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AN EVALUATION OF ALTERNATIVE REACTOR VESSEL CUTTING TECHNOLOGIES FOR THE EXPERIMENTAL BOILING WATER REACTOR AT ARGONNE NATIONAL LABORATORY

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ABSTRACT

Metal cutting techniques that can be used to segment the reactor pressure vessel of the Experimental Boiling Water Reactor (EBWR) at Argonne National Laboratory (ANL) have been evaluated by Nuclear Energy Services. Twelve cutting technologies are described in terms of their ability to perform the required task, their performance characteristics, environmental and radiological impacts, and cost and schedule considerations.

Specific recommendations regarding which technology should ultimately be used by ANL are included. The selection of a cutting method was the responsibility of the decommissioning staff at ANL, who included a relative weighting of the parameters described in this document in their evaluation process.

Table S.1 in the Executive Summary lists the cutting technologies analyzed and the key parameters of each. This synopsis permits a rapid comparison of the techniques. For each metal cutting technique, the cutting speed in a single pass for 2.5-in. thick steel is based on vendor information. Auxiliary systems that would be required to support the cutting system are listed. If additional development is required, before the technology may be used to cut the EBWR vessel, it is so noted. Costs are broken down into three capital components (cutting system, manipulator and viewing, contamination control) and consumables. Manipulator systems are assumed to be designed for cutting from inside the vessel. Some cost savings may be realized by cutting from the outside. In addition, if there are particular limitations or shortcomings of a cutting technique, they are noted.

EXECUTIVE SUMMARY

PLASMA-ARC CUTTING

The plasma-arc cutting process utilizes a direct-current (DC) arc established between a tungsten electrode and the conductive workpiece. This arc is created within a gas flow of nitrogen or argon combined with hydrogen that flows through a constricting orifice in the torch nozzle. 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. The plasma is ejected from the torch nozzle at a high velocity and in combination with the arc, melts the contacted workpiece and blows the molten metal away. Nozzle life is greatly increased with a water-injection system that insulates the nozzle from the intense heat of the arc.

The speed expected from the plasma-arc system in cutting the 2.5-in.-thick material of the EBWR vessel is 13 in./min. The estimated cost for the plasma-arc cutting equipment is $40,000, which includes the torch assembly, power supply, control panel, and cooling-water system. The remote manipulation and viewing system to support the plasma-arc system is estimated to cost between $148,000 and $278,000. The lead time required for delivery of a plasma-arc system is estimated to be 6-8, weeks with additional time needed for design and fabrication of the remote-handling system.

This process would require supplementary equipment, such as an atmospheric-containment envelope, an air-filtration system, and, if a water-injection system is used, a liquid-waste-processing system at a total cost of between $45,000 and $82,000.

ARC-SAW CUTTING

The arc saw is a circular, toothless, rotating blade that produces a cut in conductive materials by means of a high-current electrical arc between the blade and the material being cut. Blade rotation removes the molten metal generated by the arc in the kerf of the workpiece. Water cooling (5-20 gal/min) of the saw blade) during in-air cutting is recommended. The depth of the cut is limited only by blade diameter. For 2.5-in.-thick carbon steel with a 0.1-in.-thick stainless steel cladding, a single-pass cut using a 20-in. blade is recommended. Cutting rates of up to 280 in.^{2}/min have been achieved with stainless steel and high-alloy steels; however, carbon steel cutting is impeded by slag buildup in the kerf, reducing the cutting rate. A cutting rate of 60 in./min might be expected.

Arc-saw cutting equipment, including the remote manipulator and associated hydraulics, is estimated to cost between $300,000 and $500,000. Additional costs are represented by supplementary equipment, such as the required atmospheric containment and air-filtration system, as well as processing and disposal of the 5-20 gal/min blade cooling water.

FLAME CUTTING

Flame cutting, also known as oxyacetylene cutting, typically cannot be used to cut nonferrous or ferrous/high-percent alloy metals. This is due to the formation of refractory oxides that have high melting point temperatures and form an insulating coating on the workpiece, thus hindering progress of the cut. These metals can be cut if the torch flame temperature can be increased above the melting point of the refractory oxides, or if the formation of these oxides can be prevented. Otherwise, the vessel must be jacked up to permit flame cutting from the outside diameter (OD).

