I
	Np 239	I
NICKEL (28)	Ni 56	III
	Ni 59	IV
	Ni 63	IV
	Ni 65	IV
NIOBIUM (41)	Nb 93 m	IV
	Nb 95	IV
	Nb 97	IV
OSMIUM (76)	Os 185	IV
	Os 191 m	IV
	Os 191	IV
	Os 193	IV
PALLADIUM (46)	Pd 103	IV

FIGURE 9.10
(Continued)

ELEMENT	RADIONUCLIDE	GROUP
	Pd 109	IV
PHOSPHORUS (15)	P 32	IV
PLATINUM (78)	Pt 191	IV
	Pt 193 m	IV
	Pt 197 m	IV
	Pt 197 m	IV
	Pt 197	IV
PLUTONIUM (94)	Pu 238(F)	I
	Pu 239 (F)	I
	Pu 240	I
	Pu 241 (F)	I
	Pu 242	I
POLONIUM (84)	Po 210	I
POTASSIUM (19)	K 42	IV
	K 43	III
PRASEODYMIUM (59)	Pr 142	IV
	Pr 143	IV
PROMETHIUM (61)	Pm 147	IV
	Pm 149	IV
PROTACTINIUM (91)	Pa 230	I
	Pa 231	I
	Pa 233	II
RADIUM (88)	Ra 223	II
	Ra 224	II
	Ra 226	I
	Ra 228	I
RADON (86)	Rn 220	IV
	Rn 222	II
RHENIUM (75)	Re 183	IV
	Re 186	IV
	Re 187	IV
	Re 188	IV
	Re NATURAL	IV
RHODIUM (45)	Rh 103 m	IV
	Rh 105	IV
RUBIDIUM (37)	Rb 86	IV
	Rb 87	IV
	Rb NATURAL	IV
RUTHENIUM (44)	Ru 97	IV
	Ru 103	IV
	Ru 105	IV
	Ru 106	III
SAMARIUM (62)	Sm 145	III
	Sm 147	III
	Sm 151	IV
	Sm 153	IV
SCANDIUM (21)	Sc 46	III
	Sc 47	IV
	Sc 48	IV
SELENIUM (34)	Se 75	IV
SILICON (14)	Si 31	IV
SILVER (47)	Ag 105	IV
	Ag 110 m	III
	Ag 111	IV
SODIUM (11)	Na 22	III
	Na 24	IV
STRONTIUM (38)	Sr 85 m	IV
	Sr 85	IV
	Sr 89	III
	Sr 90	II
	Sr 91	III
	Sr 92	IV
SULPHUR (16)	S 35	IV
TANTALUM (73)	Ta 182	III
TECHNETIUM (43)	Tc 96 m	IV
	Tc 96	IV
	Tc 97 m	IV
	Tc 97	IV

ELEMENT	RADIONUCLIDE	GROUP
	Tc 99 m	IV
	Tc 99	IV
TELLURIUM (52)	Te 125 m	IV
	Te 127 m	IV
	Te 127	IV
	Te 129 m	III
	Te 129	IV
	Te 131 m	III
	Te 132	IV
TERBIUM (65)	Tb 160	III
THALLIUM (81)	Tl 200	IV
	Tl 201	IV
	Tl 202	IV
	Tl 204	III
THORIUM (90)	Th 227	II
	Th 228	I
	Th 230	I
	Th 231	I
	Th 232	III
	Th 234	II
	Th NATURAL	III
THULIUM (69)	Tm 168	III
	Tm 170	III
	Tm 171	IV
TIN (50)	Sn 113	IV
	Sn 117 m	III
	Sn 121	III
	Sn 125	IV
TRITIUM (1)	H 3	IV
	H 3 (AS A GAS, AS LUMINOUS PAINT, OR ABSORBED ON SOLID MATERIAL)	VII
TUNGSTEN (74)	W 181	IV
	W 185	IV
	W 187	IV
URANIUM (92)	U 230	II
	U 232	I
	U 233(F)	II
	U 234	II
	U 235 (F)	III
	U 236	II
	U 238	III
	U NATURAL	III
	U ENRICHED (F)	III
	U DEPLETED	III
VANADIUM (23)	V 48	IV
	V 49	III
XENON (54)	Xe 125	III
	Xe 131 m	III
	Xe 131 m (UNCOMPRESSED)	V
	Xe 133	III
	Xe 133 (UNCOMPRESSED)	VI
XENON (54)—CON	Xe 135	II
	Xe 135 (UNCOMPRESSED)	V
YTTERBIUM (70)	Yb 175	IV
YTTRIUM (39)	Y 88	III
	Y 90	IV
	Y 91 m	III
	Y 91	III
	Y 92	IV
	Y 93	IV
ZINC (30)	Zn 65	IV
	Zn 69 m	IV
	Zn 69	IV
ZIRCONIUM (40)	Zr 93	IV
	Zr 95	III
	Zr 97	IV

The determination of Special Form Materials is important, since its quantity limit is independent of the transport group. "Special Form (Radioactive) Materials" (49 CFR 173.389(g)) means those which, if released from a package, might present some direct radiation hazard but would present little hazard due to radiotoxicity and little possibility of contamination. This may be the result of inherent properties of the material (such as metals or alloys), or acquired characteristics, as through encapsulation. The criteria for determining whether a material meets the definition of special form are prescribed in Paragraph 173.398(a).

5. <u>Package Requirements</u>

Determine packaging required to satisfy the general packaging requirements for radioactive materials based on quantity type classification.

A. <u>Low Specific Activity (LSA) Packaging</u>
(173.392, 173.393 and 173.395)

LSA materials must be transported in sole-use vehicles placarded "Dangerous-Radioactive Materials" (174.541b) with specific instructions of shipment controls provided by the shipper to the carrier and such instructions are included with the shipping paper information, such consigned shipments are exempt from specification packaging, marking and labeling. <u>Packaged</u> LSA materials must not have a transport index greater than 10 nor may the maximum package accessible external surface temperature exceed 180°F. <u>Unpackaged</u> (<u>bulk</u>) shipments of LSA materials suitably wrapped or enclosed must be transported in closed vehicles whose external radiation levels must not exceed 200 mrem/hr on contact, 10 mrem/hr six feet from the vehicle and 2 mrem/hr in any occupied position in the vehicle. Bulk shipments must be loaded by the consignor and unloaded by the consignee with no leakage of radioactive material from the vehicle.

B. Low Specific Activity Packaging

In Quantities Greater than Type A (10 CFR 71.7)

NRC regulations specify an upper limit on the total curie content that is contained in a single package. If the total curie count exceeds that specified as Type A quantity (in normal form), the package must meet the specifications for greater than Type A, as described in Subpart C of 10 CFR 71.

C. Type A Packaging

(173.398b)

Typically, the Type A packaging provided for the regulations is the performance-oriented DOT Spec. 7A, Type A general package. The shipper must make his own assessment of his particular package design against the performance requirements.

The regulatory framework provides for the use of all Type A packaging without specific regulatory approvals of the package designs via the use of the DOT Spec. 7A performance specification.

The shipper of each DOT Spec. 7A package is required to maintain on file for at least one year after the last shipment, and be prepared to provide to the Department, a complete certification and supporting safety analyses demonstrating that the construction methods, packaging design and materials of construction of the package are in compliance with the specification. (173.394a, 173.395a).

D. Type B Packaging

(173.393(a), 173.398(c))

Type B packaging must be designed to withstand certain serious accident damage test conditions with resultant limited loss of shielding capability and essentially no loss of containment. These requirements are in addition to the general packaging requirements and the performance standards for <u>normal</u> conditions of transport. The performance criteria for Type B packaging are identified in Paragraph 173.398(c).

E. Large Quantity Packaging
(173.394(c), 173.395(c))

Large Quantity Packaging is any Type B package that meets 10 CFR 71 requirements or International Atomic Energy Agency requirements and is authorized under 49 CFR 170 for such use, or packaging that meets 173.398(b), (c) and (d).

Typical examples of Type A and B packaging are shown in Figure 9.11. Selected DOT approved container descriptions are given in Appendix A of this chapter. A method for estimating the external dose rate for packages is presented in Appendix B.

6. Contamination Control

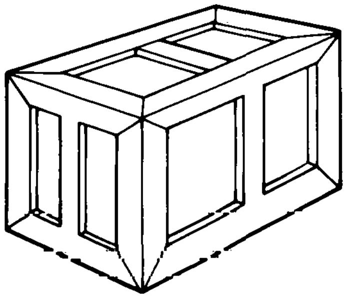
Determine the need to reduce surface contamination prior to transport (173.397). Removable (non-fixed) radioactive contamination will be determined to be insignificant and within the limits of 173.397(a) if the average amount of radioactive (non-fixed) contamination measured does not exceed 10% of following limits:

1. 10^{-4} μCi/cm^2 (220 disintegrations/minute per cm^2) of beta-gamma and 10^{-5} μCi/cm^2 (22 disintegrations/minute per cm^2) of alpha for all contaminants of radionuclides except natural or depleted uranium and natural thorium; or
2. 10^{-3} μCi/cm^2 (2200 dpm/cm^2) of beta-gamma and 10^{-4} μCi/cm^2 (220 dpm/cm^2) of alpha where the only contaminant is known to be natural or depleted uranium and natural throium.

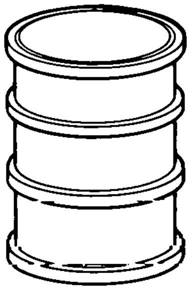
FIGURE 9.11

TYPICAL PACKAGING

TYPICAL TYPE A PACKAGING

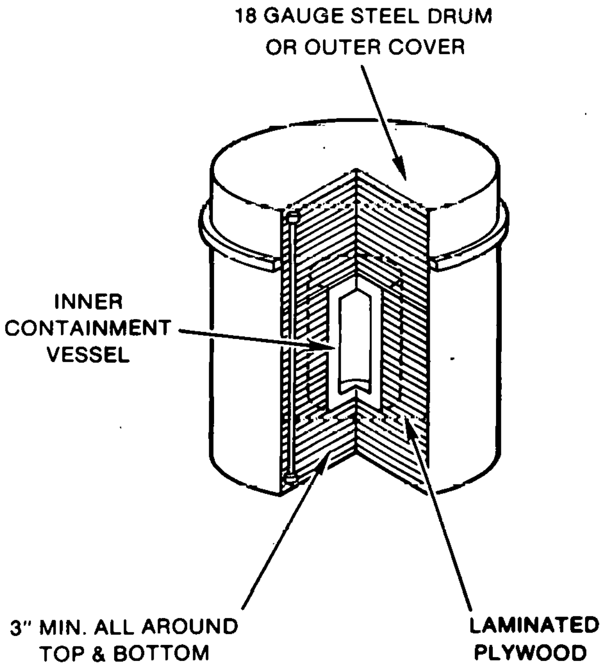


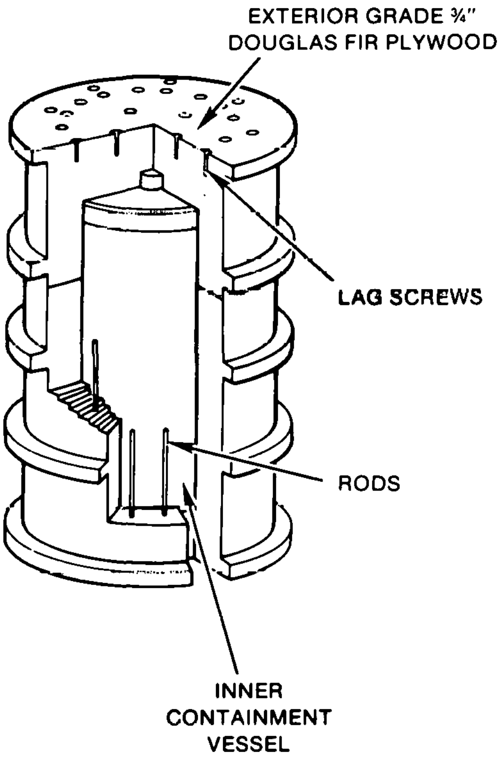
WOODEN BOX



STEEL DRUM

TYPICAL TYPE B PACKAGING





When radioactive material packages are consigned as exclusive-use (per 173.389(o)), removable non-fixed radioactive contamination may not exceed the above limits.

Each exclusive-use transport vehicle used to transport radioactive materials must be surveyed after each use and may not be returned to service until: the radiation dose rate at any accessible surface is 0.5 millirem per hour or less; and there is no significant removable radioactive surface contamination as defined in paragraph 6(1) above.

7. Labeling and Marking Requirements

A. Determine the radioactive warning label required for each package of the shipment. Labeling for radioactivity depends on the transportation index and the radiation level at the surface of the package. In addition, the following requirements apply to completion of information in the blank spaces of the radioactive package labels:

(1) Contents

The name of the radionuclide. Symbols may be used which conform to established radiation protection terminology (^{60}Co, ^{99}MO, etc). For mixtures of radionuclides on the basis of radiotoxicity, the mixtures must be listed as space on the label allows.

(2) Number of Curies

Units shall be expressed in appropriate curie units (Ci, mCi or µCi abbreviations are authorized).

(3) Transport Index

The highest radiation dose rate, in millirem/hr, at three feet from any accessible external surface of the package, rounded upwards to the next highest tenth (e.g., 1.15 becomes 1.2).

When materials are shipped according to the provisions of low specific activity material (173.392), each package must be stencilled or otherwise marked: "RADIOACTIVE-LSA".

B. Determine labeling for other hazards. Radioactive materials having other hazardous characteristics, as defined in Title 49CFR, must also be labeled with other levels according to the hazards of the commodity. For example, packages containing charcoal may require both a radioactive material label and a white flammable solid label unless exempt by 173.162. (173.2a, 173.402, 173.162)

C. Determining other shipper labeling and marking requirements. The outside of the package must also be marked as follows:

(1) With the specification number or certificate number, if applicable (173.24(c))

(2) With the shipping name as shown in the list of hazardous materials (172.101)

(3) In addition to any other markings required, each package containing radioactive materials must be marked as follows: (172.310)

(a) Each package of radioactive materials in excess of 110 pounds (50 kilograms) must have its gross weight plainly and durably marked on the outside of the package.

(b) Each package of radioactive materials which conforms to requirements for Type A (173.389(j) and 173.398(b)) and Type B (173.389(k) and 173.398(c)) must be plainly and durably marked on the outside of the package in letters at least 1/2-inch high, and the words "TYPE A" or "TYPE B" as appropriate.

8. Shipping Papers

Certain essential elements of information must also be included on the shipping paper description (172.203j). These requirements also apply to packages containing small quantities and radioactive devices, except that the notation "no label required" must be entered in lieu of the type of label applied (173.391).

Suggested forms for shipping papers showing applicable 49CFR paragraph references are given in Appendix C. The carrier's shipping papers will be prepared from the information provided on the shipper's shipping papers (174.24, 175.35, 176.24, 177.817).

Shipper's certification: the shipping papers must include a certificate signed by the shipper. The following statement is required by Section 172.204(a).

> "This is to certify that the above-named materials are properly classified, described, packaged, marked and are in proper condition for transportation according to the applicable regulations of the Department of Transportation."

9. Security Seal

The outside of each radioactive materials package must incorporate a feature such as a seal that is not readily breakable and which, while intact, will be evidence that the package has not been illicitly opened (173.393(b)).

For this requirement, some ingenuity may be called for on the part of the package designer, especially on such packages as fiberboard cartons and wooden boxes. Past experience has proven that an attempt had been made by shippers to use a padlock as both a security seal and a closure mechanism. Most padlocks, however, are not an adequate security seal, let alone a closure device, since it is usually not possible with most types of padlocks to ascertain if they have been illicitly opened.

Such combinations as serially numbered lead wire seals along with closure mechanisms such as slotted screw-in plugs, bolted flanges and positive-action shutter mechanisms are usually a better approach toward meeting the dual function.

10. Quality Assurance Requirements

Prior to the first shipment of any package, the shipper shall determine by examination or appropriate test that (173.393m): the packaging meets the specified quality of design and construction; and the effectiveness of the shielding and containment of the package are within the limits applicable to or specified for the package design.

Prior to each shipment of any package, the shipper shall insure by examination or appropriate test that (173.393n):

A. The package is proper for the contents to be shipped
B. The packaging is in unimpaired physical condition except for superficial marks
C. Each closure device of the packaging, including any required gasket, is properly installed and secured and free of defects
D. Any special instructions for filling, closing and preparation of the packages for shipment have been followed
E. Each closure, valve, and any other opening of the containment system through which the radioactive content might escape is properly closed and sealed

F. External radiation and contamination levels are within the allowable limits.

Each shipper of a package (containing radioactive material) which has been approved by the USNRC (173.393a) in accordance with:

A. Type B packaging of Type B quantities of special form radioactive materials
B. Type B packaging of large quantities of radioactive materials in special form
C. Type B packaging of Type B quantities of normal form radioactive materials
D. Type B packaging of large quantities of normal form radioactive materials should also comply with the following:

   (1) Before the first shipment in a package is approved by the USNRC for use by another person, each shipper shall register in writing with the USNRC, Division of Materials Licensing, his name and address, the name of the person to whom the USNRC approval was issued and the approval number assigned to the package. Each shipper shall have a copy of the USNRC approval and the document referred to in the approval in his possession. Each shipment must be made in compliance with the terms and conditions of the approval.
   (2) The outside of each package must be durably and legibly marked with the package identification marking indicated in the USNRC approval.

(3) Each shipping paper related to the shipment of this package must bear a notation of the package identification marking indicated in the USNRC approval.

9.7 DISPOSAL OF WASTES

The wastes generated by decommissioning are dispositioned in accordance with the radioactive characteristics of the waste. Noncontaminated wastes may be disposed of by selling for scrap, by using as backfill at the decommissioning site or by shipping to a landfill site. Activated or contaminated wastes are dispositioned by shipping them to a radioactive waste burial site.

There are only three commercial low-level waste burial sites currently receiving shipments of commercial low-level waste in the United States. They are:

1. Washington Nuclear Center (Nuclear Engineering Co.), located in Richland, Washington
2. Nevada Nuclear Center (Nuclear Engineering Co.), located in Beatty, Nevada
3. Barnwell Nuclear Burial Site (Chem-Nuclear Services, Inc.), located in Barnwell, South Carolina.

Information pertinent to each site is presented in the following sections.

9.7.1 Washington Nuclear Center

NECO's Washington low-level radioactive waste disposal facility (27 miles northwest of Richland, Washington) operates under the following authorizations: License Number WN-1019-2 issued by the Department of Health, State of Washington; and License Number 13-10042-1 issued by the U.S. Nuclear Regulatory Commission.

1. Possession Limits

   A. 60,000 curies of radioactive by-product material (except Source Material and Special Nuclear Material)

B. 4,000 pounds of source material (specifically Uranium 238 and Thorium 232).

2. Types of Waste

Only solid, packaged radioactive waste material is authorized for disposal, including:

A. Those liquid radioactive waste materials that have been solidified by either a chemical or cement solidification system
B. Those substances described as ion-exchange resins that have been solidified in an integral manner, with either a chemical or cement solidification system.

Gaseous radioactive waste materials are authorized provided that no container of gaseous waste shall be received or disposed of if the pressure within the container exceeds one (1) atmosphere. Liquid radioactive waste materials are not authorized for disposal.

NOTE: The above information summarizes NECO's Federal and State License requirements. It has been prepared solely for general information and in no event should be construed to detail or encompass all relevant License provisions.

9.7.2 Nevada Nuclear Center

NECO's Nevada low-level radioactive waste disposal facility (11 miles southeast of Beatty, Nevada) operates under the following authorization: License Number 13-11-0043-02 issued by the Department of Human Resources, State of Nevada.

1. Possession Limits

A. 50,000 curies of radioactive by-product material (except Source Material and Special Nuclear Material)

B. One (1) curie of Radium-226

C. 25,000 pounds of source material (specifically Uranium 238 and Thorium 232).

2. Type of Waste

A. Only solid, packaged radioactive waste material is authorized for disposal, including:

(1) Those liquid radioactive waste materials that have been solidified by either a Tiger Lock or cement solidification system

(2) Those substances described as ion-exchange resins which have been solidified in an integral manner, with either a Tiger Lock or cement solidification system.

B. Gaseous radioactive waste materials are authorized provided that:

(1) Each primary container does not exceed 1,000 curies

(2) Each primary container containing 100 curies but less than 1,000 curies be encased in concrete with at least six inches of concrete surrounding the primary container in every direction from the outside surface of the primary container

(3) No container of gaseous waste shall be received or disposed of if the pressure within the container exceeds one (1) atmosphere.

C. Liquid radioactive waste materials are authorized provided that:

(1) Any radioactive liquids received for disposal shall not exceed the concentration limits specified by U.S. Department of Transportation transport groups listed:

Transport Group I	0.01 microcuries/ml
Transport Group II	0.50 microcuries/ml
Transport Group III	30.00 microcuries/ml

(2) No Special Nuclear Material will be received or disposed of in liquid form.