One method of eliminating the formation of refractory oxides for inside diameter (ID) cutting is to remove the stainless steel cladding before flame cutting. This can be done with the electric-arc gouging process or by mechanical methods, such as machine cutting or abrasive cutting. Another method is to increase the oxyacetylene flame temperature through the introduction of a fine iron or iron/aluminum powder. In addition to raising the flame temperature, this powder assists the cutting action by producing an increased mass flux in the torch flame and oxygen stream. For flame cutting 2.5-in. mild steel plate in air, cutting speeds of 10-14 in./min are considered optimum. In this range, 10-20 ft^3 of oxygen and 2-3 ft^3 of acetylene would be required per linear foot of cut. Therefore, considering the expected 600 linear feet of cut necessary to section the EBWR vessel, the estimated cost of the oxygen is $450-$900, and the estimated cost of the acetylene is $500-$800. Equipment for the oxyacetylene flame cutting process would include the cutting torch, gas lines, counterweight, and a heat shield. The estimated price for this equipment is $1,700. Total estimated cost of this cutting system, including consumables and remote manipulation equipment, is $160,000 to $278,000. Since flame cutting cannot perform a complete cut of the reactor vessel wall from the inside diameter without preliminary removal of the stainless steel cladding, the additional cost of either supplementary processes or vessel jacking must be taken into account.

ELECTRIC-ARC GOUGING

The combination of electric-arc gouging and flame cutting utilizes two separate metal-removal operations to cut through carbon steel plate with a stainless steel cladding. When cutting is performed from the clad surface of the plate, the arc gouge technique is used to remove a strip of the stainless steel cladding. This exposes the carbon steel plate beneath for flame cutting.

In air, electric-arc gouging can achieve travel speeds of 20 in./min for removal of 1/4-in. stainless steel cladding at an electrode feed rate of 1-2 in./min. Standard electric-arc electrodes are available in 12- to 20-in. lengths. Mild steel strip electrodes have been developed to allow continuous operation without the need to replace consumed electrodes. Cutting of the EBWR vessel would be limited by the flame cutting rate of 10-14 in./min.

Capital costs for the electric-arc gouging equipment is $31,000. The standard electrodes (consumable) used with this equipment cost $150 per 100 electrodes. It is estimated that 100 electrodes would be needed to complete the job. Since this process produces large amounts of smoke, a high-efficiency particulate air (HEPA) filtration system and an atmospheric-containment tent would be required.

MECHANICAL CLADDING REMOVAL/FLAME CUTTING

Flame cutting (oxyacetylene cutting) as a method for reactor vessel sectioning from inside the vessel requires the removal of the 0.1-in. stainless steel cladding to a width of 1 in. to expose the carbon steel base metal. This allows the use of the flame cutting process without the buildup of refractory oxides that would be present with the cladding in place. This building would hinder progress of the cut.

Abrasive cutting would be an effective method for mechanical removal of the cladding. A pneumatically operated abrasive scarfing wheel with a diameter of 16 in. is estimated to be able to cut through the 0.1-in. cladding at the rate of 20 linear feet per hour. An electrically operated abrasive belt is also an effective means of mechanical manipulator unit that carries the oxyacetylene torch.

Pneumatic, right-angle-drive, scarfing wheels (2.5 hp, 5/8-in. arbor) are commercially available at $275-$575 each. Resin-bonded scarfing wheels (16-in. x 1-in.) are available at approximately $85 each. It is estimated that eight wheels would be required to perform 600 linear feet of cutting. A collective price of $955-$1,255 is estimated for the abrasive equipment. The cost of the electric belt drive system ranges from $750 to $3,000. These costs do not include supplementary equipment, such as the necessary air compressor and associated equipment and hoses. Use of this system would require an atmospheric-containment envelope and filtration system to contain airborne radionuclide particulates generated during cutting.

EXOTHERMIC-REACTION CUTTING PROCESSES

The exothermic-reaction cutting process utilizes hand-held equipment and is classified as a gross cutting technique. The two such cutting techniques examined in this document are the thermite-reaction lance and the exothermic cutting rod. The cutting speeds of the two processes are not continuous and are further limited by the burn time of the rods. The equipment cost for the exothermic cutting rod system is $1,000. The estimated cost of consumables to complete cutting operations on the EBWR vessel (based on 600 linear feet of cut) is $1,000 for the exothermic cutting rods and $1,000 for the necessary industrial oxygen. The cost for the thermite-reaction lance is $5 per lance. The lance-holder and oxygen supply valve cost $55. Welding supply wholesalers can provide the remaining equipment necessary for approximately $500. The feasibility of developing a remote manipulation system for the exothermic-reaction cutting process would need to be evaluated. A ventilation system and an atmospheric-containment tent would be required because this cutting process produces large amounts of smoke.

DIAMOND-WIRE CUTTING

Diamond-wire cutting is a relatively new technique that is typically used to cut through concrete and stone. Use of this method to cut through 2.5-in.

carbon steel would be at a cutting speed of 1-2 in./min, but the diamond wire would have an extremely low life expectancy. The diamonds might fracture or lose their sharpness, or the bonding between the diamonds and the wire might fail when cutting through metal. The diamond wire is successful in cutting through reinforcing steel present in concrete because the aggregate tends to resharpen the diamonds that have been blunted by the steel rebar. In addition, a clearance of 24 in. on both sides of the vessel wall is required to use wire cutting. Diamond-wire cutting is a wet cutting technique that uses water (3-5 gal/min) to cool the wire and flush the debris from the cut. Based on a cutting requirement of 600 linear feet, this system would require a total of 18,000 gallons of water for cutting. The capital cost for the necessary equipment is $35,225. Diamond wire, available at $110/ft, would cost between $660,000 and $990,000 to complete the job.

The diamond-wire cutting system described here has been designed for cutting concrete. Another diamond cutting system that has been designed for cutting metals is available. It employs high-tensile-strength wires that range in size from 0.003 to 0.015 in. and have diamonds embedded on their surface. Information on exact cutting rates for those wires currently is not available, but the rates are known to be low. It is possible that the cutting rates can be significantly increased through the use of appropriate acids.

WATER-JET CUTTING SYSTEM

The water-jet cutting system, when combined with the use of abrasives such as crushed garnet, can produce a cutting speed of 3 linear inches per minute of travel in a 2.5-in.-thick carbon steel plate. The water-jet cutting system is easily adapted to remote manipulation, as the nozzle head assembly can be located (piped) remotely from the intensifier pump and abrasive supply systems. The working tolerance between the workpiece and the carbide nozzle is not critical, and adequate cutting can be performed with a gap as large as 1.5 in. The equipment cost for the water-jet system, abrasive supply system, control panel, and a one-year supply of spare parts is estimated to be $90,000. The estimate cost of crushed garnet, sapphire orifices, and carbide nozzles required to complete cutting operations on the EBWR vessel (based on the estimation of 600 linear feet of cut) is $1,800. An estimated 3,500 gallons of water would be required for this process. Processing, transport, and disposal costs of the spent garnet, water, and reactor vessel particles (fines) represents an additional expenditure.

LASER CUTTING

By exposing a material to a focused laser beam, the energy transferred to the region directly below the beam is so high that it cannot be dissipated fast enough by conduction. This energy forms a cavity on the surface of the workpiece, and if the laser beam is powerful enough, this cavity will completely penetrate the workpiece. By directing a high-velocity gas stream into this cavity, the molten material will be ejected through the back of the workpiece. The cutting action is obtained by moving the laser-induced cavity and the assist-gas nozzle along the desired path of the desired cut. With a 25-kw laser system, a cutting speed of 5-10 in./min is achievable for 2.5-in. steel.