(3) Scintillation vials packaged, received and processed are authorized for disposal provided they have been received or placed in a DOT specification steel drum (either 30 or 55 gallon), into which enough absorbent material (for example: pelecel, diatomaceous earth, or Microcel-E) has been added to absorb at least twice the volume of scintillation liquid contained, should leakage from all vials occur simultaneously.

3. Certification

Pursuant to the provisions of NECO's Site Operations Manual customers utilizing the Beatty facility for disposal of radioactive waste must certify to NECO and the State of Nevada that they have read certain sections of the manual (Sections 5.1.1.3 through 5.1.1.6, 5.4.6.1, and 5.4.6.2) (see Appendix D) and that each shipment is in compliance with all stated requirements.

A complete Certification Form (see Appendix D) is a license requirement and must accompany each radioactive waste shipment sent to NECO for disposal. Failure to submit the Certification will result in having that shipment returned at the customer's sole expense.

NOTE: The above information summarized NECO's Federal and State License requirements. It has been prepared solely for general information and in no event should it be construed to detail or encompass all relevant License provisions.

9.7.3 Barnwell, South Carolina Nuclear Burial Site

CNSI's South Carolina low-level radioactive waste disposal facility (5 miles northwest of Barnwell, South Carolina) operates under the following authorization: License Number 097 (Amendment 16) issued by the South Carolina Department of Health and Environmental Control, Bureau of Radiological Health.

1. Possession Limits

   A. 15,000 curies of Radioactive Material (excluding Source Material and Special Nuclear Material)
   B. 60,000 pounds of Source Materials

2. Type of Waste

   A. Only solid, packaged radioactive material is authorized for disposal, including:

      (1) Radioactive waste containing transuranic elements may be buried, provided the concentration of such elements is not greater than 10 nanocuries per gram of radioactive waste.
      (2) Ion exchange resins must be in a dewatered form for transportation and subsequent burial and an isotopic analysis (quantitative and qualitative) has been performed and data supplied.

   B. Gaseous radioactive waste materials consisting of Krypton-85 and Xenon-133 are authorized for burial provided that:

      (1) Burial containers must be approved by the Department of Transportation
      (2) Internal pressure of containers may not exceed 1.5 atmospheres

(3) Total activity of containers may not exceed 100 curies each

(4) Containers must be marked and transported for burial in an upright position.

C. Liquid radioactive waste materials are not authorized, except for:

(1) Liquid scintillation vials that are packaged unopened in vermiculite at a two-to-one ratio (vermiculite to liquid) and contained within sealed steel drums.

(2) Liquid waste from academic, research and medical institutions that is packaged in double-wall containers:

(a) Consisting of a thirty (30) gallon tight head drum filled with vermiculite in turn contained in a fifty-five (55) gallon drum the remaining volume of which has been filled with vermiculite. No more than fifteen (15) gallons of liquid shall be placed in the inner container, or

(b) Consisting of a thirty (30) gallon 17-H steel container having a five (5) gallon polyethylene carboy inner container surrounded by vermiculite.

(3) Solidified liquids and evaporation bottoms are authorized for burial provided they are solidified with one of the following solidification medias prior to receipt at the site:

Cement
Urea Formaldehyde
Dow Media
Delaware Custom Media
Asphalt

NOTE: The above information summarizes CNSI's License requirements. It has been prepared solely for general information and in no event should it be construed to detail or encompass all relevant License provisions.

9.8 REFERENCES

1. Kibbey, A.H. et al.: A Review of Solid Radioactive Waste Practices in Light Water Cooled Nuclear Reactor Power Plants, NUREG/CR-0144, Oak Ridge National Laboratory (October, 1978)

2. Schneider, K.F. et al.: Technology, Safety and Costs of Decommissioning a Reference Nuclear Fuel Reprocessing Plant, NUREG-0278, Battelle Pacific Northwest Laboratory (October, 1977)

3. Smith, R.I. et al.: Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station, NUREG/CR-0130, Battelle Pacific Northwest Laboratory (June, 1978)

4. Manion, W.J. and LaGuardia, T.S.: An Engineering Evaluation of Nuclear Power Reactor Decommissioning Alternatives, AIF/NESP-009, National Environmental Studies Project of the Atomic Industrial Forum, Inc. (November, 1976)

5. American Nuclear Society: American National Standard, Boiling Water Reactor Liquid Radioactive Waste Processing System, ANS-55.3/ANSI N197-1976 (June 25, 1976)

6. American Nuclear Society: American National Standard, Liquid Radioactive Waste Processing System for Pressurized Water Reactor Plants, ANS-55.2/ANSI N199-1976 (June 25, 1976)

7. Weast, R.C. (Ed.): "CRC Handbook of Chemistry and Physics," 53rd Edition, CRC Press (1972)

8. Goodbee, H.W. and Kibbey, A.H.: The Use of Evaporation to Treat Radioactive Liquids in Light Water Cooled Nuclear Reactor Power Plants, NUREG/CR-0142, Oak Ridge National Laboratory (September, 1978)

9. Perry, J.H. (Ed.): "Chemical Engineers' Handbook," 4th Edition, McGraw Hill Book Company, New York, N.Y. (1963)

10. Mullarkey, T.B., et al.: A Survey and Evaluation of Handling and Disposing of Solid Low-Level Nuclear Fuel Cycle Wastes, AIF/NESP-008, National Environmental Studies Project of the Atomic Industrial Forum, Inc. (October, 1976)

APPENDIX A

TYPICAL CONTAINERS FOR PACKAGING RADIOACTIVE WASTE MATERIALS

This Appendix presents descriptions, dimensions and capacity information of commercially available shipping casks and transporters that meet DOE requirements. Figure A-1 shows a typical top-loading shipping cask and Figure A-2 is an example of an end-loading transporter.

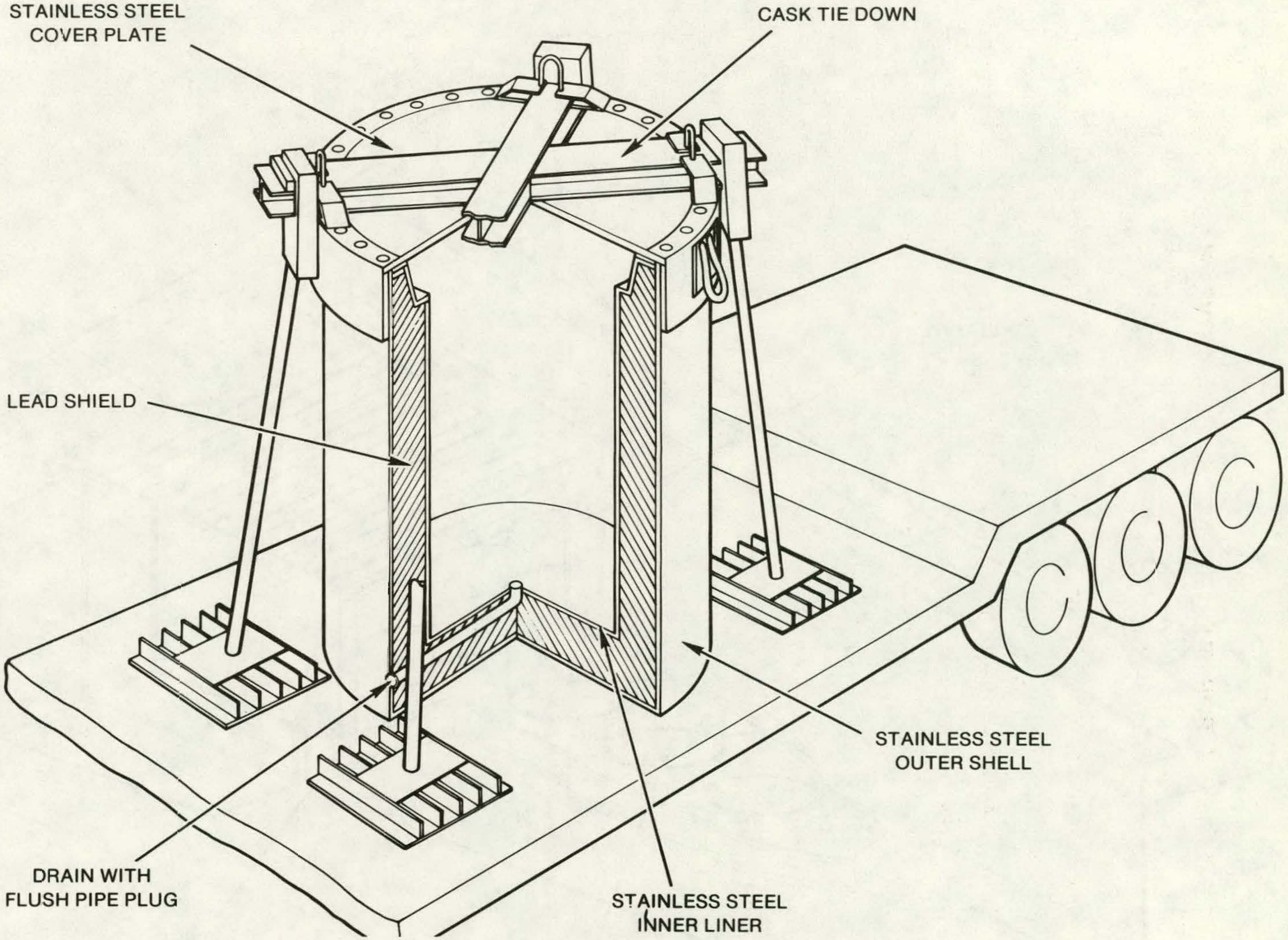


FIGURE A-1

TOP-LOADING SHIPPING CASK

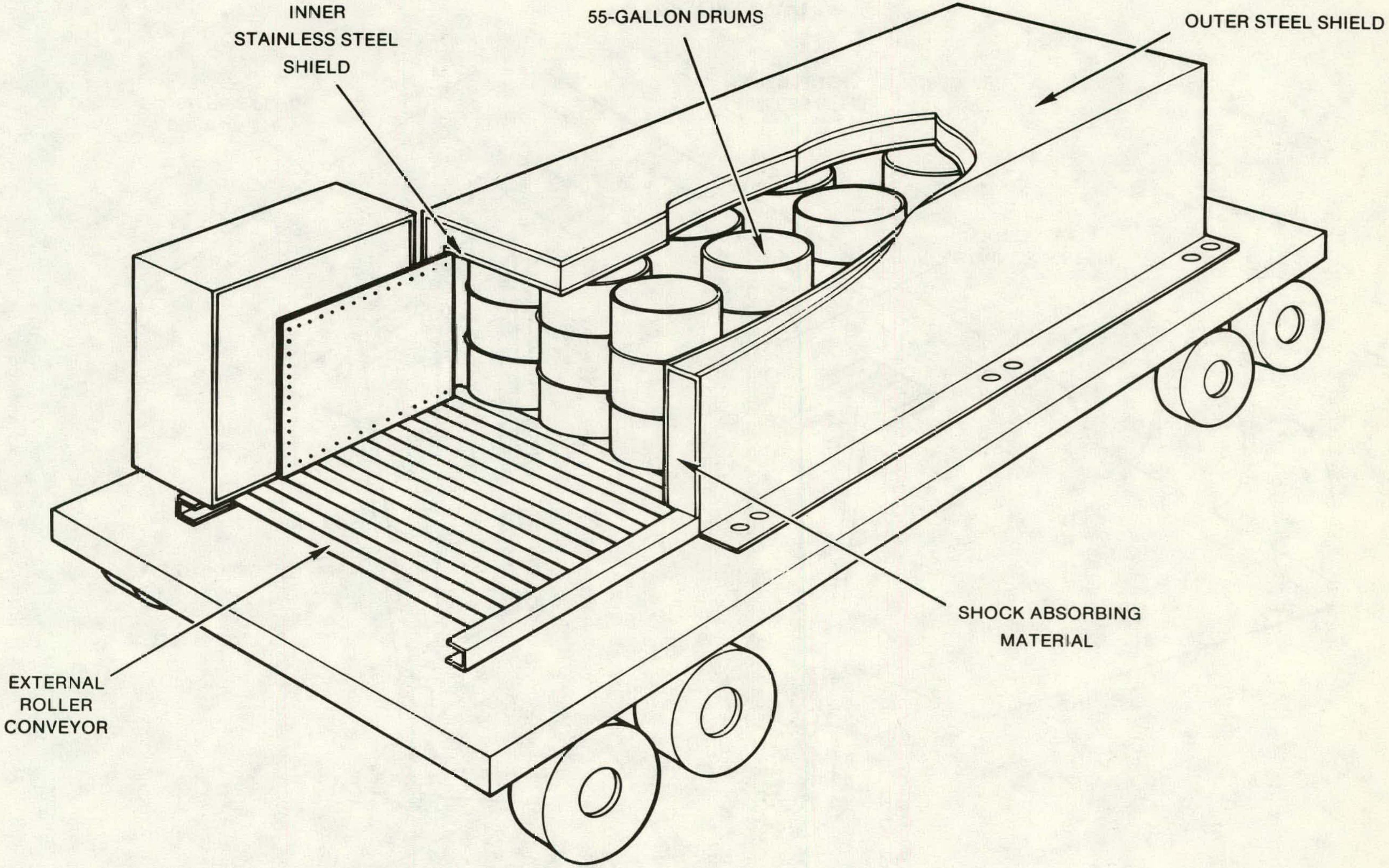


FIGURE A-2

END-LOADING TRANSPORT CASK

RADWASTE SHIPPING CASKS

HITTMAN NUCLEAR & DEVELOPMENT CORPORATION

9190 Red Branch Road
Columbia, Maryland 21045

TRANSPORT EQUIPMENT

Top Loading Casks

HN-100

The HN-100 series of casks are reusable transportation shields designed for greater than Type A quantities of Low Specific Activity (LSA) materials in either drums or large containers. These casks are capable of handling fourteen 55-gallon drums or one (1) 163 cubic foot large container. The standard HN-100 cask can handle drums with radiation levels up to 12R per hour.*

HN-100 Series 1
ID: 74-1/2" x 75-1/2"
Empty Weight: 35,500 lbs
Shielding: 1-1/4" steel, 1-3/4" lead
USNRC#: USA/9086/A

HN-100 Series 2
ID: 72" x 75-1/2"
Empty Weight: 33,800 lbs
Shielding: 1-1/4" steel, 1-3/4" lead
USNRC#: USA/9079/A

HN-100S
ID: 74-1/2" x 75-5/8"
Empty Weight: 26,000 lbs
Shielding: 3" steel
USNRC#: USA/9089/A

HN-100 Liner
This disposable container was designed for use with the HN-100 Series casks. The 1,325 pound liner has a capacity of 163 cubic feet.

HN-600

This cask is also designed for greater than Type A quantities of LSA materials in either drums or large containers. The cask is capable of handling seven (7) 55-gallon drums or one (1) 83 cubic foot container. The shielding is adequate for drums up to 125R per hour or containers up to 100R per hour.

HN-600
ID: 40-1/2" x 75-1/2"
Empty Weight: 35,000 lbs
Shielding: 1-1/2" steel, 2-3/4" lead
USNRC#: USA/9080/A

HN-600 Liner
Designed for use with the HN-600 cask this disposable container weighs 1,256 pounds and has a capacity of 83 cubic feet.

* All radiation levels are based on Cobalt-60 gamma energy.

HN-200

This cask is specifically designed to handle Type B and large quantity shipments. The cask is capable of handling three (3) 55-gallon drums or one (1) 71 cubic foot capacity large container. The cask will adequately shield pre-packaged drums or large containers with contact surface radiation levels up to 800R per hour.

HN-200	ID:	62-1/8" x 54"
	Empty Weight:	37,325 lbs
	Shielding:	1-1/4" steel, 3-3/4" lead
	USNRC#:	USA/6574/B

HN-200 Liner	This disposable container was designed for use with the HN-200 cask. It weighs 80 pounds and has a capacity of 71 cubic feet.

End Loading Containers

HN-300

This trailer-mounted box cask has a remotely-operated tray to receive drums. The cask is designed for Type A and LSA shipments and can handle twelve (12) 55-gallon drums with radiation levels up to 5R per hour.

HN-300	ID:	40-1/2" x 52-1/2" x 12' 0"
	Empty Weight:	35,000 lbs
	Shielding:	3-3/4" steel

HN-400

This trailer-mounted box cask with powered trays is designed to handle type A and LSA shipments. The cask can transport eighteen (18) 55-gallon drums with radiation levels in the 1-4R per hour range or three (3) 70 cubic foot containers with levels up to 1R hour.

HN-400	ID:	39" x 84-5/8" x 12' 2"
	Empty Weight:	31,000 lbs
	Shielding:	2-1/2" steel

HN-800

This cask was developed to provide the safety of full containment with maximum shipping efficiency for wastes in the 0.1-1.0R per hour range. Each cask can handle twenty-four (24) 55-gallon drums or two (2) 125 cubic foot containers.

HN-800	ID:	36" x 76"
	Empty Weight:	24,000 lbs
	Shielding:	1-1/2" steel

Disposable Vaults

HN-150

This cask is a disposable, concrete-shielded vault with a steel liner. The cask weighs 32,000 pounds, has a capacity of 200 cubic feet, and is used primarily for solidified, intermediate-level LSA wastes.

The large disposable containers, or liners, mentioned above are specifically fabricated to fit the various shielded shipping casks and to have a high volume efficiency. The standard liners come equipped with snap-tight lids and slings. Liners capable of withstanding pressure or vacuum can be provided where required, as can liners equipped to accommodate resin dewatering and/or in situ waste solidification.

RADWASTE SHIPPING CASKS

CHEM-NUCLEAR SYSTEMS, INC.

The Exchange - Suite 203
270 Farmington Avenue
Farmington, Connecticut 06032

TRANSPORT EQUIPMENT

Top Loading Casks

CNS 0-4 (LL-28-4)

This container is designed to handle Type B, large quantity, and fissile radioactive materials. It is suitable for underwater loading and can accommodate 3.5 cubic feet of waste materials with radiation levels up to 50,000R per hour.*

CNS 0-4	ID:	40" x 15"
	Empty Weight:	28,150 lbs
	Shielding:	11-1/2" lead equivalence
	USNRC#:	USA/6275/B

CNS 1-8

This steel and polyurethane foam cask is designed to handle Type B materials. The 1-8 provides essentially no shielding and can accommodate one (1) 55-gallon or nine (9) cubic feet of otherwise properly-packaged material.

CNS 1-8	ID:	34-1/2" x 24"
	Empty Weight:	200 lbs
	Shielding:	Nil lead shielding
	USNRC#:	USA/9070/B

CNS 1-13G & CNS 1-13C

These casks are designed to transport one (1) 55-gallon drum or one (1) 13 cubic foot liner of Type B waste material. Both casks are similiar in design except that the 1-13G has an additional overpack, which allows it to contain radiation levels up to 5,000R per hour, as compared to the 1-13C, which will contain up to 1,000R per hour.

CNS 1-13G	ID:	54" x 26-1/2"
	Empty Weight:	23,250 lbs
	Shielding:	6" lead equivalence
	USNRC#:	USA/9044/B
CNS 1-13C	ID:	54" x 26-1/2"
	Empty Weight:	20,950 lbs
	Shielding:	5-3/4" lead equivalence
	USNRC#:	USA/9081/B

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* Based on Cobalt 60 gamma energy, these Rad levels are generally found to be conservative; however, equivalent shielding should be carefully evaluated in relation to the specific isotopes involved.

CNS 3-55 (LL-57-65)

The CNS 3-55 (LL-57-65, Vandenburgh) transport cask is designed to contain Type B, large quantity and spent nuclear fuel materials up to 10,000R per hour. This underwater loading cask can accommodate three (3) 55-gallon drums or a 60 cubic foot capacity disposable liner. The CNS 3-55 is suitable for use with either the redundant crane or dashpot type of cask drop protection system.

CNS 3-55
ID: 36" x 116-3/4"
Empty Weight: 57,000 lbs
Shielding: 7" lead equivalence
USNRC#: USA/5805/B

CNS 4-45

This cask is specifically designed for the transportation and shielding of spent fuel. The 4-45's large internal capacity and lead shielding equivalence make it readily suited for the transport of irradiated reactor hardware up to 10,000R per hour. Four (4) drums or one (1) 45 cubic foot liner can be contained.

CNS 4-45
ID: 26" x 159"
Empty Weight: 57,050 lbs
Shielding: 7-1/2" lead equivalence
USNRC#: USA/6375/B

CNS 4-85

The 4-85 is designed to transport four (4) 55-gallon drums or one (1) 88 cubic foot liner. It is especially useful for the transport of 50-100R per hour resins and/or other materials.

CNS 4-85
ID: 100" x 46"
Empty Weight: 40,300 lbs
Shielding: 3-1/3" lead equivalence
USNRC#: USA/6244/B

CNS 6-75 (AL-33-90)

This cask is designed for shipping sold waste with radioactive levels up to 170R per hour. It can accommodate six (6) 55-gallon drums in two (2) palletized tiers of three (3), or 75 cubic foot capacity disposable liner.

CNS 6-75
ID: 74-1/2" x 53"
Empty Weight: 31,000 lbs
Shielding: 4" lead equivalence
USNRC#: USA/9108/A

CNS 6-80-1 & CNS 6-80-2**

The 6-80-1 and 6-80-2 are designed to transport radwaste radiating up to about 500R per hour. The 6-80-1 will accommodate six (6) 55-gallon drums or an 85 cubic foot liner. The 6-80-2 will accommodate four (4) drums or an 85 cubic foot liner. The 6-80-1 is classified as a "strong, tight container" for Type A quantities only. The 6-80-2 is classified for Spec. 7A quantities.

CNS 6-80-1	ID:	58" x 59"
	Empty Weight:	32,220 lbs
	Shielding:	5" lead equivalence
CNS 6-80-2	ID:	58" x 59"
	Empty Weight:	44,000 lbs
	Shielding:	5" lead equivalence
	USNRC#:	USA/9111/A

End Loading Containers

CNS 6-101 Spec. 7A

The self-loading 6-101 container is designed to transport six (6) 55-gallon drums with radiation readings of up to 60R per hour.

CNS 6-101	ID:	40" x 34" x 13' 0"
	Shielding:	3-1/4" lead equivalent
	USNRC#:	USA/9105/A

CNS 12-180 (AL-31-120)

This transport container is designed to accommodate twelve (12) 55-gallon drums of Type A quantities or less of radwaste material. The 12-180 is equipped with roller conveyors compatible with most PWR and BWR drum loadout facilities.

CNS 12-180	ID:	40" x 54" x 12' 7"
	Empty Weight:	31,000 lbs
	Shielding:	2" lead equivalence

Shielded Vans

Standard 40 foot, closed trailers are provided; however, 1/2 inch lead shielding, 35 inches in height, is placed around the interior perimeter and on the floor of the van. Up to 26,000 pounds of drummed or otherwise properly packaged radwaste may be transported per shipment. Radwaste radiating up to about one rem per hour may be readily transported herein.

** These casks are considered "strong, tight containers" and radiation levels of the contents shall not exceed one rem per hour at three feet from the unshielded surface. The 6-80-1 and 14-195L casks are currently in licensing for Spec. 7A certification.

CNS BTC-C Transport Container

The top-loading CNS BTC-C containers are dump-type vehicles which may be utilized for the transport of bulk radioactive wastes. Each container has an available volume of 620 ft^3. Up to 36,000 pounds of payload may be transported per shipment. Dimensions - 52" x 84" x 18' 0".

CNS BTC-S Transport Container

The top-loading CNS BTC-S is a strong, tight container assigned for the shipment of bulk or LSA radioactive wastes. The BTC-S has an interior capacity of 360 cubic feet. Each container consists of an outer shell with three (3) removable steel boxes therein, each of 120 ft^3 capacity.

CNS 7-100

This transport cask is designed to contain seven (7) drums or one (1) 100 cubic foot liner with radiation levels up to 100R per hour.

CNS 7-100
ID: 40-3/4" x 75-1/2"
Empty Weight: 35,000 lbs
Shielding: 3-1/2" lead equivalence
USNRC#: USA/9113/A

CNS 8-120 (LL-50-100)

The CNS 8-120 is a lead and steel cask certified for Type B and large quantities of radioactive materials with levels up to 250R per hour. This cask can accommodate eight (8) standard 55-gallon drums or a 124 cubic foot disposable liner and is suitable for underwater loading.

CNS 8-120
ID: 75" x 62"
Empty Weight: 58,000 lbs
Shielding: 4-1/2" lead equivalence
USNRC#: USA/6601/B

CNS 14-190 (BC-48-220)

This steel and concrete cask is certified for Type B quantities of radioactive material with levels up to 15R per hour. It will accommodate 14 standard size drums or a 195 cubic foot liner.

CNS 14-190
ID: 88-1/4" x 73"
Empty Weight: 60,280 lbs
Shielding: 2-3/4" lead equivalence
USNRC#: USA/5026/B

CNS 14-195L**

The 14-195L is designed to transport 14 drums or one (1) 200 cubic foot liner with radiation levels up to approximately 7R per hour at the surface.

CNS 14-195L
ID: 80-1/8" x 77"
Empty Weight: 31,550 lbs
Shielding: 2" lead equivalence

CNS 14-195H

This cask is designed to contain 14 drums or one (1) 200 cubic foot liner with radiation levels up to approximately 25R per hour.

CNS 14-195H	ID:	80" x 77"
	Empty Weight:	39,650 lbs
	Shielding:	2-3/4" lead equivalence
	USNRC#:	USA/9094/A

CNS 14-220L (AL-27-240)**

This steel and concrete cask can accommodate fourteen (14) 55-gallon drums or a 200 cubic foot container of Type A quantities with levels up to 1R per hour.

CNS 14-220L	ID:	89" x 77-1/2"
	Empty Weight:	33,200 lbs
	Shielding:	1-3/4" lead equivalence

CNS 14-220H**

This cask is the AL-27-240 with supplementary shielding. The cask weighs 39,900 pounds and has a volume of 228 cubic feet. Inside dimensions are 75-1/2" in diameter and 88" in height. With a lead equivalence of 2-3/4", the 14-220H can accommodate 14 drums of Type A radwaste.

CNS 15-160S**

The top-loading 15-160S is designed to transport fifteen (15) 55-gallon drums or two (2) 80 cubic foot liners, with radiation levels up to 15R per hour.

CNS 15-160S	ID:	72" x 124"
	Empty Weight:	42,000 lbs
	Shielding:	2-1/2" lead equivalence

CNS 15-160B

This cask is designed to transport 15 drums or two (2) 80 cubic foot liners of Type B shipments with radiation levels up to 5R per hour.

CNS 15-160B	ID:	75" x 126"
	Empty Weight:	37,000 lbs
	Shielding:	1-1/2" lead equivalence
	USNRC#:	USA/6144/B

** These casks are considered "strong, tight containers" and radiation levels of the contents shall not exceed one rem per hour at three feet from the unshielded surface. The 60-80-1 and 14-195L casks are currently in licensing for Spec. 7A certification.

CNS 18-450 Spec. 55

The 18-450 is designed to transport one (1) 308 cubic foot liner or eighteen (18) 55-gallon drums reading one to five rem per hour at contact. Supplemental shield plates located on the cask's exterior provide an additional inch of lead equivalence.

CNS 18-450	ID:	88" x 100"
	Empty Weight:	36,950 lbs
	Shielding:	1-2" lead equivalence

CNS 21-300 Spec. 7A Cask

The 21-300 is designed to transport twenty-one (21) 55-gallon drums or one (1) 315 cubic foot liner of radwaste with radiation levels of one to five rem per hour being readily shielded.

CNS 21-300	ID:	109" x 83"
	Empty Weight:	30,200 lbs
	Shielding:	1-1/2" lead equivalence
	USNRC#:	USA/9096/A

RADWASTE SHIPPING CASKS

ANEFCO, CO.

222 Mamaroneck Avenue
White Plains, New York 10605

TRANSPORT EQUIPMENT

AP 101 Cask

This cask consists of two concentric stainless steel cylindrical shells and is designed to transport cut up spent fuel channels and other non-fuel bearing components.

AP 101	ID:	28" x 167-1/16"
	Inner Shell:	5/8" thick x 28" diameter
	Outer Shell:	1-1/2" thick x 39-1/4" diameter

The space between is filled by a 3-1/2" poured lead shield. The outer shell is surrounded by a 0.14" thick steel thermal shield separated by a 0.175" thick stainless steel spacer wire. The cask's gross weight is 62,000 lbs.

APPENDIX B

ESTIMATING PACKAGE EXTERNAL DOSE RATE

ESTIMATING PACKAGE EXTERNAL DOSE RATE

The method for estimating the exposure rate at the surface of a shipping package involves determining the gamma flux due to the curie source strength of the component as a function of shielding characteristics and then determining the exposure rate as function of the flux and the gamma energies. The equations used are as follows:

For the gamma flux

$$\phi_b = \frac{B\,S_v}{2\,\mu_s}\left\{E_2(b_1) - E_2(b_3)\right\} \qquad (1)$$

Where:

ϕ_b = gamma flux, γ/cm^2-sec
B = Buildup factor, dimensionless
S_v = Volumetric source strength, γ/cm^3-sec
μ_s = Linear attenuation coefficient of source, 1/cm
$E_2(\ )$ = "E" function of: $b_1 = \mu t$
Where:
μ = linear attenuation coefficient of container, 1/cm
t = thickness of container, cm
b_3 = $b_1 + \mu_s h$
Where:
μ_s = linear attenuation coefficient of source, 1/cm
h = thickness of source, cm

For the dose rate:

$$\dot{X} = 0.0659\,(E_o)\left(\frac{\mu_a}{\rho}\right)_{air}\phi_b \qquad (2)$$

Where:

$\dot{X}$ = dose rate, mR/hr
E_o = gamma energy, MeV
$\left(\frac{\mu_a}{\rho}\right)$ = mass absorption coefficient, cm^2/g
ϕ_b = flux level, γ/cm^2-sec

The principal source of gammas is considered to be the decay of ^{60}Co, as the radiation due to other nuclides, such as ^{55}Fe, ^{63}Ni, ^{59}Ni and ^{94}Nb, is relatively small in comparison. Therefore, all curies of the source are assumed to be those of ^{60}Co.

The above equations (1 and 2) will be used to ensure that the package chosen will supply sufficient shielding to meet package external exposure rate limitations. The specific procedure is as follows:

1. OBTAINING NECESSARY INFORMATION

1.1 Package Dimensions

1. Geometric Configuration
2. Wall (and/or shielding) Thickness
3. Overall Volume

1.2 Package Material Properties

Linear attenuation coefficient, μ: a function of the energy of the gamma(s) emitted by the source. Linear attention coefficient for some common packaging materials are found in Table B.1 of this chapter.

For a wood or a fiber package, assume $\mu = 0$, unless shielded.

Buildup Factor B: a function of the package thickness, the linear attenuation coefficient, μ, of the package and its thickness, and the gamma energy. Buildup factors for some typical materials are shown in Table B.2.

For wood or fiber package, use $B = 1$ unless shielded.

1.3 Component Dimensions

1. Geometric Configuration
2. Thickness
3. Volume of Material

TABLE B.1

LINEAR ATTENUATION COEFFICIENTS, (μ), CM^{-1} FOR SOME TYPICAL PACKAGING AND SHIELDING MATERIALS

Source: ANL-5800, Reactor Physics Constants, Argonne National Lab, July 1973

ENERGY (MeV)	LEAD μ	WATER μ	CONCRETE μ	AIR μ	STAINLESS STEEL μ
0.1000	0.637697E 02	0.167417E 00	0.399360E 00	0.184370E-03	0.270533F 01
0.2000	0.109956E 02	0.136049E 00	0.291950E 00	0.150180E-03	0.110843E 01
0.3000	0.436788E 01	0.118297E 00	0.250480E 00	0.129430E-03	0.855655E 00
0.4000	0.250760E 01	0.105583E 00	0.223100E 00	0.116360E-03	0.738689E 00
0.5000	0.174781E 01	0.964392E-01	0.203460E 00	0.105980E-03	0.665730E 00
0.6000	0.136183E 01	0.891312E-01	0.188010E 00	0.981680E-04	0.610818E 00
0.7000	0.112199E 01	0.831914E-01	0.175450E 00	0.921855E-04	0.567497E 00
0.8000	0.971555E 00	0.782192E-01	0.165030E 00	0.862030E-04	0.532567E 00
0.9000	0.876709E 00	0.742983E-01	0.156680E 00	0.830895E-04	0.505484E 00
1.0000	0.781863E 00	0.703773E-01	0.148330E 00	0.799760E-04	0.478402E 00
1.2500	0.646274E 00	0.629691E-01	0.132600E 00	0.692310E-04	0.427285E 00
1.3000	0.632550E 00	0.618479E-01	0.130260E 00	0.680100E-04	0.419807E 00
1.5000	0.577655E 00	0.573630E-01	0.120900E 00	0.631260E-04	0.389893E 00
1.7000	0.542553E 00	0.537324E-01	0.113444E 00	0.596096E-04	0.367440E 00
1.7500	0.533778E 00	0.528247E-01	0.111580E 00	0.587305E-04	0.361827E 00
2.0000	0.510635E 00	0.491874E-01	0.104240E 00	0.543350E-04	0.340753E 00
2.2000	0.495510E 00	0.466513E-01	0.991880E-01	0.521860E-04	0.326628E 00
2.5000	0.480994E 00	0.435145E-01	0.929000E-01	0.489625E-04	0.309715E 00

TABLE B.1
(Continued)

ENERGY (MeV)	LEAD µ	WATER µ	CONCRETE µ	AIR µ	STAINLESS STEEL µ
2.7500	0.474396E 00	0.413454E-01	0.886100E-01	0.462762E-04	0.298737E 00
3.0000	0.471097E 00	0.395101E-01	0.849749E-01	0.435900E-04	0.289785E 00
3.5000	0.467468E 00	0.363733E-01	0.789640E-01	0.405375E-04	0.275326E 00
4.0000	0.469778E 00	0.339373E-01	0.743500E-01	0.374850E-04	0.265142E 00
4.5000	0.474726E 00	0.319284E-01	0.705990E-01	0.354700E-04	0.257432E 00
5.0000	0.481324E 00	0.302599E-01	0.675470E-01	0.334550E-04	0.251805E 00
5.5000	0.487592E 00	0.288283E-01	0.649840E-01	0.319900E-04	0.247632E 00
6.0000	0.494850E 00	0.276103E-01	0.628630E-01	0.305250E-04	0.244584E 00
6.1500	0.497225E 00	0.272970E-01	0.623248E-01	0.302503E-04	0.243902E 00
6.5000	0.502768E 00	0.265659E-01	0.610690E-01	0.296092E-04	0.242311E 00
7.0000	0.511345E 00	0.256715E-01	0.595320E-01	0.286935E-04	0.240655E 00
7.5000	0.520582E 00	0.248907E-01	0.582030E-01	0.277777E-04	0.239348E 00
8.0000	0.529819E 00	0.242033E-01	0.570620E-01	0.268620E-04	0.238401E 00
8.5000	0.539386E 00	0.235959E-01	0.560370E-01	0.263125E-04	0.237699E 00
9.0000	0.548294E 00	0.230553E-01	0.551740E-01	0.257630E-04	0.237285E 00
10.0000	0.562809E 00	0.221410E-01	0.538930E-01	0.246640E-04	0.237909E 00

TABLE B.2

BUILDUP FACTORS FROM SOME TYPICAL MATERIALS

Source: "Nuclear Engineering Handbook," H. Etherington (Ed.), McGraw-Hill (1958)

	Eo	(μ x t) container or shield						
Material	MeV	1	2	4	7	10	15	20
Water	0.255	3.09	7.14	23.0	72.9	166	456	982
	1.0	2.13	3.71	7.68	16.2	27.1	50.4	82.2
	3.0	1.69	2.42	3.91	6.23	8.63	12.8	17.0
	6.0	1.46	1.91	2.76	3.99	5.18	7.09	8.85
	10.0	1.33	1.63	2.19	2.97	3.72	4.90	5.98
Aluminum	0.5	2.37	4.24	9.47	21.5	38.9	80.8	141
	2.0	1.75	2.61	4.62	8.05	11.9	18.7	26.3
	4.0	1.53	2.08	3.22	5.01	6.88	10.1	13.4
	8.0	1.34	1.68	2.37	3.45	4.58	6.56	8.52
Iron	0.5	1.98	3.09	5.98	11.7	19.2	35.4	55.6
	2.0	1.76	2.43	4.13	7.25	10.9	17.6	25.1
	4.0	1.45	1.94	3.03	4.91	7.11	11.2	16.0
	8.0	1.27	1.56	2.23	3.49	5.07	8.50	13.0
Tin	0.5	1.56	2.08	3.09	4.57	6.04	8.64	
	2.0	1.57	2.17	3.53	5.87	8.53	13.6	19.3
	4.0	1.38	1.81	2.82	4.82	7.41	13.2	21.2
	8.0	1.19	1.42	2.05	3.57	6.19	15.1	34.0
Lead	0.5	1.24	1.42	1.69	2.00	2.27	2.65	9.0
	2.0	1.39	1.76	2.51	3.66	4.84	6.87	12.3
	4.0	1.27	1.56	2.25	3.61	5.44	9.80	16.3
	6.0	1.18	1.40	1.97	3.34	5.69	13.8	32.7
Uranium	0.5	1.17	1.30	1.48	1.67	1.85	2.08	
	2.0	1.33	1.64	2.23	3.09	3.95	5.36	16.2
	4.0	1.24	1.50	2.09	3.21	4.66	8.01	12.7
	8.0	1.12	1.27	1.66	2.61	4.36	11.2	28.0

1.4 Component Weight

1.5 Component Activity

1.6 Component (source) Material Properties

1. Linear Attenuation Coefficient, μ_s function of gamma energy. Also found in Table B.1
2. Density, from standard handbooks

1.7 Gamma Energy

The packaging (and shielding) required is dependent on the frequency and the energy of the gamma (or gammas) emitted during the decay of certain radionuclides.

The mode of decay for each radionuclide on the list of radionuclides obtained during the activation analyses can be found in standard radiological handbooks (e.g. U.S. DHEW Radiological Health Handbook, 1970)

Included in the mode of decay should be the energy of the gamma and its frequency of emission.

Major radiations for some typically occurring activation radionuclides are shown in Table B.3.

2. CALCULATE GAMMA FLUX

Calculate the gamma flux using Equation 1 and the following procedure:

1. Calculate the volumetric source strength, S_v, in units of γ/cm^3-sec, for each gamma energy and relative intensity, from component weight, activity and density:

$$\left\{ \frac{\text{Act.,Ci}}{\text{Wgt., lb}} \times \text{Density, } \frac{\text{lb}}{\text{cm}^3} \right\} \times \left\{ 3.7 \times 10^{10} \frac{\text{dis}}{\text{Ci-sec}} \right\} \times \frac{\text{No. of } \gamma\text{'s}}{\text{disint.}} = \frac{\gamma}{\text{cm}^3\text{- sec}} = S_v \qquad (3)$$

TABLE B.3

MAJOR RADIATIONS FOR TYPICALLY OCCURRING ACTIVATION RADIONUCLIDES

Source: Radiological Health Handbook, DHEW, 1970.

	Energy of Beta Emissions	Frequency of of Emissions	Energy of Gamma	Frequency of Emissions
Co-60	1.48 MeV .314	0.12 % 99 %	1.173 MeV 1.332	100 % 100 %
Fe-55	Mn X-rays, continuous bremsstrahlung to 0.23	0.004 %	none	
Ni-63	0.067 MeV Max		none	
C-14	0.156 MeV Max		none	
Ni-59	Co X-rays, continuous bremsstrahlung to 1.06			
Nb-94	0.49 MeV Max		0.702 MeV 0.871	100 % 100 %

2. Calculate "b_1" for the container.
3. Determine E_2 (b_1) from appropriate curve in Figure B.1.
4. Calculate "b_3" for component (source).
5. Determine $E_2(b_3)$ from appropriate curve in Figure B.1.
6. Make any simplifying assumptions.
7. Calculate ϕ_b.

3. CALCULATE DOSE RATE

Calculate the exposure rate using Equation 2. The only parameter not yet identified is the mass absorption coefficient, ($\frac{\mu_a}{\rho}$). In the case of external dose rate, the value for air is used. Values of ($\frac{\mu_a}{\rho}$) for several materials are shown in Table B.4.