The CO_2 laser cutting system consists of the following components: a laser-beam generator with associated controls, pumps, high voltage supplies, gas supply and cooling system; beam-handling optics; focusing optics; and cutting nozzle assembly. Estimated cost for the equipment is over $1,200,000, and robotic remote manipulation equipment required for the application is estimated to cost an additional $228,000-$378,000. Additional equipment required to support the laser-beam cutting process would consist of a contamination-control containment and a HEPA filtration system to remove potential airborne particulates generated from the small amount of smoke created during the cutting.

MECHANICAL MILLING

The outside diameter pipe milling machine is a portable, hydraulically powered unit designed to be strapped onto a pipe or vessel with twin mounting chains. The blade is a rotating, multiple-tooth, circular cutter designed to remove metal from the workpiece. Cutting speeds of 3 in./min are possible in 3-in.-thick stainless steel with this mechanical milling system. Supplementary equipment, such as atmospheric containment and filtration systems, would be required because this process has the potential to generate airborne radioactivity. The estimated cost for mechanical milling equipment adapted to the dimensions of the EBWR vessel is approximately $60,000, with an additional

$20,000 needed to develop a machine to cut from the inside diameter. Neither inside nor outside diameter cutters are capable of making vertical cuts; however, a linear track could be developed. The costs for containment construction and air and water purification systems are additional.

CONTROLLED EXPLOSIVE CUTTING

Explosive cutting is a method of segmenting metal or other materials with an explosive that is formed into a geometric shape especially designed and sized to produce the desired separation of the workpiece.

To cut 2.5-in. metal, approximately 0.5 lb of explosives is required per foot of cut (4000 grains/ft). This translates to an estimated materials cost of $150/ft. The total cost for shaped charges to complete the cutting requirement of 600 linear feet is about $90,000.

Additional equipment to support controlled explosive cutting would consist of an atmospheric-containment tent and a HEPA filtration unit to remove the airborne radioactivity generated during the blasting/cutting operations. Some of the charges could be placed on the EBWR vessel wall through the use of an articulating inside circular cutter (estimated to cost $96,000). The remaining charges may be placed either manually or remotely at additional cost.

Assuming that a more cost-effective method of placing the charges could be found, the amount of charge required to fracture the vessel might be reduced by two orders of magnitude if the vessel could be locally chilled below the null ductility temperature. Because of the amount of research and development that would be required, this method was not pursued further.

ELECTRICAL-DISCHARGE MACHINING

Electrical-discharge machining (EDM) is a precise cutting process used in machining operations with critical tolerances. Applications of the EDM process generally require the workpiece to be of a limited size (small parts) because the workpiece is placed within a dielectric fluid container for processing. The tolerance between the workpiece and the EDM electrode must be controlled from 0.0005 to 0.002 in. Remote manipulation of the EDM equipment as applied to dissection of the EBWR vessel would necessitate a specifically designed system requiring 6 months of engineering time to produce, if it were even feasible to do so. The capital cost for the EDM equipment is approximately $61,000, which does not include manipulation or contamination-control systems.

CONTAMINATION-CONTROL MEASURES

For most of the cutting methods described in this report, an atmospheric-containment system and a filtration system would be required to control airborne radioactivity and high concentrations of smoke and gases.

Atmospheric-containment tents can be constructed from various materials to facilitate the use of specific cutting technologies. Herculite and metal frame containment tents can be used with cutting technologies that do not produce fire hazards. Herculite material is available at prices from $\$5.00/ft^2$. Assuming that 2,000 ft^2 of Herculite would be required, the cost of material, excluding the structural framework, would be about $10,000. The aluminum framework would cost an additional $3,000.

Fire-retardant, modular containment enclosures constructed from Lexan or stainless steel could be used with cutting technologies that include inherent fire hazards. The average cost of such a containment is about $600 for a 4 ft x 8 ft panel and slightly more for special panels, such as doors and windows. A fire-resistant contamination-control envelope would cost from $30,000 to $40,000.

Filtration systems such as HEPA filters are used in conjunction with cutting technologies that may produce airborne radionuclides or generate large amounts of smoke. The HEPA filter system should effect at a minimum 10 air changes per hour within the containment envelope. A typical HEPA filter unit that would meet this requirement costs approximately $7,100.