FIGURE B.1

VALUES OF "E FUNCTION"

Source: Rockwell, Shielding Design Manual

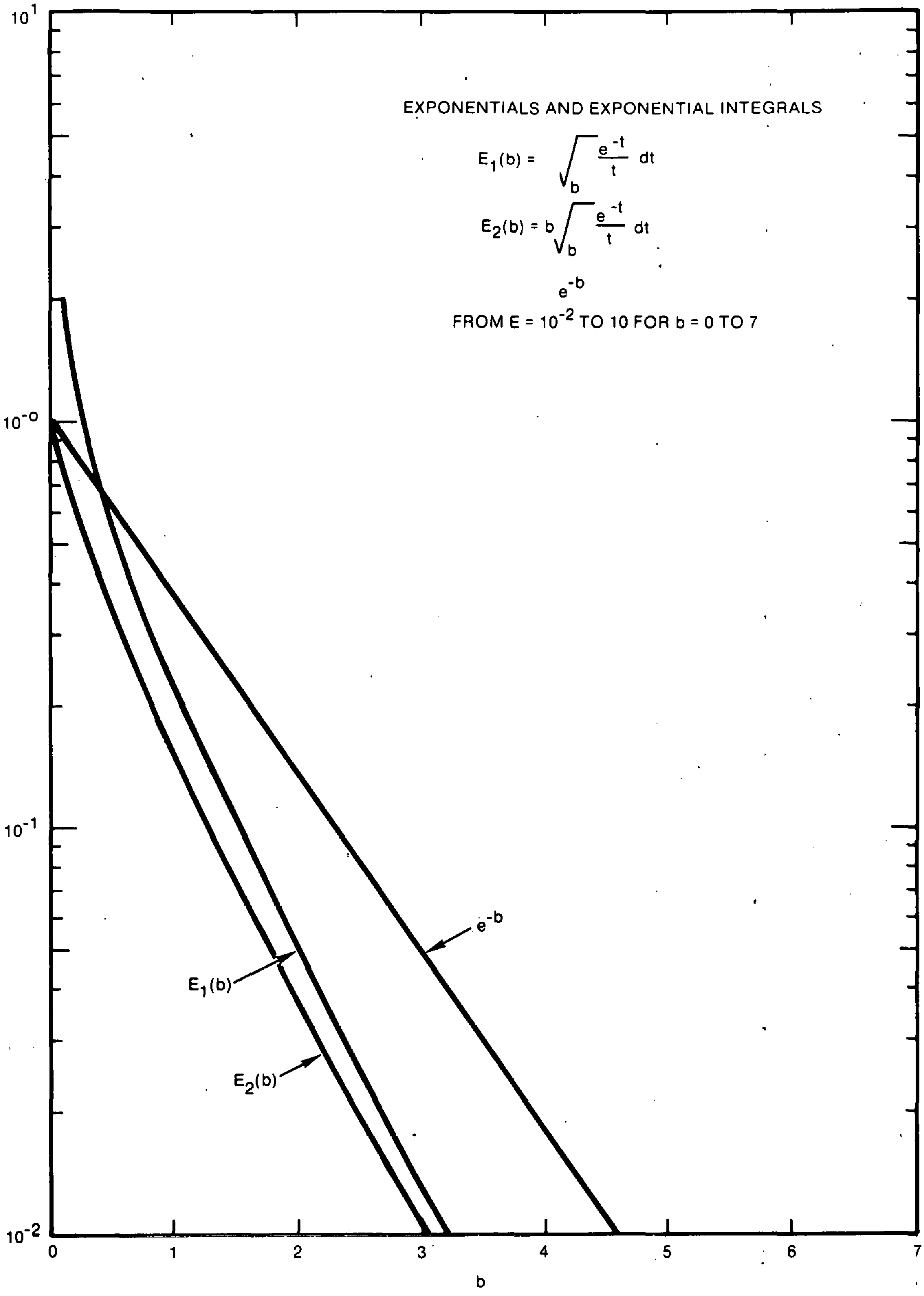

FIGURE B.1

(Continued)

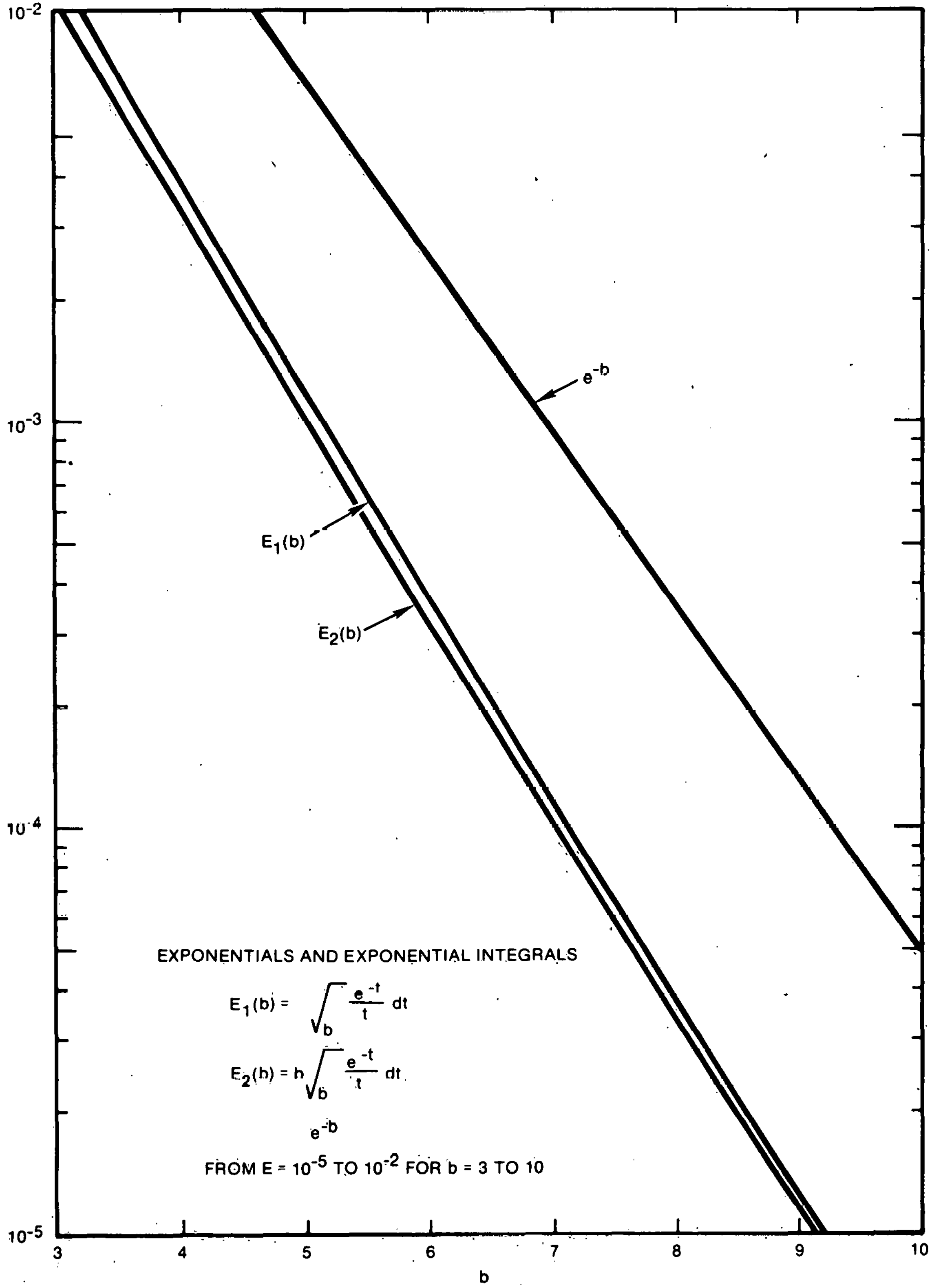

TABLE B.4

MASS ABSORBTION COEFFICIENT FOR SOME TYPICAL MATERIALS *

$(\frac{\mu_a}{\rho})$ cm²/gm

	Gamma-Ray Energy, MeV							
Material	0.1	0.2	0.5	1.0	2	4	6	10
H	.0411	.0531	.0591	.0557	.0467	.0354	.0291	.0255
O	.0233	.0271	.0297	.0280	.0238	.0195	.0175	.0157
Al	.0373	.0275	.0286	.0270	.0232	.0200	.0188	.0182
Fe	.225	.0489	.0294	.0261	.0231	.0224	.0231	.0250
Pb	5.193	.821	.0994	.0402	.0293	.0330	.0373	.0450
U	9.63	1.096	.132	.0482	.0324	.0352	.0394	.0474
Air	.0233	.0268	.0297	.0280	.0238	.0194	.0172	.0153
H_2O	.0253	.0300	.0330	.0311	.0264	.0213	.0188	.0165
Concrete	.0416	.0289	.0296	.0278	.0239	.0203	.0188	.0177

* From L.T. Templin, editor, Reactor Physics Constants, ANL-5800, 2nd Edition, 1963; based on G.W. Grodstein, National Bureau of Standards Circular 583, 1957.

The calculated dose rate in millirems/hour should then be compared to the limits. If it is assumed that for this calculation the dose rate at the surface of the package is approximately equal to the dose rate at 6 feet, then the dose rate calculated above should be less than 10 mRem/hr.

4. IF THE DOSE RATE EXCEEDS THE VALUE OF 10, THEN:

4.1 Alternate packaging with more adequate shielding must be used:

Choose another package from the list of containers in Section 9.6 and/or Appendix A of this chapter.

4.2 The container must be protected by an "overpack" or transport shield:

Choose a shield from Section 9.6 of this chapter.

4.3 The component must be protected by additional shielding inside the container.

Add lead, concrete, steel, polyethylene or other appropriate material inside the package.

The dose rate then must be recalculated based on the method of additional shielding. The exact method should be chosen based on the conditions and economics of the case at hand.

APPENDIX C

SHIPPING PAPERS

This appendix presents the specific consignment information required for shipping radioactive materials. Also, a typical example of the form for shipping papers is presented.

SHIPPING PAPERS

HAZARDOUS MATERIALS - SPECIFIC CONSIGNMENT INFORMATION

1.	U.S. NRC Shipment Approval Number:	49 CFR 173.393	
2.	Shipment Package Number	49 CFR 173	49 CFR 178
3.	Package U.S. DOT Spec. Number	10 CFR 71	
4.	Type of Licensed Material	10 CFR 20.3	10 CFR 71.62
5.	Hazardous Material	49 CFR 173.401	49 CFR 173.402
	A. Classification:	49 CFR 173.2	49 CFR 172.4
	B. Shipping Name:	49 CFR 172.5	
	C. Weight:	49 CFR 173.427	
	D. Volume:	49 CFR 173.427	
6.	Radionuclides	49 CFR 173.390	49 CFR 173.427
7.	Activity of Package (curies)	49 CFR 173	
8.	Transport Index	49 CFR 173.389	49 CFR 177.842
9.	Radioactive Material: 10 CFR 71.62	49 CFR 173.401	49 CFR 173.402
	A. Normal Form	49 CFR 173.427	
	(1) Physical Form		
	(2) Chemical Form		
	(3) Name of Radionuclides		
	(4) Transport Group		
	(5) Type A Quantity		
	(6) Type B Quantity		
	(7) Large Quantity		
	B. Special Form:	49 CFR 173.389	49 CFR 173.398
	(1) Material Description		
	(2) Type A Quantity		
	(3) Type B Quantity		
	(4) Large Quantity		
10.	Type of Label Required:	49 CFR 173	
	A. No Label Required	49 CFR 173.427	
	B. Radioactive - White I		
	C. Radioactive - Yellow II		
	D. Radioactive - Yellow III		
	E. Other		

SHIPPING PAPERS
TYPICAL FORM FOR HAZARDOUS MATERIALS

General Description of Consignment

1. Shipper	
Name:____________________	49 CFR 171
Phone:____________________	
Address:____________________ ____________________ ____________________	49 CFR 177
NRC Approval No.:____________________	49 CFR 173.393
DOT Special Permit No.:____________________	49 CFR 171.6
Type of Protective Signature Service:____________________	
Type of Constant Surveillance Service:____________________	
Origin of Shipment (Address):____________________ ____________________ ____________________	
Date Shipment Departed:____________________	10 CFR 71.62
Date Shipment Due to Arrive:____________________	49 CFR 173.22
2. Shipper's Consignment	10 CFR 71.62
(This Shipment Only)____________________ ____________________	
Total Activity (curies):____________________	49 CFR 177
Total Number of Packages:____________________	49 CFR 171.6
Total Quantity of Licensed Material:____________________	10 CFR 71.62
Weight:____________________	
Volume:____________________	
Total Transport Index Limit:____________________	
Total Transport Index:____________________	

TYPICAL FORM FOR HAZARDOUS MATERIALS

(Continued)

3. Shipper's Certification: 49 CFR 173.430

"This is to certify that the above-named articles are properly classified, described, packaged, marked and labeled and are in proper condition for transportation, according to the applicable regulations of the Department of Transportation."

____

(Signature of Shipper)

4. Carrier

Name:________________________________ 49 CFR 173.393

Address:________________________________

____

____

Transport Vehicle:(Type)__________________________

Mode of Shipment:____________________________

5. Incident Information 49 CFR 177.86

____

____

Special Shipper Requirement:______________________

____

____

6. Transport Vehicle

Placarding Required:____________________________ 49 CFR 173

____

7. Transferee

Name:________________________________ 10 CFR 71.62

Address:________________________________ 49 CFR 177

____

____

Destination of Shipment:__________________________

Site Manager:(Name)____________________________

Address:________________________________

____

____

APPENDIX D

NECO SITE OPERATIONS MANUAL EXCERPTS

5.1.1 Records Review of Material Transported to the Site

Upon arrival of low level radwaste at the Beatty, Nevada, Nuclear Waste Disposal Site, the Site Manager, Assistant Site Manager, Site Radiological Control and Safety Officer or a Radiological Control and Safety Technician shall conduct an initial review of the shipping forms including the Radioactive Shipment Records, for accuracy and completeness. This review shall also ascertain whether or not the material received for disposal meets the Beatty Site licensing requirements prior to the acceptance of the material by NECO.

NECO will not receive, or possess, unburied, at any time, radioactive waste materials (i.e.: by-product, special nuclear, source and any other naturally occuring or artifically produced radionuclides) in excess of the following:

5.1.1.1 By-product Radioactive Waste Material

50,000 curies of radioactive material, other than source material, with atomic number 1-91 except radium 226 which shall be limited to 1 curie.

When waste is to be removed from its DOT shipping container prior to burial, such waste shall be limited to 1600 curies, equivalent Cobalt 60, per package.

Before exceeding this limit, procedures for handling and projected exposures must first be reviewed and approved by the Chief Radiological Control and Safety Officer and Nevada State Radiological Health Department.

5.1.1.2 Source Radioactive Waste Material: 11,340 kilograms

5.1.1.3 Special Nuclear Radioactive Waste Material

5.1.1.3.1 Each accumulation of packages shall not contain more than 350 grams of Uranium 235 or 200 grams of Uranium 233 or combinations thereof such that the sum of the ratios of the quantity of each special nuclear material to the quantities specified herein does not exceed unity, as determined by the following formula:

$$\frac{\text{Grams Contained U235}}{350} + \frac{\text{Grams Contained U233}}{200} \leq 1$$

5.1.1.3.2 No single package shall contain more than 100 grams of Uranium 235 or 60 grams of Uranium 233 or any combination thereof such that the sum of the ratios of the quantity of each special nuclear material to the quantities specified herein does not exceed unity, as determined by the following formula:

$$\frac{\text{Grams Contained U235}}{100} + \frac{\text{Grams Contained U233}}{60} \leq 1$$

5.1.1.3.3 No single package shall contain more than 15 grams of any combined Uranium 235 and Uranium 233 per cubic foot of total volume.

5.1.1.3.4 The average concentration of plutonium shall not exceed 10 nanocuries per gram of waste in any container.

5.1.1.4 Transuranic Radioactive Waste Material

For quantities of radioactive material with atomic numbers greater than 92, the average concentration for these materials shall not exceed 10 nanocuries per gram of waste in any container.

5.1.1.5 Liquid Radioactive Waste Material

No liquid radioactive waste material will be received in excess of the following concentrations:

Transport Group I*	0.01 microcurie per milliliter
Transport Group II	0.50 microcurie per milliliter
Transport Group III and Group IV	30.00 microcuries per milliliter

* Except for special nuclear material which is not authorized for possession in liquid form. (Please note that the above applies to liquid received by pre-arrangement for solidification. Unless covered by Section 5.4.6.1 or by Section 5.4.6.2, free liquids, other than those received for solidification are not accepted.)

5.1.1.6 Gaseous Radioactive Waste Material

Will be limited to Krypton 85 and tritium. The primary container pressure will be limited to one atomosphere and activity will be limited to 1000 curies total.

5.4.6 Liquid Waste

The burial of radioactive liquid waste received for solidification is covered in Section 6.0 of this NECO manual.

Radioactive liquid waste, which does not exceed the concentration limitations in Section 5.1.1.5 and are received as scintillation vials or in volumes of no more than one gallon, may be buried unsolidified, subject to the following requirements.

5.4.6.1 Scintillation vials will only be buried when they have been received or placed in a DOT specification steel drum (either 30 or 55 gallon) into which enough absorbent material (for example: Pel-E-Cel, diatomaceous earth, Micro-Cel-E, etc.) has been added so that at least twice the volume of scintillation liquid could be absorbed in the event release of all liquid in the vials were to occur simultaneously.

5.4.6.2 Small quantities (no more than one gallon per inner container) of rad liquid waste will only be buried when they have been received or placed in a DOT specification steel drum (either 30 or 55 gallon) into which enough absorbent material (for example: Pel-E-Cel, diatomaceous earth, Micro-Cel-E, etc.) has been added so that at least twice the volume of liquid could be absorbed in the event release of all liquid were to occur simultaneously.

Certification Requirements

5.9 The minimum requirements for records and certifications required for disposal operations will be as follows:

5.9.1 In addition to the RSR, NECO will require customer certifications including shipment compliance to requirements in Section 5.1.1.3; 5.1.1.4; 5.1.1.5; 5.1.1.6; 5.4.6.1; and 5.4.6.2 for waste received for burial at the Beatty facility on all Radioactive Shipment Records. For shipments of SNM containers, customers shall seal such containers with a tamper proof seal, or in truckload quantities, the door of such trailers shall carry a tamper proof seal. For shipments of SNM, an ERDA Form 741 will accompany such shipments and be consigned to either the Site Manager, Assistant Site Manager, or Radiological Control and Safety Officer by name, and instruct the carrier to receive positive identification of the receiver by signature before consigning over such shipments.

License Renewal Application

2.5.2 Beginning May 19, 1978, only radioactive liquid waste material in scintillation vials in concentrations less than or equal to 0.02 microcurie per milliliter will be received for burial. Liquids absorbed in a container of absorbing material will not be accepted, and liquids in double-walled containers will not be permitted.

2.5.3 No special nuclear material will be received in liquid form.

Certification

This is to certify that I have read and understand the requirements of License #13-11-0043-02 issued to Nuclear Engineering Company (NECO) by the Nevada Department of Human Resources for the receipt and disposal of radioactive materials at Beatty, Nevada, as described in paragraphs 5.1.1.3 through 5.1.1.6; 5.4.6.1; and 5.4.6.2 of the NECO Site Operations Manual, and I further certify that the materials in this shipment are in conformity with those requirements:

______________________	______________________
Company	Authorized Signature
______________________	______________________
Date	Title

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CHAPTER 10

ASSESSMENT OF ENVIRONMENTAL IMPACTS

10.1 INTRODUCTION

The environmental impacts of a decommissioning program must be determined to provide a basis for the evaluation of risks and benefits of the various decommissioning alternatives, and to meet certain state and federal regulations concerning environmental impact assessments. This chapter identifies generic environmental impacts of decommissioning activities and provides guidance in evaluating their significance.

10.1.1 Government Regulation

The decommissioning of nuclear facilities in the United States requires implementation of a review process by a responsible federal agency. The National Environmental Policy Act (NEPA) of 1969 requires that the responsible federal agency (hereafter referred to as the "Agency") determine the need for an environmental impact statement for actions or proposals with potential for significant impact to the human environment.

For commercial nuclear facilities the US Nuclear Regulatory Commission (NRC) is the responsible federal agency. NRC procedures for NEPA implementation are provided in 10 CFR 51, "Licensing and Regulatory Policy and Procedures for Environmental Protection".

For federal and military nuclear facilities the US Department of Energy (DOE) is the responsible agency. DOE procedures for implementing NEPA regulations are provided in "DOE Guidelines for Compliance with the National Environmental Policy Act," published in 44 CFR 2136, July 18, 1979.

The applicant is instrumental in supporting the federal agencies in this phase of licensing. The Agency may request the applicant to prepare an environmental assessment, the purpose of which is to identify potentially significant environmental impacts of the proposed action. The Agency would evaluate all available information and make a determination as to the need for an Environmental Impact Statement (EIS).

If an EIS is not deemed necessary, a negative declaration (i.e, a conclusion by the Agency that the potential or proposed action will not have significant environmental consequences) is issued. This is supported by an environmental impact appraisal that describes the potential impacts and provides the basis for the negative declaration. When an agency decides that an EIS will be prepared, a notice of intent will be issued. The applicant may be required to submit an environmental report that will assist the Agency in preparation of the EIS.

10.1.2 Environmental Impact Categories

Section 5.8 of USNRC Regulatory Guide 4.2, "Preparation of Environmental Reports for Nuclear Power Stations," defines the key elements to be addressed in the licensing phase relative to decommissioning and dismantling. The items include:

1. Long-term use of the land and post-decommissioning site condition
2. Amount of land irretrievably committed
3. Environmental consequences of decommissioning
4. Costs of decommissioning

These categories would also be covered in an assessment of an actual decommissioning program with significant expansion of the specific environmental consequences.

The following areas are expected to be included in an environmental assessment of a specific decommissioning program:

1. Impact on land resources
2. Occupational radiation exposure
3. Non-occupational radiation exposure
4. Industrial safety considerations
5. Non-radiological effluent releases
6. Sociological-economic impacts
7. Program-related resource commitments.

Section 10.2 of this chapter contains a discussion of the generic factors within these categories.

10.1.3 Methods of Evaluating Environmental Impact Significance

Government regulations and guidelines for evaluating the environmental impacts of decommissioning are being developed, however, the basic philosophy for environmental impact review of decommissioning is not expected to differ from that found in current licensing for the design, construction and operation of nuclear facilities. Until environmental standards for decommissioning have been issued, the environmental impact evaluations may be conducted using methods that are consistent with current licensing practices. These methods are:

1. Comparison of environmental impacts of decommissioning with the environmental impacts caused by the construction or operation of the facility
2. Comparison of decommissioning environmental impacts with federal, state and local environmental regulations
3. Pathway analysis of effluent releases to the environment.

It is expected that the first two methods will find the greatest utilization in a decommissioning assessment.

10.2 GENERIC ENVIRONMENTAL IMPACT FACTORS

This section describes the generic impacts that might result from a protective storage or dismantling program of a nuclear facility. It is obvious that the relative importance of these factors is dependent on site-specific considerations. Also, quantitative information cannot be presented because of site-specific import.

10.2.1 Impact on Land Resources

Of significance in any mode of decommissioning of any facility is the short term and long term impact on land resources. The short term impacts associated with site preparation include new building construction, new road construction, water channel modification, equipment laydown area establishment, area dewatering and water run-off provision, and associated effects on site water bodies and local biota. The long-term effects include commitment of site land and commitment of a portion of a licensed radioactive waste repository to accept the products generated by the program.

A protective storage program, either permanent or as part of a delayed dismantling option, will cause a long-term commitment of a section of the site land for this purpose. Since this in itself can be viewed as a negative impact, it will most likely require justification on such bases as minimization of occupational radiation exposure, optimum cost, and maintenance of a hazard-free potential to public health and safety.

A partial or complete dismantling program may result in laydown and staging areas for the packaging, loading and carrier preparation activities associated with radioactive and non-radioactive waste, scrap and salvage disposal. In addition, new facilities may be required to provide locker and change facilities for the decommissioning work force, for the processing of radioactive wastes from a major decontamination program, or to improve the transfer of large components and material sections from existing structures such as containment or reactor buildings. It is expected that most decommissioning programs will entail site preparations that cause little or no disturbance to site water bodies or biota.

10.2.2 Occupational Radiological Exposure

The exposure mechanisms to be evaluated include direct radiation and airborne emissions. Radioactive airborne emissions will result from activities such as decontamination, cutting of a reactor vessel and its internals, cutting of contaminated piping and components, demolition of activated or contaminated concrete structures and radwaste processing.

Airborne emissions should not be a significant contributer to occupational exposure in any decommissioning program. It should be demonstrable that all work activities are controlled to the degree necessary to prevent dispersion of airborne contamination. For example, it could be shown that all major cutting activities will be accomplished within a local contamination control envelope, i.e. an enclosure maintained under negative pressure with the effluent air flow passed through absolute filters. The same principle can be applied to contaminated concrete surface removal. The control of airborne radioactive dust particles during the demolition of activated concrete by blasting has been demonstrated in the Elk River Reactor dismantling program with the use of water spray prior to, during, and after the explosion.[1]

Direct radiation represents the significant mechanism for exposure of the work force. An immediate dismantling program for any facility will result in greater cumulative dose than a protective storage progam. Radiation exposure data for dismantling of three types of facilities are summarized in Table 10.1.

The major elements of a reactor dismantling program contributing to an occupational exposure dose include:

1. Segmenting and handling steam generators, pressurizer, main coolant pumps, and main coolant piping

2. Removing the primary purification system
3. Removing other primary auxiliary systems
4. Fuel handling.

TABLE 10.1

RADIATION EXPOSURE DATA FOR DISMANTLING PROGRAMS

Dismantling Program	Manhours Used	Total Exposure (Rem)	Unit Exposure (mRem/manhour)
Eurochemic Reprocessing Plant Dismantling of Plutonium Tail-end Unit (Actual)[2]	1,000	6	6
Mixed Oxide Fuel Fabrication Plant (Study)[3]	148,000	70	0.47
Large PWR (Study)[4]	140,000	2900	20.7

A reactor entombment program could also have a significant direct radiation occupational exposure if all contaminated systems outside the containment structure were removed. The estimate of this exposure for a large PWR is 1980 man-rem or 68% of the complete dismantling exposure.[4] A simple protective storage (mothballing) program could reduce this exposure to that received from any required decontamination and fuel handling.

A reasonable evaluation of this impact could be developed by comparing the occupational exposure received during operation of the facility to the allowable regulatory levels. For example, the average occupational exposure for an operating light water reactor in the year 1976, as reported in Reference 5, was 499 man-Rem. This is approximately equal to the average yearly exposure predicted for decommissioning a reactor in Reference 4.

10.2.3 Non-Occupational Radiological Exposure

Determining exposure to the general public during decommissioning program would include evaluation of:

1. Radioactive gaseous emissions
2. Liquid releases
3. Transportation of solid radioactive waste
4. Direct radiation from the facility as a source.

Exposure to the public after program completion would also require a similar evaluation for a protective storage mode, although a "zero release" criteria should be able to be demonstrated over the required life of the facility structure. In a complete removal mode there will be no need for evaluation of public exposure after program completion since that factor would have been considered in licensing of the burial ground or repository.

1. Radioactive Gaseous/Airborne Emissions

It is a logical postulate that all airborne gaseous and contamination control systems at a facility will remain in operation while the major radioactive airborne generating activities are taking place. For example, in the complete dismantling of the Elk River Reactor the containment and its associated ventilation system remained operative until all activated and contaminated material was packaged and removed from the containment building. In addition, special provisions were made in each airborne contamination activity (e.g., contaminated pipe cutting, activated vessel cutting, and activated concrete demolition) for local retention and control of the airborne radioactive effluent. The Atomic Industrial Forum's study on decommissioning of large reactors treated this exposure quantitatively.[6] It was demonstrated, that if the work activity leading to the greatest amount of airborne particulate (in-air cutting of an activated reactor vessel) were to continue 24 hours per day for an entire year, the total dose to an individual in continuous residence at the site boundary would be less than 1.0 mRem for the critical organ, the lung. Obviously, elimination of the time-oriented conservatism in this analysis would place the dose at a much lower level. The acceptability of this dose is easily demonstrated.

2. Radioactive Liquid Releases

The amount of fluids containing radioactive materials that will be generated in a decommissioning program will depend on the amount of decontamination performed. The Dow Chemical Company NS-1 process is expected to produce a solvent specific activity of 10 μCi/cc,[7] whereas the actual decontamination campaign at the Eurochemic Reprocessing Plant produced 140 KCi(β) in 370 m^3 of liquid wastes.[2] This corresponds to a specific activity level of about 400 μCi/cc. Depending on the type of decontamination process utilized, the waste treatment may consist of neutralization, filtration, demineralization, evaporation or a combination thereof. Since evaporation can effect an overall reduction in the specific activity of the distillate by approximately 2×10^5,[8] and since the concentrate will be processed as solid radioactive waste, it should be easily demonstrated that the liquid effluent from a decommissioning will be less than allowable discharge limits (e.g. Appendix B, Table II of 10 CFR 20). Most likely, the releases will be less than those experienced during normal facility operation.

3. Transportation of Solid Radioactive Wastes

Any decommissioning program will result in the shipment of some radioactive wastes to a licensed repository. Obviously a complete dismantling program will generate the largest quantity of radioactive wastes to be considered. The shipments will consist of solidified decontamination waste, high level activated components and low-level contaminated or activated materials. The general public will receive some exposure from the direct radiation emitted by the contained material while it is in route to the repository. The amount of this exposure is dependent on the number of shipments, carrier surface dose level, distance to the repository, and the population density along the transportation pathway. A regulatory standard, WASH-1238[9], defines an accepted methodology for evaluating this total dose. Since each shipment must meet the transportation radiation criteria of 49 CFR 170-189, it is expected that the integrated dose to the general public from all shipments will be a very small quantity that can easily be demonstrated as acceptable.

4. Direct Radiation from the Facility

It is possible that a particular work activity in a decommissioning program may introduce an unusual situation that could cause a potential direct radiation hazard to the public; e.g., one-piece removal and transfer of an irradiated reactor vessel to its transport carrier. Therefore, the program should be examined to identify any such activities, and their impact on direct radiation at the site boundary should be calculated. In most cases it is expected that the precautions taken to reduce occupational exposure coupled with the shut-down status of the facility will result in direct radiation from the site to the general population being much less than the levels permitted during plant operations.

10.2.4 Industrial Safety

The individual work activities of any decommissioning program are not unique. They consist of operations that may have been performed at some time during facility operation (e.g. component removal and decontamination), or that have been experienced elsewhere (e.g. concrete demolition). It will be necessary to examine these activities from the perspective of imposing applicable Occupational Safety and Health Act

(OSHA) standards and preventive safety measures. The use of respiratory protection equipment in situations of excessive radioactive and non-radioactive airborne particulate and gaseous levels; the evacuation of work areas to a safe perimeter during controlled explosive demolition; and the protective measures employed during the handling, mixing and processing of chemical reagents are examples of topics that may be addressed under this category.

10.2.5 Non-Radiological Effluent Releases

There are two types of releases to be considered in this category, liquids and gases. The non-radioactive liquid releases from the site will usually consist of processed water such as the distillate from the liquid waste processing evaporator. In this case there are quantitive limits that have been established by the Environmental Protection Agency (40 CFR 423) that define allowable liquid effluent characteristics including pH, polychlorinated biphenol content, suspended solids, oil and grease concentrations and metal concentrations. These can be met by administrative control of any liquid releases during the program.

The non-radioactive gaseous effluent consideration would appear to apply only to a major demolition program where there may be a potential for particulate release to the environment during controlled blasting of massive concrete structures. Presumably, it can be shown that the local concentration of these airborne particulates generated during a controlled explosive demolition program will be diluted well below allowable standards for suspended particulates at the site boundary due to dispersion. Any explosive demolition within an operative containment boundary will have no significant impact on the environment.[6]

10.2.6 Economic Impacts

This general category can be defined as including the following impact factors:

Sociological

1. Site Aesthetics
2. Site Restoration
3. Historical, Cultural, Archaeological, and Natural Landmarks
4. Local Traffic

Economic

1. Local Work Force
2. Taxes
3. Housing
4. Educational Facilities
5. Road Improvements

Certainly each item is site- and area-specific and must be addressed on that basis. However, the following qualitative observations are made:

1. A protective storage program will leave the facility with the same outward appearance as during its operation; therefore, there is no degradation of aesthetics.
2. A dismantling/removal program will enhance site aesthetics.
3. A partial or complete restoration of the site would be a positive impact. Reuse of all or part of the site for some other productive purpose would require additional evaluation of the impact of that usage on the local environment.
4. Landmarks should not be a consideration in the decommissioning evaluation since they would have been addressed prior to construction.
5. Local traffic will only be slightly impacted by the decommissioning work force since its size will be very small relative to the construction force that built the facility.
6. There may be significant truck traffic in a dismantling program for the transport of radioactive waste and non-radioactive scrap and salvage materials. It is expected that these shipments can be shown to be of no greater negative impact than the import of construction equipment and materials during plant erection.

7. Termination of plant operation may displace the skilled operating staff, however, there will most likely be a demand for these personnel in other similar facilities.
8. The temporary dismantling work force is relatively small and will have significantly less impact on the local economy, housing and schools than did the construction force.
9. Termination of plant operation will, most likely, reduce its tax base classification. This may have a significant, but inevitable, negative impact.
10. It is possible that local road improvements or channel improvements may be required in a major decommissioning program, which should be credited as a positive impact.

10.2.7 Program-Related Resource Commitments

This category includes an evaluation of the materials and energy consumed in accomplishing the specific decommissioning program. Typically, this would encompass water consumption, building materials and electrical energy. It is expected that water consumption can be shown to be less than in plant operation and that little, if any, construction materials are required for a decommissioning program.

10.3 APPLICABLE REGULATIONS

This section includes a brief summary of the more pertinent standards, regulations and guides that may be applied in the evaluation of environmental impacts. They are not peculiar to decommissioning but are pertinent to the general topics of radiation protection, effluent discharge, transportation, industrial safety and waste disposal.

10.3.1 Occupational Radiation Exposure

10 CFR 20, "Standards for Protection Against Radiation," defines quantitative limits for direct and airborne radiation exposure to workers. 10 CFR 20 requires the application of the principles of "as low as

reasonably achievable" in the planned exposure of the work force. Therefore, USNRC Regulatory Guide 8.8, "Information Relevant to Ensuring that Occupational Radiation Exposures at Nuclear Power Station Will Be As Low As Is Reasonably Achievable (ALARA)," should be utilized in the program.

10.3.2 Non-Occupational Radiation Exposure

10 CFR 50, Appendix I, imposes the ALARA concept on radiation exposures from an operating nuclear power plant to the general public. The quantitative limit guide is 3 mRem total body or 10 mRem to any organ per year per individual in an unrestricted area. 10 CFR 20, Appendix B, Table II, specifies the limits of concentration of specific nuclides in effluent gaseous and liquid releases to the environment.

10.3.3 Transportation of Radioactive Materials

10 CFR 71 defines the basic licensing requirements and exemptions to shipping regulations. 10 CFR 73 covers physical protection aspects of radioactive materials in transit. And 49 CFR 170-189 defines the detailed requirements imposed by the Department of Transportation on the shipment of radioactive materials; including definition of material types and quantities, packaging requirements and allowable external radiation levels for all packages.

10.3.4 Industrial Safety

29 CFR 1910, "Occupational Safety and Health Standards," establishes requirements for safe working conditions including: airborne radiation (10 CFR 20 invoked); airborne gases, vapors, fumes, particulates, dust and mists (Tables Z-1, Z-2 and Z-3); and occupational noise (29 CFR 1910.95). Other subparts of 29 CFR 1910 cover all other aspects of worker safety such as scaffolding, portable tools, cutting, materials handling and general environmental controls.

10.3.5 Non-Radiological Effluent Releases

40 CFR 423.12 establishes limits on the liquid discharges from steam electric power generating plants for non-radiation characteristics. 40 CFR 50.7 defines the non-radiation suspended particulate ambient air standards for the general public.

10.4 REFERENCES

1. AEC - Elk River Reactor, Final Program Report, USAEC-C00-651-93 (September, 1974)

2. Detilleux, E. et al.: Experience Gained with the Decontamination of a Shut-Down Reprocessing Plant, delivered at the International Symposium on the Decommissioning of Nuclear Facilities, Vienna, IAEA-SM-234/39 (November 13-17, 1978)

3. Jenkins, C.E., Murphy, E.S., Schneider, K.J.: Technology, Safety, and Costs of Decommissioning a Reference Small Mixed Oxide Fuel Fabrication Plant, NUREG/CR-0129, Battelle Pacific Northwest Laboratory, Richland, Washington (February 1979)

4. Smith, R.I., Konzek, G.J., Kennedy, W.E., Jr.: Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station, NUREG/CR-0130, Battelle Pacific Northwest Laboratory, Richland, Washington (June 1978)

5. Occupational Radiation Exposure at Light Water Reactor Cooled Power Plants, NUREG-0323, U.S. Nuclear Regulatory Commission (1976)

6. Manion, W.J., LaGuardia, T.S.: An Engineering Evaluation of Nuclear Power Reactor Decommissioning Alternatives, AIF/NESP-009, Nuclear Energy Services (November, 1976)

7. Dresden-1 Chemical Cleaning License Submission, Commonwealth Edison Company, Docket No. 50010 (December 16, 1974)

8. Douglas Point Nuclear Plant Preliminary Safety Analysis Report, Docket No. 50448, Table 11.2-2.

9. U.S. Atomic Energy Commission: Directorate of Regulatory Standards, Environmental Safety of Transportation of Radioactive Materials to and from Nuclear Power Plants, WASH-1238, Washington, D.C. (1972)

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CHAPTER 11

HOW TO PREPARE DECOMMISSIONING COST ESTIMATES

11.1 INTRODUCTION

Cost estimates of the various decommissioning options serve as a very important parameter of comparison when selecting a course of action. Reliable cost estimates of facility decommissioning are essential to the planning of an economically sound decommissioning program and the selecting of a practical funding mechanism.

Estimations of decommissioning costs have been performed by many organizations, however, the published results of these estimates indicate a wide disparity. In some cases the differences can be associated with different workscopes, different labor force costs, and different money values due to inflationary considerations. Yet, many of the divergences cannot be explained by logic. This lack of consistent agreement has produced undesirable results in the socio-political arena of nuclear power as well as caused confusion for those with financial planning and regulatory responsibilities.

There is insufficient experience to date to allow for direct correlations which might relate decommissioning costs to such parameters as initial capital cost or thermal power rating. Until such a correlation is conceived and proven, a reasonable degree of reliability and accuracy will be achieved only by developing estimates of decommissioning costs on a case by case basis.

The general cost estimating method detailed in this handbook is based on a "building block" approach. That is, the decommissioning program is broken down into a series of discrete and measurable work activities. The breakdown should be carried to a level of detail such that measurable events are repetitive. For example, removal of four-inch Schedule 80 contaminated piping could be considered a single discrete work activity. With prior knowledge of the cost of removing a unit length of that piping, the total cost estimate of the piping removal activity could be described as a function of the total length of piping in that category.

The cost factors used in this cost estimating process are of two basic types, activity-dependent and period-dependent. They both include the work-related elements of labor, materials, equipment, energy and services. These elements are combined into cost factors which can be applied to the specific "building block" activities to derive both the estimated cost of accomplishing those activities and the phase-related period costs that occur on a continuing basis throughout the program.

The sources of information for developing cost factors include recorded experience (such as that accumulated during the Elk River Reactor dismantling),[1] estimating handbooks, and equipment catalog performance data. Calculations of activity-dependent cost factors include set-up time, operating time, required crew size, consumables usage, support services and energy consumption. Because of their manner of derivation, the cost factors presented in the handbook are applicable to all nuclear facilities.

One last word of caution. There will undoubtedly be facility cost estimates which include many work activities and cost factors that do not appear in this handbook. In this case it will be necessary to derive a specific factor for that application. The methodology of factor development is presented in this chapter and can be followed for this purpose.

11.2 SUMMARY OF COST ESTIMATING PROCESS

The process of preparing a facility decommissioning cost estimate consists of the following steps:

1. Preparation of a detailed description of the decommissioning program in a logical, time-related sequence of series and parallel work activities.

2. Each work activity is then estimated as to cost and required period of performance. The estimate of cost is made using activity-dependent cost factors.
3. The overall program schedule is then finalized through graphical relationship of the time oriented series and parallel work activities.
4. Period-dependent costs are then calculated as a function of work phase duration.
5. The entire program cost is arrived at by summation of all activity-dependent costs, period-dependent costs, and inclusion of appropriate contingency factors.

11.2.1 Work Sequence Development

The scope of the detailed work sequence will include all preparatory and implementing steps of the decommissioning program including planning, licensing, detailed engineering, work performance, and site or facility closeout. The pre-decommissioning period includes all planning and engineering tasks such as performance of radiation surveys, calculation of activation and contamination inventories, performance of engineering studies, preparation of a decommissioning plan, preparation of major activity specifications and descriptions, design of special tools, and preparation of detailed decommissioning procedures. The accomplishment phase would include all physical tasks such as decontamination, equipment removal, structure removal, radioactive waste packaging, shipping and burial, and final site and facility restoration or preservation.

11.2.2 Application of Activity-Dependent Cost Factors

Activity-dependent cost factors are further divided into two types: (1) unit cost factors and (2) fixed cost factors. Unit cost factors are expressed in cost per unit output, e.g. \$/inch of cut, \$/ton, \$/cubic yard, \$/pump, \$/valve, etc. The unit factors may be developed by calculation or from actual field experience. Those derived through calculation based on a performance parameter, for example speed of cut, must be tempered by allowance for operator efficiency and work area conditions. Work output in radiation areas can be reduced by as much as 50 percent from theoretical just due to protective clothing and other radiation control measures.

Fixed cost factors reflect the fixed costs (fixed by lease or outright purchase) of equipment and materials utilized in the performance of one or more specific work activities. An example of a fixed cost factor is the purchase or lease price of the special rigging and handling equipment used during the removal of a reactor vessel and its internals.

The cost of each activity is calculated by multiplying the appropriate activity parameter (e.g. volume of activated, heavily reinforced concrete) by the corresponding unit cost factor. The duration of the activity performance is calculated by selecting the degree of parallel activity considered reasonable for the work, e.g., determination of how many crews can be effectively utilized for pipe removal during that period of work.

11.2.3 Program Schedule Development

At this point a detailed program schedule can be developed based on the calculated activity durations and the sequential relationship between activities. Alterations of the schedule would be expected to optimize the duration of activities that can be accomplished with multiple, parallel crews.

11.2.4 Application of Period-Dependent Cost Factors

Period-dependent cost factors represent costs related to specific phases of a decommissioning program and are expressed in cost per unit time. Period-dependent costs include such items as administration, insurance, site security, health physics support, quality assurance, and certain equipment rentals when their use is common to many activities.

The schedule described above can be broken into phases such as: planning, license in effect, license terminated, or any other convenient separation that reflects major influences on period-dependent factors. For example, site security would be required during a "license in effect" phase but not during a "license terminated" phase when conventional demolition would be the only type of activity being performed.

The cost of all period-dependent items are calculated by multiplying each cost factor by its corresponding assigned period.

11.2.5 Development of Total Program Costs

The sum of the activity-dependent and period-dependent costs represents a "best estimate" of the actual costs of decommissioning. However, there will always be a range of variability as influenced by program assumptions and factor accuracy. The study issued by the Atomic Industrial Forum included an accuracy analysis of the cost estimates.[2] As a result, that study recommends addition of a 25 percent contingency factor to each "building block" cost estimate for prudent financial planning. The recent study issued by the Nuclear Regulatory Commission concerning decommissioning of larger pressurized water reactors also included a 25 percent contingency factor in its estimated costs.[3]

11.3 DETERMINING THE BASIC ELEMENTS OF COST

The basic elements of cost for any task or subtask in a decommissioning work sequence are:

1. Labor
2. Materials Consumed
3. Equipment
4. Energy
5. Services

11.3.1 Labor Costs

Decommissioning is a labor-intensive activity. Therefore, labor cost data must be carefully selected and applied. All of the relevant factors, such as benefits, per diem expenses, administrative overhead, and contractor profit must be included and clearly stated.

Since most decommissioning activities require work crews of several different crafts, it is convenient to express the labor costs in terms of crew cost per hour, rather than listing the craft labor rates individually. This approach simplifies cost estimation since the same crew may be utilized for several activities.

The cost of labor is determined by multiplying the hourly crew cost by the number of hours the crew is utilized. The calculations in this chapter are based on an 8 hour day and 5 day work week.

If the crew handles radioactive materials, provision must be made for the time required to put on and take off anti-contamination clothing, and the additional time needed to perform manual functions while encumbered by gloves, masks and protective clothing. Provision should be made for the time spent wrapping contaminated material in plastic or fixing the contamination with a coating. Also to be taken into account is the time needed to carry out the required radiation surveys of personnel and equipment. These considerations have been included in appropriate cost factors shown in Section 11.6.

All of the labor rates used to calculate crew costs in this handbook include fringe benefits (i.e., base labor rate = wage rate + fringe benefits). Labor rates for most crafts may be obtained from guides such as "Building Construction Cost Data" by the Robert Snow Means Company,[4] the "Dodge Guide" by McGraw-Hill,[5] and the U.S. Bureau of Labor Statistics publication entitled "Employment and Earnings."[6] The labor rates given in References 4 and 5 include wages and fringe benefits. The labor rates in Reference 6 are "base earnings" and do not include fringe benefits.

If a particular craft cannot be found in the listed references, reasonable approximations can be made. For example, jack hammer operators and air compressor operators can be considered to be light equipment operators.

The labor costs shown in Section 11.6 are national average costs. Decommissioning cost estimates for a specific site must be based on regional labor rates. References 4 and 5 provide, in addition to national average labor rates, either regional labor rates or regional labor rate indexes (See Section 11.3.9).

For activities contracted out by the facility owner-operator, an allowance must be made for the contractor's overhead and profit. In this handbook, an allowance of 25% to 60% is added to the calculated crew costs to provide for contractor's overhead and profit (see Section 11.3.6). The low end of this range (25%) applies to administrative and craft labor provided by a prime contractor. The 60% end of the range applies to labor supplied by subcontractors. It consists of 45% for subcontractor overhead and profit and 15% markup for the prime contractor to cover his subcontracting costs. No profit is charged for the personnel employed by the facility owner-operator.

In some cases, a per diem may have to be paid to work crews brought in from outside the immediate community. This cost is added to labor costs. Note: per diem expenses vary and the appropriate local rate should be determined.

11.3.2 Material Costs

Some decommissioning activities require various amounts of consumable materials such as chemicals, explosives, torches and cutting gas, saw blades, and disposable protective packaging and small tools. The subdivision of each major activity into constituent parts permits the identification of the consumable materials required for a task. For example, "removal of piping and components, and cutting pipe into lengths suitable for disposal" would require cutting by a power hacksaw or torch, replacement saw blades, torch gas supplies, torch tips, etc. The quantities of materials required can be estimated from the size and length of piping to be removed.

Sources of information on the cost of materials are: "Producer Prices and Price Indexes Data for April, 1979" by the U.S. Bureau of Labor Statistics;[7] "Building Construction Cost Data 1979" by the Robert Snow Means Company;[4] "Dodge Guide" by McGraw-Hill;[5] "Building Construction Estimating Standards" by Richardson Engineering Services.[8]

References 4 and 5 contain cost indexes that can be used to estimate regional material costs from the national average costs that are given (See Section 11.3.9 for regional variability of material costs).

11.3.3 Equipment Costs

Depending on the circumstances, equipment costs can be categorized as unit costs, fixed costs or period-dependent costs. For example, special tooling rented for a particular job can be included in the unit cost factor for the job. Equipment that is purchased for a decommissioning project, such as decontamination rig components, can be categorized as fixed costs. Equipment that is on the site for long periods, such as cranes, loaders, dump trucks, etc., are considered to be period-dependent costs.

Sources of information on equipment costs include: "Building Construction Cost Data" by the Robert Snow Means Company;[4] "Dodge Guide" by McGraw-Hill;[5] "Producer Prices and Price Indexes" by the U.S. Bureau of Labor Statistics;[7] "Building Construction Estimating Standards" by Richardson Engineering Services, Inc.;[8] and the catalog of the McMaster-Carr Supply Company.[9]

References 4 and 5 contain cost indexes that can be used to estimate regional equipment costs from the national average costs that are given. For equipment not included in the listed references, vendor catalogs are a source of information for cost estimates. Cost estimates of specialized equipment should be developed from detailed cost information when it is available. An example of how to calculate the estimated cost for special tooling is given in 11.4.3. This example is based on experience in the decommissioning of the Elk River reactor and shows that design and development for special tooling can amount to as much as 50% of the total cost for the special tooling.

Subsequent re-use of the special equipment in other decommissioning programs may permit amortization of the development cost. If re-use is likely, it is advisable to consult the suppliers of tooling and equipment to obtain their guidance on estimated costs.

11.3.4 Energy Costs

The sources of energy for a decommissioning program may include electricity, fuel oil, natural gas, gasoline and diesel fuel. For activities that consume large amounts of energy, such as evaporation of water during liquid waste treatment, specific estimates should be made. For activities such as small tool operation, the energy consumption is small and it is convenient to estimate the energy costs as a percentage allowance of the base energy cost.

Specific estimates should be made for the operation of plant support equipment. The following listing of equipment should be considered when estimating the operating electrical loads during decommissioning:

Air compressors
Heating
Air conditioning
Fuel pool cooling pumps
Overhead cranes
Service water pumps
Fill pumps or recharging pumps
Lighting
Ventilation
Spot cooling fans
Battery chargers
Sump pumps
Evaporators
Water purification and recirculation pumps

The total operating time of the equipment is estimated and the time is multiplied by the kw-rating of the equipment to determine energy consumption. The total kWh consumption is multiplied by the electrical billing rate to obtain the operating energy cost for the facility during decommissioning.

In calculating the energy cost of evaporating waste water, the total volume of water to be evaporated must be estimated. The energy required to evaporate that volume of water is determined in (kwh or Btu) and the total energy requirement is multiplied by the electrical billing rate or the cost of the fuel used.

Energy costs vary regionally. Data on regional and national average costs for fuel oil, gasoline, diesel fuel and electricity are given in "Producer Prices and Price Indexes Data" by the U.S. Bureau of Labor Statistics.[7]

Electric utilities often charge themselves a lower rate than the industrial rates given in Reference 7, and the lower cost should be taken into consideration when estimating the cost of decommissioning a utility-owned power plant by utility personnel.

11.3.5 Service Costs

The major decommissioning service costs are for:

1. Fabrication of radioactive waste packaging
2. Waste shipping
3. Waste burial

Shipping and burial costs are activity-dependent and are fixed by the quantity and type of decommissioning wastes being disposed of. Packaging costs are either fixed or period-dependent costs (depending on reuseability of the package).

1. Packaging

Low Specific Activity (LSA) radioactive waste materials from a decommissioned facility are packaged in strong, tight containers (wooden or metal boxes) and shipped to a licensed burial site. The waste is buried in the disposable containers. The containers are considered a fixed cost of the activity.

Type B and large quantity radioactive waste from a decommissioned facility is packaged in steel or steel-and-lead liners, and shipped to a licensed burial site in special casks. At the site, the loaded liners are removed from the casks and buried; the casks are returned for re-use. Since the liners are disposed of, liner costs are considered to be fixed costs, and the cask costs are period-dependent costs.

The cost of shipping casks varies with the quantity and type of shielding used. For example, a 50 ft^3 (internal volume) cylindrical cask will cost from \$20,000 to \$50,000 depending on the degree of shielding.[10] The low end of the range is a 1-inch thick steel liner and the high end is a 4 inch thickness of lead plus a steel liner jacket.

The costs of strong, tight wood packaging for LSA wastes can be a subcontracted service cost, or these containers can be fabricated on site by subcontracted carpenters. In either case, such wooden packages are fixed activity-dependent costs.

2. Shipping

For the shipment of non-radioactive material, regular shipping rates will apply. Special consideration is needed for radioactive material shipments. Motor freight, rail and barge shipping methods may be employed, but large shipments are limited by the accessibility of navigable waterways. Motor freight and rail shipping rates may be readily obtained from carriers.

Motor freight is convenient but weight limited. In most states the maximum legal vehicle weight without special permits is 73,800 lb (35,000 lb is for the vehicle alone). The weight of shipping casks and liners will reduce the amount of payload that can be shipped.

Rail shipping loads of 140,000 lb are not uncommon. However, rail service may not be available at a decommissioning site, and it may be necessary to use specially designed multi-axle road transporters to haul material to the nearest rail loading point.

3. Burial

Burial costs for radioactive material are dependent on weight, curie content and surface radiation (R/hr), with additional charges for handling.

Only three licensed burial sites for radioactive waste disposal exist at the present time in the U.S.A. They are located near Barnwell, South Carolina, in Beatty, Nevada, and Hanford, Washington. The sites near Beatty and Hanford are operated by Nuclear Engineering Company (NECO) and have identical rate schedules. The Barnwell Site is operated by Chem-Nuclear Service, Inc. (CNSI).

11.3.6 Overhead, Profit, and Contingency

In decommissioning programs where the owner of the facility carries out some or all of the activities, administrative overhead is often charged to the program. Typically, the overhead is 75% to 80% of the base annual salary for each staff member. The overhead charge is for administrative salaries, benefits, vehicles, buildings, office equipment and supplies.

When decommissioning work is carried out by a contractor, estimates of the costs should include the contractor's overhead plus his profit. References 4 and 8 provide guidelines for overhead and profit percentages based on the contractor's average annual business volume and the firmness of the bidding price. When calculating unit cost factors for labor and materials, this handbook recommends the inclusion of 25% for prime contractor overhead and profit and 60% for subcontractor overhead and profit.

The contingency allowance takes into account the variability of the cost estimates and unforseen expenses. For financial planning purposes, a contingency of 25% is recommended.

11.3.7 Salvage and Scrap

Salvage and scrap values can potentially reduce decommissioning costs, however, radioactive equipment and scrap metal have virtually no market value. In general, non-radioactive components and metals can be sold to a scrap dealer at prices dependent on the market demand for metals. The net cost of removal of materials is the total removal cost minus salvage or scrap value of the materials.

The Bureau of Labor Statistics[2] and "Iron Age" Magazine[11] give current national average scrap metal prices. The scrap value of typical nuclear facility metals is given in Section 11.6 (values based on Reference 11).

11.3.8 Insurance and Property Tax

A site is insured during decommissioning for the estimated salvage and scrap value it contains. Property insurance premiums for nuclear facilities are approximately 35 per $100 of property value per year.[12] The property insurance premiums will decrease as reactor fuel, radioactive sources, equipment and buildings are removed from the site.

The average rates for nuclear indemnity insurance for decommissioning are estimated in Section 11.6 (estimates are based on information from References 2 and 13). Nuclear indemnity insurance rates decrease as material is removed from the facility. The premiums will depend on the operating history of the facility relative to comparable facilities throughout the country, in other words, on the safety performance of the facility.

Property taxes on a facility being decommissioned will also decrease as structures are removed from the site. The cost impact of taxes will vary between a maximum of the facility's operating tax (for the site and all of its structures) to a minimum of land tax alone (following complete removal/dismantling).

11.3.9 Variability of Cost Elements

The major variable affecting decommissioning costs are the regional differences in the cost of labor. The variability of the remaining cost elements (materials, equipment, energy and services) has a lesser effect on the overall cost estimates.

1. Regional Variation in Labor Rates

Regional variations in labor rates are shown in the listing below, which is based on data from References 4 and 5. The maximum variations from the average are -16% to +17%. If per diem expenses are required, they are added to the base labor rates. A $20 per diem for room and board would add $2.50 per hour to the base rate. Note: per diem expenses vary considerably and local rates must be determined.

Overhead and profit for the contractor vary from job to job and from contractor to contractor. Typical values for overhead and profit range from 23% to 27% for prime contractors to 36% to 55% for subcontractors.[4]

2. Material and Equipment Cost Variations

Building Construction Cost Data[4] gives the material price indexes. From this listing it is apparent that regional costs for material and equipment vary from -12% to +18%.

3. Overhead, Profit and Scrap Value Variations

Data from Reference 4 indicates that material overhead and profit varies from ± 2% for prime contractors (from a mean of 25%) to ± 9.5% for subcontractors (from mean of 45.4%).

Scrap value for steel varies regionally and values of this variation may be obtained from "Iron Age Magazine".[11] Generally, No. 1 heavy melt steel scrap varies by up to 24% from the national average.

4. Energy Cost Variations

The data included in Section 11.6 lists fuel oil prices and electrical rates based on information from the Bureau of Labor Statistics.[7] A utility usually charges itself lower electrical rates than the industrial rates shown. In the Northeastern region, the in-house rate is 17% to 22% lower than the industrial rate. In the East North Central region, the in-house rate is 34% to 47% lower than the industrial rate.

5. Service Cost Variations

Variations in shipping costs depend on the services needed. There is little variability in motor freight rates due to the fact that they are regulated by the Interstate Commerce Commission. The major sources of variability for motor freight are penalty charges and services. The variations are approximately 25%.

Rail freight rates vary regionally from point to point and vary with the services selected. The rates for rail shipping may vary approximately 27%.

There are only two radioactive waste burial companies operating three burial sites in the U.S.A. For solid materials, the burial rates (based on package contact dose rates) vary by ± 19% from the average of the two company rates. The variability for decontamination service charge is ± 18% from the average.

11.4 DEVELOPING COST FACTORS

The procedure for developing cost factors is as follows: (See Figure 11.1 for flow diagram.)

1. Develop the work sequence by listing all tasks and activities
2. Divide the major tasks into subtasks
3. Determine the elements of cost for the subtasks
4. Combine the costs into the appropriate cost factors.

For example, the task may be the removal of a contaminated 3 ton pump. The subtasks would be those shown on Figure 11.1. The cost of labor, material, equipment, energy and services are estimated for each subtask along with the time required for its completion.

The following examples will demonstrate, in detail, the development of typical cost factors.

11.4.1 Example 1

Unit Cost Factor for Cutting Reactor Internals With a Remotely Controlled Underwater Plasma Torch

The internals are stainless steel and have a thickness of two inches or less. A total length of 1516 inches is to be cut. The task is divided into the following subtasks:

Subtask	Calculated Work Periods, (days)
1. Install contamination control envelope	7
2. Install portable and fixed exhaust systems	10
3. Install remote cutting tool (includes initial installation & subsequent moves)	19
4. Test remote cutting tool	5
5. Cut vessel internals into segments	22
6. Rig and transfer segments to underwater cask loading area (including loading)	9
Total	72

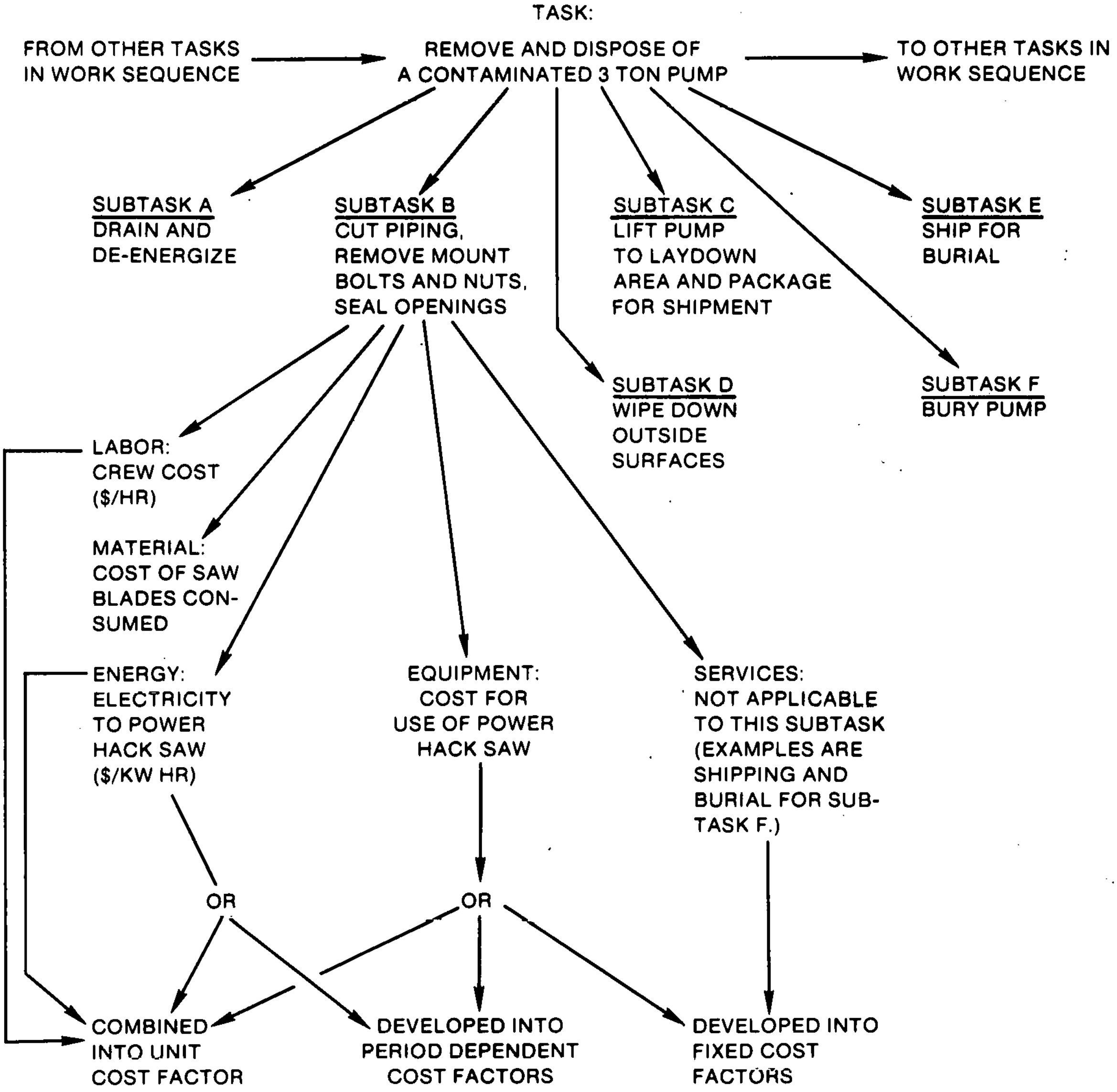
The cost elements of these subtasks are:

1. Labor

Base labor rates are from References 4, 5, and 6 or based on actual decommissioning experience.

FIGURE 11.1

FLOW DIAGRAM FOR DEVELOPING COSTS



Craft	Crew Number	Crew Base Labor Rate, $/hr	Cost in $/hr
Laborers	2	10.40	20.80
Crane Operator	1	13.80	13.80
Tooling Operators	2	10.70	21.40
Control Panel Operator	1	10.70	10.70
Dismantling Supervisor	1	15.10	15.10
Total Crew Cost			81.80

The tasks require 72 days and with an 8-hour workday, or 576 work hours (72 days x 8 hr/day).

Labor Cost = Work Duration x Crew Cost
= 576 hr x $81.80/hr
= $47,117

Labor Cost per-inch Cut:
Total Length Cut = 1516 in
$47,117 ÷ 1516 in = $31.08/in cut

2. Material

The plasma torch requires gases, nozzles and other materials worth an estimated $3815.00. Material cost per inch cut:

$3815 ÷ 1516 in = $2.52/in cut

3. Energy

The plasma torch requires 46.8 Kw of electricity for operation. Twenty-two 8 hour days were required to cut 1,516 inches. For conservatism, it is considered that the torch operated all of this time.

22 days x 8 hr/day x 46.8 Kw = 8,237 Kwh

At 3.4¢/Kwh the energy cost for cutting is:

$$\frac{8{,}237 \text{ Kwh} \times \$0.034/\text{Kwh}}{1516 \text{ in cut}} = \$0.18/\text{in cut}$$

Cost Factor Calculation

Labor Cost/in cut	$ 31.08
Material Cost/in cut	2.52
Energy Cost/in cut	+ .18
	$ 33.78
Add 45% for Subcontractor Overhead and Profit and 15% for Prime Contractor Markup (i.e. 60%)	+ 20.27
The Unit Cost Factor	$ 54.05/in cut

4. Discussion of Example 1

The example is based on experience in decommissioning the Elk River reactor. The crew is utilized for the duration of the task (72 days). The time for suiting-up in and taking off anti-contamination clothing, for radiation surveys of personnel and equipment, and unavoidable idle time are included in the 72 day task duration. Quality Assurance, engineering and administrative staff costs for this task are considered to be period-dependent and are not included in the unit cost factor. Special tooling is considered to be a fixed cost (See Example 3).

11.4.2 Example 2

Unit Cost Factor for Removal of Heavily Reinforced, Activated, or Contaminated Concrete

This calculation is based on experience in the removal of a biological concrete shield at the Elk River reactor. (Calculations and back-up data from Reference 2). The subtasks are:

1. Survey or sample the area to be dismantled to set exposure limits
2. Place demolition charges
3. Cover with blasting mats and evacuate building
4. Water spray area
5. Ignite charges
6. Load and remove concrete rubble

The time required is 180 work days, and approximately 1400 cubic yards of reinforced concrete are to be removed.

1. Labor

	Crew		
Craft	Number	Base Labor Rate, $/hr	Cost in $/hr
Laborers	6	10.40	62.40
Crane Operator	1	13.80	13.80
Truck Driver	1	10.75	10.75
Air Compressor Operator	1	12.70	12.70
Demolition Expert	1	20.58	20.58
Loader Operator	1	15.10	15.10
Dismantling Supervisor	1	15.10	15.10
Crew Cost			$150.43/hr

The task requires 180 work days and with an 8-hour workday, the duration of the task is 180 days x 8 hr/day = 1440 hours.

Labor Cost = Work Duration x Crew Cost
= 1440 hr x $150.43/hr
= $216,619.20

Labor Cost per Cubic Yard Removed:

$\$216,619.20 \div 1400\ \text{yd}^3 = \$154.73/\text{yd}^3 = \$154.73/\text{yd}^3$

2. Equipment And Services

	Total Cost
3 Rock Splitters	$ 20,274
Rock Drills and Bits	14,868
Air Hose and Fittings	1,500
Tips for Rock Splitters	1,419
Explosives, Detonators	6,981
Heavy Equipment (rental and fuel), Planking, Wheel Barrows, Misc.	32,972
Demolition Consulting Engineering	52,147
Total	$130,161

Equipment Cost per Cubic Yard Removed:

$\$130,161 \div 1400\ \text{yd}^3 = \$92.97/\text{yd}^3$

3. Cost Factor Calculation

Labor Cost/yd^3	\$ 154.73
Equipment and Services/yd^3	+ 92.97
	\$ 247.70
Add 45% for Subcontractor Overhead and Profit and 15% for Prime Contractor Markup (60%)	+ 148.62
Total	\$ 396.32

Or approximately, \$400/yd^3 of concrete removed.

3. Discussion of Example 2

The costs are based on the cost data given in the references and on actual experience. Energy to operate heavy equipment is included with rental costs. The crew is utilized for the duration of the task (180 days). This duration includes productive time, time consumed in the accomplishment of radiation control procedures (radiological surveys of personnel and equipment, obtaining filtered face masks, etc.) and unavoidable idle time.

Fixed equipment costs (for rock splitters, air hoses and fittings), fixed material costs (for rock drills, bits and rock splitter tips), and period-dependent costs (for consulting and equipment rental) have been combined into equipment costs for this unit cost factor. When this approach is used, care must be exercised to avoid double listing of costs in the unit cost factor and the program's fixed and period-dependent cost factors.

11.4.3 Example 3

Fixed Cost Factor for Special Equipment Used to Remove Reactor Internals

This example estimates the cost of a remotely manipulated plasma torch, lifting tools, and supports for cutting and removing reactor internals. The equipment was designed and developed for dismantling the Elk River reactor. The approximate cost for the original design and construction of the equipment in current dollars is $1,375,000. The breakdown costs are:

Description	% of Cost	Cost, $
Design and fabrication of torch, remote manipulator and controls	40%	$549,980
Development of torch, remote manipulator and controls	25%	$343,740
Design and fabrication of lifting tools and supports for segment cutting	11%	$151,240
Development of lifting tools and support for cutting	14%	$192,490
Development and engineering support	10%	$137,000
	100%	$1,375,000

Plasma torch technology would have to be developed to cut through a large reactor vessel. Existing technology can cut through 7 inches of material in air and 5-1/2 inches of material under water. Lifting tools and cutting supports would also have to be designed for each torch application to account for vessel internal geometry peculiarities. Therefore, significant design and development costs are still required for plasma torch cutting today. They are accounted for in this estimate.

Discussion of Example 3

Overhead and profit for the contractor were included in the original tooling cost, and are carried throughout the calculations. When possible, vendor (fabricator) estimates should be used for site specific tooling when tooling specifications are known.

11.4.4 Example 4

Period-Dependent Cost Factors for Administrative Staff Costs

Administrative staff costs are not included in activity-dependent factors because they are independent of the individual activities. For example, explosives experts are only used for certain jobs in a decommissioning program (i.e., they are activity-related) while program supervisors, engineers and clerical workers are there for the full duration (i.e. they are period-dependent).

A decommissioning administrative staff consists of facility staff personnel and other administrators specifically hired for decommissioning. The administrators hired for the decommissioning will be provided by a prime contractor. It is convenient to estimate administrative staff costs on a monthly or yearly basis.

The costs of facility personnel and prime contractor personnel are calculated differently. The cost of the facility administrative staff consists of the yearly base salary plus an additional 80% for overhead expenses such as insurance, medical coverage, fringe benefits and office expenses. No profit is accounted for in this component of the decommissioning staff. The cost of the prime contractor's administrative staff includes yearly base salary and 25% for overhead and profit.

The administrative staff for each decommissioning program will depend on the scope and duration of the decommissioning alternative selected, the quantity of material to be removed and the size of the workforce. For smaller reactors, some of the positions listed in Section 11.6 will not be required or might be performed by other personnel.

11.4.5 Example 5

Period-Dependent Cost Factors for Security

A security force for the protection of a nuclear power plant during operation and at the start of decommissioning may consist of:

5 Response Guards
2 Guards at Security Control Centers
1 to 3 Supervisory Personnel (sergeants, lieutenants, captains)

The security force must be trained to NRC nuclear site requirements. The trained force must remain at the site until all nuclear fuel has been removed. Security then may be maintained by a premium guard force.

Section 11.6 includes data on billing rates based on information provided by several security services.[14] The costs are approximate national averages for security force costs. The security costs can be estimated from these rates and the composition of the force.

11.5 AN EXAMPLE OF THE COST ESTIMATING PROCESS

The following example demonstrates the "building block" approach to cost estimating. It identifies "building blocks" as tasks and subtasks and shows their relationship to project cost calculations. The example to be developed is the activity of removing and disposing of a contaminated 3 ton pump, and hereinafter referred to as Task #56. The physical description of the subject pump and other pertinent facts are listed below:

Size	6'x 5'x 10' (major dimensions)
Weight	3 tons
External Surface Area	Approx. 240 ft^2
Mounting	Welded to adjacent piping; bolted to structural steel beams embedded in concrete foundation
Use	Transfer of water containing low concentrations of radioactive fission and activation products
Shipping Distance	500 miles to Hanford, WA.
Contamination	Less than 300 curies fixed on inside surfaces.

11.5.1 Relationship to Work Sequence

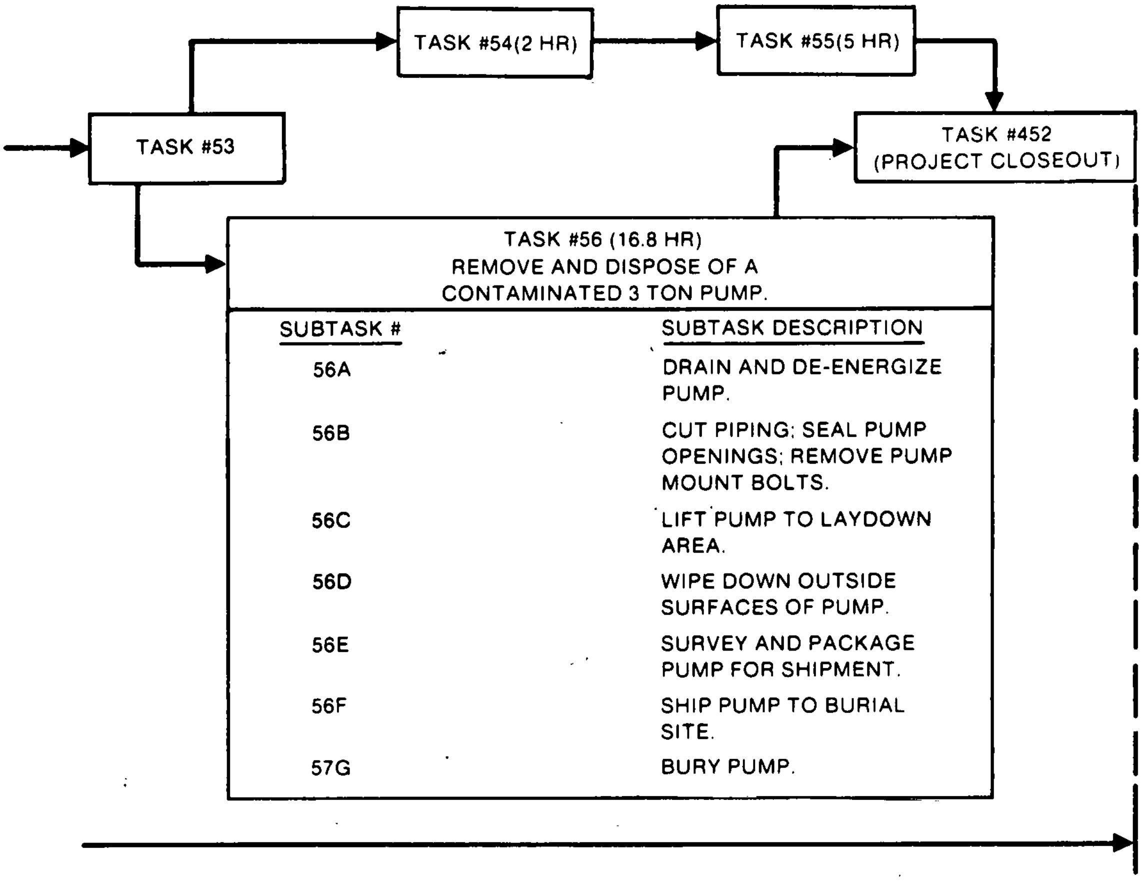
The subject task is one of many identified in a decommissioning work sequence. Its relationship to other tasks and its component subtasks are shown graphically in Figure 11.2.

11.5.2 Activity Costs

Activity-dependent cost factors, derived as described in Section 11.4 of this chapter (using the information of Section 11.3), can be applied to each subtask as shown below:

FIGURE 11.2

BUILDING BLOCK REPRESENTATION OF SCHEDULE



1. Relevant Cost Factors (from Section 11.6)

Removal of Pump 5000 - 10,000 lb	= \$ 1,900/pump
Surface Decontamination Wipedown	= \$ 1.35/ft^2
Wooden Box (8'x8'x12'; wgt. 1300 lb)	= \$ 520/each
Trucking Cost	= \$ 2.56/100 lb
Bulk Burial Rate at Hanford	= \$ 4.75/ft^3

2. Cost Calculations

For Subtasks 56(A,B,C,and E)
(Packaging): 1 pump @ \$1,900/pump = \$ 1,900

For Subtask 56D: 240 ft^2 @ \$1.35/ft^2 = \$ 324

For Subtask 56E:
- a. Radiation surveying is performed by the decommissioning staff as a period-dependent cost. = 0
- b. 1 wooden box @ $ 520/each = $ 520

For Subtask 56F:
- (6000 lb + 1300 lb) @ $2.56/100 lb = $ 187 *

For Subtask 56G:
- a. (8'x 8'x 12') @ $4.75/ft^3 = $ 3,648
- b. weight surcharge = 0
- c. curie surcharge = 0
- d. cask handling fee = 0

<u>Total Activity Cost for Activity 56</u> $ <u>6,579</u>

11.5.3 Duration and Schedule

1. Duration

The time estimated to perform generic decommissioning tasks is established during the determination of cost factors. For the subject example, the duration can be tabulated as follows:

For Subtasks 56A, 56B, and 56C:	12 hr
For Subtasks 56D and 56E:	4.8 hr
For Subtask 56F: (time for shipping does not impact on program cost for this example - it would if cask rental were involved)	0 hr
For Subtask 56G: (time spent at burial site does not impact on program cost for this example - it would if cask rental were involved)	0 hr
<u>Total Duration of Activity 56</u>	<u>16.8 hr</u>

* The minimum shipment at the rate shown is 30,000 lb. If this 7300 lb package was shipped alone, the $2.56/100 lb rate would be charged against the 30,000 lb minimum load (i.e. $768 would be the shipping charge rather than $187). The $187 cost shown above assumes waste packages from other tasks will be combined to make a truck load between 30,000 lb and 45,000 lb.

2. Schedule

In this example, Task #56 is on the critical path (i.e. activities #54 and #55 take less time than activity #56, per Figure 11.2). Therefore, its duration is a component of total project duration. If task #56 occurred in parallel with other tasks of longer duration, it would control neither project duration nor period-dependent costs.

Graphical evaluation of the "building block" (task) durations of a decommissioning project, by means of PERT or CPM networks (similar to the segment of a project shown in Figure 11.2), is necessary to adequately determine project schedule.

11.5.4 Period-Dependent Costs

Once project duration is calculated (by adding the durations of each task on the critical path), period-dependent project costs can be calculated as shown below:

1. Relevant Cost Factors (only 3 shown for simplicity)

Decommissioning Staff (arbitrarily selected for this example) = $466,200/yr

Security Cost (arbitrarily selected for a premium force, per Section 11.6) = $402,000/yr

Nuclear Liability Insurance (arbitrarily selected to represent dismantling per Section 11.6) = $ 12,000/yr

Total = $880,200/yr

2. Cost Calculation

From Figure 11.2, project duration for this example is 72 months. All of the period-dependent costs are assumed to occur throughout the total project duration.

($880,200/12 months) (72 months) = $5,281,200

11.5.5 Totalization of Project Costs

When all activity and period dependent costs of a project have been determined, the total project cost is calculated as shown below:

Cost Item	Cost
Activity-dependent Costs	$ 6,579 + Σ other task activity costs
Period-dependent Costs	+ $ 5,281,200
	subtotal
Contingency	+ 25% of subtotal
Decommissioning Program Cost	Total

11.6 COST FACTOR TABLES

Tables 11.1 through 11.16 of this section list various decommissioning cost factors. All factors listed represent current national average costs.

Table 11.1 through 11.8 define activity dependent cost factors. These Tables include:

Table	Scope of Activity
11.1	Metal Cutting
11.2	Demolition of Structures
11.3	Component Removal
11.4	Shipping of Waste Materials
11.5	Radioactive Waste Burial
11.6	Decontamination and Waste Processing
11.7	Miscellaneous Activities

Table 11.8 presents the period-dependent cost factors and Tables 11.9 and 11.10 give more detail on administrative staff and security service costs, respectively.

Table 11.11 includes definitive information on shipping rates and surcharges and Table 11.12 gives detailed cost data on burial charges at the NECO and CUSI waste burial sites. Table 11.13 presents more in-depth cost data on shipping casks and shipping cask liners. Liner cost factors are based on data from "Iron Age" Magazine and experience gained in the fabrication of liners for decommissioning work (taken from calculations for Reference 2).

Table 11.14 presents the maximum variability in the cost factor elements, while Table 11.15 shows regional variations in the United States for the categories of labor, material, and enargy. Finally, Table 11.16 depicts the scrap value of various metals.

The tables represent the types of factors that should be established for decommissioning cost estimation. Each project will vary in scope; therefore, all cost factors specific to a particular decommissioning job may not be shown in these tables. When this situation occurs, the methodology of Section 11.4 can be used to calculate the additional cost factors.

Craft labor costs include 60% of base labor costs (as defined in Section 11.3) for prime and subcontractor overhead and profit. No per diem is included in craft labor costs. Time spent suiting up in anti-contamination clothing, inefficiency in working while encumbered by protective clothing, and time spent performing radiological surveys of people and equipment at radiation central check points is included in the calculation of craft labor costs when applicable.

The cost factors listed should be adjusted for regional cost variations, as described in Section 11.3 before being used for cost estimation.

TABLE 11.1

ACTIVITY DEPENDENT COST FACTORS FOR METAL CUTTING

Metal Cutting	Cost Factor
Remote Arc Saw Cutting "thin" steel sections (0-2 in)	\$ 30/in^2 cut
Remote Plasma Torch Cutting "thin" steel sections (0-2 in)	\$ 55/in cut
Remote Arc Saw Cutting "thick" steel sections (2-3 in)	\$ 20/in^2 cut
Remote Plasma Torch Cutting "thick" steel sections (2-3 in)	\$ 50/in cut
Arc Saw (locally controlled, can cut thicknesses up to 19"; includes power supply and controls)	\$ 182,400/ea
Plasma Torch (locally controlled, can cut thicknesses up to 4"; includes power supply and controls)	\$ 25,000/ea
Remotely Controlled Plasma Torch (to cut thicknesses up to 10"; includes power supply and controls)	\$ 962,500/ea
Remotely Controlled Arc Saw (to cut thicknesses up to 19"; includes power supply and controls)	\$ 1,110,000/ea
Manual Torch Cutting steel sections (0-2 in)	\$ 0.35/in cut
Mechanical Nibbler (manually operated, can cut thicknesses up to 3/16")	\$ 1,000/ea

TABLE 11.2

ACTIVITY DEPENDENT COST FACTORS FOR DEMOLITION OF SITE STRUCTURES

Demolition of Site Structures	Cost Factor
Heavily Reinforced Activated/Contaminated Concrete (by controlled blasting)	\$ 430/yd^3
Contaminated Concrete Demolition Equipment (includes equipment rental, demolitions expert and consumable materials)	\$ 95/yd^3
Containment and Other Heavily Reinforced Seismically Designed Concrete (blasting, wrecking ball, hauling to local landfill)	\$ 110/yd^3
Lightly Reinforced, Standard Concrete (non-radioactive, using controlled blasting)	\$ 40/yd^3
Non-reinforced High Density Concrete (radioactive, using controlled blasting)	\$ 40/yd^3
Lightly Reinforced Standard Concrete (radioactive, using controlled blasting)	\$ 215/yd^3
Massive Non-reinforced Standard Concrete (non-radioactive, using controlled blasting)	\$ 15/yd^3
Lightly Reinforced Concrete (by wrecking ball)	\$ 20/yd^3
Standard Concrete (by wrecking ball)	\$ 40/yd^3
Non-Reinforced Concrete (by wrecking ball)	\$ 13/yd^3
Concrete Block (by wrecking ball)	\$ 10/yd^3
Heavily Reinforced Concrete (by wrecking ball)	\$ 110/yd^3
Lightly Reinforced Concrete (less than 2 ft thick, using ram hoe)	\$ 43/yd^3
Flame Cutting Concrete	\$ 190/ft^2 (area of cut)
Non-Reinforced Concrete Saw Cutting (non-radioactive)	\$ 8/ft^2 (area of cut)
Concrete Wall Sawing	\$ 22/ft^2 (area of cut)
Non-reinforced Concrete (by paving breaker or chipping hammer)	\$ 32/yd^3
Reinforced Concrete (by paving breaker or chipping hammer)	\$ 62/yd^3
Concrete Floor Grinding	\$ 36/yd^2
Scarifying of Concrete Floors (by Scabbler)	\$ 2.35/yd^2
Concrete Block Walls	\$ 0.85/ft^2 (of surface)
Concrete Walls (not reinforced)	\$ 8/ft^3
Structural Steel	\$ 80/ton
Steel Buildings (non-seismic, common commercial construction)	\$ 9/yd^3 (of bldg. vol.)
Built Up Roofing	\$ 75/100 ft^2

TABLE 11.3

ACTIVITY DEPENDENT COST FACTORS FOR COMPONENT REMOVAL

Component Removal	Cost Factor
Reinforce Overhead Crane for Heavy Lifting	$ 7,300/set-up
Steam Generator (250-500Mw)	$ 34,800/generator
Pipe:	
0-6 in (Sawing - carbon and stainless steels)	$ 70/10 ft length
6-12 in (Torch cutting - carbon & stainless steels)	$ 80/10
12-24 in (Torch cutting - carbon & stainless steels)	$ 160/10
Valves:	
(Torch cutting, 6-12 in)	$ 160/valve
(Torch cutting, 12-24 in)	$ 325
Pumps:	
0 - 300 lb	$ 110/pump
300 - 5000 lb	$ 230
5000 - 10,000 lb	$ 1,900
Heat Exchangers:	
0 - 3000 lb	$ 325/exchanger
3000 - 6000 lb	$ 970
Filters	$ 220/filter
Ion Exchangers, 0 - 500 gal	$ 220/item
Ion Exchange Resin	$ 65/bed
Tanks:	
0 - 1000 gal	$ 220/tank
1000 - 10,000 gal	$ 320
10,000+ gal	$ 0.85/inch cut
Electrical Consoles, Panels and Components:	
0 - 300 lb	$ 100/item
300 - 1000 lb	$ 205
1000 - 3000 lb	$ 305
Cable Trays	$ 35/10 ft section
Conduit	$ 65/100 ft length
Feedwater Heaters	$ 1,200/heater
Miscellaneous Process Equipment:	
0 - 300 lb	$ 110/item
300 - 5000 lb	$ 230
5000 - 10,000 lb	$ 1,900
De-energize and Disconnect	
Pumps:	
0 - 300 lb	$ 20/pump
300 - 5000 lb	$ 70
5000 - 10,000 lb	$ 100
Process Filter Elements	$ 20/each
Ventilation Filters	$ 3/each
Electrical Consoles, Panels, and Components:	
0 - 300 lb	$ 30/item
300 - 1000 lb	$ 45
1000 - 3000 lb	$ 70

TABLE 11.4

ACTIVITY DEPENDENT COST FACTORS FOR SHIPPING OF WASTE MATERIALS

Shipping of Waste Materials	Cost Factor
One-Way Trip by Truck (30,000 - 45,000 lb payload, shipped 500 miles; one driver, LSA material)	\$ 2.56/100 lb
One-Way Trip by Truck (30,000 - 45,000 lb payload, shipped 1000 miles; one driver, LSA Material)	\$ 3.88/100 lb
1000 Mile Round-Trip by Truck (50,000 - 70,000 lb payload; cask shipment, two drivers; excluding overweight permits, which depend on route)	\$ 1.48/mile
Cask Rental (7 days)	\$ 875/Shipment
One-Way Rail Shipping	\$ 8.50/(100 lb)
Steel Liner Fabrication (includes labor and materials)	\$ 190/(100 lb)
Lead and Steel-Reinforced Shipping Container (non-cask; includes labor and materials)	\$ 130/(100 lb)
Wooden Boxes:	
4'x 4'x 8' (400 lb)	\$ 170/ea
8'x 8'x 12' (1300 lb)	\$ 520
12'x 12'x 24' (2400 lb)	\$ 1,530

TABLE 11.5

ACTIVITY DEPENDENT COST FACTORS FOR RADIOACTIVE WASTE BURIAL

Burial (At Hanford, WA and Beatty, NV)	Cost Factor
General Bulk Burial Rate (0-0.2 R/hr at container surface)	\$ 4.75/ft^3
Weight Surcharge (10,000 lb and greater)	\$ 50 + \$0.01/lb (for weight over 10,000 lb)
Curie Surcharge (for 100 or more curie)	\$ 375 + \$0.05/curie (over 300 curie)
Cask Handling (min)	\$ 250/cask
Burial (at Barnwell, SC)	
General Bulk Burial Rate (0-0.2 R/hrat container surface)	\$ 3.60/ft^3
Weight Surcharge (5,000 lb and greater)	\$ 115/lb (for weights over 5000 lb; avg)
Curie Surcharge (0-500 curie)	none
Cask Handling (min)	\$ 150/cask

TABLE 11.6

ACTIVITY DEPENDENT COST FACTORS FOR DECONTAMINATION AND WASTE PROCESSING

Decontamination & Waste Processing:	Cost Factor
Tanks and Large Internal Volume Components	\$ 5.30/ft^2
Hook-Up and Flush with Decontamination Rig (labor only)	\$ 770/job
Average Chemical Costs for Decontamination Flushing of Pipe (including neutralization of flush effluents):	
0-6 in pipe	\$ 4.00/ft
6-12 in	\$ 25
12-24 in	\$ 75
Surface Wipedown	\$ 1.35/ft^2
Decontamination Flushing Rig	
(300 gallon holding capacity)	\$ 54,000/rig
(1000 gallon holding capacity)	\$ 73,000
Evaporation and Solidification of Liquid Wastes (using #2 fuel oil energy source and cement)	\$ 0.22/gal

TABLE 11.7

MISCELLANEOUS ACTIVITY DEPENDENT COST FACTORS

Miscellaneous Activities	Cost Factor
Vacuum Drying (for pump use, not purchase)	\$ 1500/month of use
Fill (common borrow)	\$ 3/yd^3
Grading (average of fine and rough)	\$ 2.50/yd^3
Landscaping (seeding and fertilizing)	\$ 770/acre
Disposal of Clean Rubble (loading, hauling, and dumping at landfill within 5 miles of site)	\$ 7/yd^3

TABLE 11.8

PERIOD DEPENDENT COST FACTORS

Personnel	Cost Factor
Engineering Consultants (per person)	$ 45/hr
Decommissioning Staff Salaries	
(No overhead included; 80% overhead recommended for facility staff personnel, 25% recommended for prime contractor personnel.)	
Nuclear Contracts Manager	$ 34,300/yr
Project Superintendent	$ 33,600
Assistant Project Superintendent	$ 28,400
Project Supervisor	$ 25,200
Project Cost Control Accountant	$ 20,100
Project Engineer	$ 27,500
Material Control Engineer	$ 19,200
Manager of Radiation Safety and Environmental Impact	$ 31,400
Packaging and Shipping Supervisor	$ 22,800
Health Physics Supervisor	$ 24,800
Secretary	$ 11,000
Clerk-Typist	$ 8,100
Instrument Technician	$ 17,200
Health Physics Technician	$ 16,900
Laboratory Technician	$ 15,200
Decontamination Technician	$ 16,500
Head Laboratory Technician	$ 20,000
Security:	
Minimal Nuclear Site Force (armed, 8 people per shift; 3 shift coverage)	$ 51,500/month
Premium Guard Force (armed, 6 people per shift; 3 shift coverage)	$ 33,500
Watchmen (1 per shift, 24 hr coverage)	$ 4,200
Insurance:	
Property Insurance (yearly premium rate)	$ 0.35/$100 value
Nuclear Liability Insurance for Dismantling (avg over 12 years with 67% premium refund)	$ 12,000/yr
Nuclear Liability Insurance for Entombment (avg over 9 years with 67% premium refund)	$ 5500
Nuclear Liability Insurance for Mothballing (avg over 7 years with 67% premium refund)	$ 3600
Nuclear Liability Insurance during Dormancy	$ 1000

TABLE 11.9

UTILITY ADMINISTRATIVE STAFF FOR DECOMMISSIONING A LARGE NUCLEAR POWER PLANT

Position Title/Number Required	Yearly Base Pay (per person)	Total Cost Yearly Salary + 80% Overhead
Contracts Manager (1)	$ 34,300	$ 61,700
Plant Manager (1)	$ 33,600	$ 60,500
Assistant Plant Manager (1)	$ 28,400	$ 51,200
Operations Manager (1)	$ 27,500	$ 49,500
Administrative Supervisor (1)	$ 25,200	$ 45,300
Assistant Operations Manager (1)	$ 24,900	$ 44,800
Accountant (1)	$ 20,100	$ 36,200
Maintenance Supervisor (1)	$ 27,500	$ 49,500
Associate Engineers/Engineering Aides (7)	$ 15,000	$ 189,000
Manager of Radiation Safety and Environmental Impact (1)	$ 31,400	$ 56,500
Packaging and Shipping Supervisor (1)	$ 22,800	$ 41,000
Engineers (13)	$ 19,200	$ 449,300
Health Physics Supervisor (1)	$ 24,800	$ 44,600
Secretary (5)	$ 11,000	$ 99,000
Clerk-Typist (5)	$ 8,100	$ 72,900
Technicians (43)	$ 17,150	$1,327,400
Assistant Maintenance Supervisor (1)	$ 24,800	$ 44,800
Janitors (5)	$ 14,000	$ 126,000
Craft Foreman (4)	$ 24,800	$ 178,600
Craftsmen (33)	$ 23,300	$1,384,000
Laborers (8)	$ 18,100	$ 260,600
Chief Stock Keeper (1)	$ 10,000	$ 18,000
Nurse (1)	$ 11,500	$ 20,700
Total Cost/Yr		$4,711,100

TABLE 11.10

SAMPLE BILLING RATES FOR SECURITY SERVICES

Security Personnel	Hourly Wage
Security Force for a Nuclear Site:	
Guard	$8.51
Sergeant	$9.31
Lieutenant	$9.31
Captain/Supervisor	$10.37
Premium Security Force (Armed):	
Guard	$7.45
Sergeant	$8.24
Lieutenant	$8.24
Captain/Supervisor	$9.31
Unarmed Security Force:	
Guard	$5.85
Supervisor	$7.45

TABLE 11.11

DETAILED SHIPPING RATES AND SURCHARGES

1. MOTOR FREIGHT RATES *

A. Mileage rates for radioactive waste shipments weighing 45,000 to 70,000 lb (payload and packaging).

	Estimated Average Rate/mile **	
Type	One Way	Round Trip
400 miles	$ 1.95	$ 1.50
500 miles	1.72	1.39
600 miles	1.65	1.33
1000+ miles	1.41	1.33

B. Rates for radioactive waste shipments per 100 lb (30,000 - 45,000 lb payload and packaging)

Type	Estimated Average Rate **
400 miles	$ 2.26/100 lb
500 miles	2.56/100 lb
600 miles	2.81/100 lb
1000 miles	3.88/100 lb

C. Non-radioactive waste materials:

24,000 lb load 0-400 miles	$ 2.46/100 lb
30,000 lb load 1000 miles	$ 4.17/100 lb

2. MOTOR FREIGHT SURCHARGES*

A. Overweight Permit Charges (for loads over 80,000 lb gross vehicle weight - these vary from state to state and by mileage)

Type	Estimated Average Rate or Charge **
Chicago to Richland, WA	$ 250
Boston to Barnwell, SC	$ 200
Chicago to Beatty, NV	$ 115

B. Oversize Charges	Max. is $0.30/mile + $0.05/mile for every foot of trailer length over 65 ft
Escort Vehicles and/or Flagman	$ 0.75/mile, $ 100/day min

TABLE 11.11
(Continued)

	Type	Estimated Average Rate or Charge **
C.	Extra Services:	
	Second driver	$ 0.15/mile, $ 60 min
	Protective signature service	$ 25/shipment
	Hourly calls to control point	$ 0.22/mile
	Continuous surveillance	$ 0.12/mile, $ 60/day min
	Armed driver	$ 0.20/mile per driver
	Security cleared driver	$ 0.15/mile
D.	Penalty Charges:	
	Extra loading time (over 3 hr allotted)	$ 17.50/hr
	Special Loading Equipment	$ 20/hr + $ 0.85/mile for hauling
	Extra Weighing	$ 10/each
E.	Trailer Set Out	$ 1.50/mile for mileage over 50 miles + $ 12.50/day
3.	RAIL RATES ***	
	Rates per 100 lb:	
	40,000 lb min, Chicago to Richland, WA or Beatty, NV	$ 8.46/100 lb
	40,000 lb min, Boston to Barnwell, SC	$ 4.87/100 lb
4.	RAIL SURCHARGES ***	
A.	Extra Switching Service	$ 75/hr
B.	Switching Charges	Depend on route ($ 1.50/mile for western shipments)
C.	Extra Crew Assignments (associated with special service)	Depend on carrier and route ($ 0.38/mile)
D.	Regular Switching Crew	Depends on carrier ($ 0.10/mile for western shipments)

* These rates were obtained from Tri-State Motor Transit, Co., Joplin, Missouri and Davis Transport, Inc., Paducah, Kentucky. The basic weight and mileage rates and most surcharges are governed by tariff. Service type surcharges are carrier dependent (i.e. vary from carrier to carrier, or are not provided by carrier).

** The rates were averaged when several sources of information were used. Some charges are based on specific routing information or calculations made for the most probable route. The individual carriers have special routing procedures that may produce costs that vary slightly from those shown on this table.

*** These rates were obtained from the following railroads: Sante Fe, Burlington Northern, Conrail, Boston, Maine, Chicago and North Western - as with trucking charges, these vary with carrier.

TABLE 11.12

DETAILED RADIOACTIVE WASTE BURIAL CHARGES

Solid Material Charges (R/hr at surface)	Average Rate (\$ per ft/^{3}) *
0 - 0.2	\$ 4.18
0.2 - 1	4.82
1 - 5	6.45
5 - 10	8.02
10 - 25	12.30
25 - 50	17.32
50 - 75	20.95
75 - 100	25.15
100 - 125	26.78
Solid Materials in Liners (R/hr at surface)	**Average Rate (\$ per ft/^{3}) ***
0.2 - 1	\$4.18 + 57.50/liner
1 - 5	4.18 + 200/liner
5 - 10	4.18 + 312.50/liner
10 - 25	4.18 + 445/liner
25 - 50	4.18 + 555/liner
50 - 75	4.18 + 652/liner
75 - 100	4.18 + 775/liner
100 - 125	4.18 + 850/liner
	Average Rate (\$)
Liquid in Vials	3.50
Weight Surcharges:	
0-10,000 lb	\$0-50/item
10,000-50,000 lb (incremental)	\$50-525/item
Curie Surcharges:	
100-300 curies	\$0-375/item
300-500 curies	\$0-400/item
Miscellaneous Surcharges (for standard size packages):	**Average Rates ***
Cask Handling Fee	\$ 200 minimum
Special Handling Fee (for equipment that must be trucked-in to handle shipments)	Billed at rental and hauling rates
Decontamination Services	\$ 25/man hr
Non-routine Man Rem Exposure	\$ 5.25/mrem

* The average is calculated from the NECO and CNSI waste burial rate schedules.

TABLE 11.13

CASK AND LINER DETAILED COST DATA

Cask Liner Cost Factors

Material Costs:	
Steel Plate	$ 22/100 lb
Lead	$ 40/100 lb
Fabrication Costs:	
Steel Liners	$ 187/100 lb
Lead and Steel Liners	$ 126/100 lb

Estimated Cask Liner Costs

Inside Dimensions (inches)	Internal Volume (ft^3)	Material	Weight (lb)	Estimated Cost ($)
25 x 55 x 68	54	Steel	3,800	7,100
61 diam x 71	120	Steel	5,650	10,600
26 x 56-1/2 x 70-1/2	60	Lead & Steel	8,500	10,700
26 x 50 x 43	32	Lead & Steel	8,587	10,800
33-1/4 x 51-3/4 x 72-1/2	72	Lead & Steel	9,330	11,800
72 diam x 17-1/4	41	Lead & Steel	17,500	22,000

Shipping Cask Rental Costs

Description * (inches)	Empty Weight (lb)	Daily Rental ($)
76 x 76 x 172 Steel Liner 30,000 lb Payload	15,000	125
76 x 76 x 85 Aluminum Liner 3000 lb Payload	42,000	125
50-3/8 x 58-3/8 x 72-3/8 Steel and Foam Lining 3000 lb Payload	3,500	50-100 depending on quantity
38 x 75 x 126 Steel Liner 5000 lb Payload	51,000	200
26-1/4 diam x 42-3/4 Stainless Steel or Lead Liner	20,000	200
74 diam x 73 Lead Liner	36,000	125
78 x 130 x 38 Unlined	27,000	125

* Dimensions are for cask cavity

TABLE 11.14

MAXIMUM VARIABILITY OF COST FACTOR ELEMENTS

Cost Factor Element	Maximum % Variability
Labor	17%
Material	18%
Equipment	18%
Overhead and Profit	2% to 9.5% *
Scrap Value	24%
Energy (electrical)	13%
Services:	
Shipping (truck)	25%
Shipping (rail)	27%
Burial	19%

* For contractors and subcontractors, respectively.

TABLE 11.15

REGIONAL VARIATIONS IN LABOR, MATERIAL AND ENERGY

Labor Cost Variations for Construction Work
(Expressed as an index with national average = 100)

Region	Index
California (Los Angeles)	117.1
Georgia (Atlanta)	83.9
Illinois (Chicago)	99.2
New York (New York)	113.2
Texas (Houston)	93.7
Washington (Seattle)	109.5

Material Cost Variations
(National average = 100)

Region	Concrete Construction (Raw Material)	Mechanical Hardware (Pipe, Machinery)	Electrical Hardware (Cable, Motors)
California (Los Angeles)	87.7	96.9	103.0
Georgia (Atlanta)	96.0	100.1	96.3
Illinois (Chicago)	105.8	101.9	117.6
New York (New York)	103.2	97.6	94.9
Texas (Houston)	103.7	99.5	97.2
Washington (Seattle)	105.8	96.5	101.0

Fuel Oil and Electrical Rate Variations
(National Average = 100)

Region	#2 Fuel Oil Cost Index *	Industrial Electrical Power Cost Index **
Mid Atlantic	104.8	112.6
South Atlantic	100.7	94.9
Pacific	92.3	90.4
West North Central	101.1	102.4
West South Central	99.8	91.6
East North Central	101.4	111.7

* Variability is approximately +5% to -8%

** Variability from the national average is approximately -10% to +13%

TABLE 11.16

FACTORS FOR SCRAP METAL VALUE

Scrap Metal Value	Cost Factor
Carbon Steel	$ 84/ton
Stainless Steel	$ 685/ton
Copper	$ 0.58/lb
Yellow Brass	$ 0.36/lb
Aluminum (Sheet and Cast)	$ 0.30/lb
Zinc	$ 0.11/lb
Lead	$ 0.35/lb

11.7 REFERENCES

1. United Power Association: Final Elk River Reactor Program Report, C00-651-93, Elk River, Minnesota, Revised (November, 1974)

2. Manion, W.J. and LaGuardia, T.S.: An Engineering Evaluation of Nuclear Power Reactor Decommissioning Alternatives, Atomic Industrial Forum, Inc., AIF/NESP-009 (November, 1976)

3. Smith, R.I., Konzek, G.J., and Kennedy, W.E.: Technology, Safety, and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station, Battelle Pacific Northwest Laboratories, NUREG/CR-0130 (June, 1978)

4. Robert Snow Means Company, Inc.: Building Construction Cost Data, Duxbury, Massachusetts (1979)

5. McGraw-Hill Information Systems Company: Dodge Guide, McGraw-Hill, New York, New York

6. Bureau of Labor Statistics: Employment and Earnings, US Department of Labor, Washington, D.C. (April, 1979)

7. Bureau of Labor Statistics: Producer Prices and Price Indexes Data, US Department of Labor, Washington, D.C. (April, 1979)

8. Richardson Engineering Services, Inc.: Building Construction Estimating Standards, P.O. Box 370, Solana Beach, California 92075

9. McMaster-Carr Catalog #84 (1978), McMaster Carr Supply, Co., P.O. Box 4355, Chicago, Illinois 60680.

10. Private communication between A. Crase of NECO Protective Packaging, Louisville, Kentucky, and R. Hykys of Nuclear Energy Services, Inc., Danbury, Connecticut (September 26, 1978)

11. "Material News Front" (steel prices), Iron Age Magazine, pp 172 & 176 (September 11, 1978)

12. Private communication between S. MacNamara of American Nuclear Insurers, and R. Hykys of Nuclear Energy Services, Inc., Danbury, Connecticut (October 28, 1978)

13. Private communication between J. Hoffman of American Nuclear Insurers, and R. Hykys of Nuclear Energy Services, Inc., Danbury, Connecticut (October 28, 1978)

14. Private communication between O. Saalborn of Nuclear Energy Services, Inc., Danbury, Connecticut, and Hall's Security and Investigation Service, Danbury, Pinkerton's Inc., Woodbridge, and Burns International Security Services, Inc., Bridgeport, Connecticut (January, 1980)

*U.S. GOVERNMENT PRINTING OFFICE: 1980-740-145/670