ANL SELECTION PROCESS

After a detailed study of 12 proposals, the decision was made by ANL that the most appropriate method for sectioning the EBWR reactor vessel would be to jack the vessel up and use an abrasive water-jet system located on the main floor to cut rings off the vessel. The decision was based on the following considerations:

1. Abrasive water-jet cutting causes very little spread of airborne contamination;
2. ANL has a facility to handle contaminated water;
3. Work would start on the least radioactive portion of the vessel first;
4. If abrasive water-jet cutting did not work as expected, it would be relatively easy to switch to oxyacetylene cutting;
5. Abrasive water-jet cutting does not create a fire hazard;
6. The abrasive water jet can be used to decontaminate or scabble concrete and steel; and
7. Abrasive water-jet cutting is estimated to be one of the least expensive approaches.

Table S.1 Summary of Cutting Technologies

Cutting Technology	Cutting Speed for 2.5" Steel	Auxiliary System Requirements	Development Required	Approximate Capital Costs ($1000): Cutting System	Manipulation and Viewing	Contamination Control	Approximate Consumable Costs ($1000)	Limitations
Plasma-Arc Cutting	13"/min	Ventilation, water processing	No	40	148-278	45-82	1.8	Limited to simple geometries
Arc-Saw Cutting	60"/min	Ventilation, water processing	Yes	160-280	148-228	45-82	1.2	Limited to linear cuts
Flame Cutting from OD	10"-14"/min	Ventilation	No	1.7	148-228	20-47	1.0-1.7	Requires jacking
Arc Gouge/Flame Cutting	20"/min for gouge; 10"-14"/min for cutting	Ventilation	No	31	148-228	20-47	1.1-1.9	
Mechanical Cladding Removal/ Flame Cutting	2"-4"/min	Ventilation, vacuum	No	2-5	148-278	23-50	1.2-3.4	-
Exothermic-Reaction Cutting	6"/min	Ventilation	Yes	0.6-1	Not feasible	20-47	1.7-3.0	Requires development of remote manipulation
Diamond-Wire Cutting	1"-2"/min	Ventilation, water pro-	No	35	98-178	45-55	660.0-990.0	Not effective for metal cutting, 24" OD clearance required
Water-Jet Cutting	3"/min	Ventilation	No	150	44	45-55	1.8	Processing, disposal of waste water and fines
Laser Cutting	5"-10"/min	Ventilation	Yes	1,200	228-378	20	0.250	Requires development of remote manipulation
Mechanical Milling	3"/min	Ventilation	Yes	50	88	45-55	6.0	Limited to circumferential cuts
Controlled Explosive Cutting	Instantaneous	Ventilation	Yes	0.1	98-178	20-47	90.0-186.0	
Electronic Discharge Machining	4"/hour	Dielectric fluid supply, containment and processing	Yes	61	228-378	25-35	0.321	Requires development for application to BWR vessel and 1" access to vessel OD

1.0 INTRODUCTION

1.1 Purpose

The purpose of this study is to evaluate and compare existing metal-cutting techniques for use in segmenting the reactor pressure vessel of the Experimental Boiling-Water Reactor (EBWR) at Argonne National Laboratory (ANL). Each metal-cutting technology will be evaluated by describing and comparing the following parameters:

- -- Performance characteristics,
- -- Feasibility for site-specific application,
- -- Environmental and radiological impacts, and
- -- Schedule and costs.

This study will be used by ANL personnel to select the cutting technique to be employed to section the EBWR pressure vessel into pieces that would fit into standard 55-gallon drums. It should be noted that ANL already has a liquid-waste-processing system, and therefore the costs estimated for disposing of liquid waste will be greatly reduced from the case if no such system were in place.

1.2 Background

The EBWR was built as a test reactor to demonstrate the feasibility of operating an integrated power plant using a direct-cycle, boiling-water reactor as a heat source. The reactor was designed to produce 20,000 kW of heat (kW_t) in the form of 600 psig saturated steam that was fed directly to a turbogenerator producing 5,000 kW of electricity (kW_e). Full-power operation at the design output of 20,000 kW_t was first achieved in December 1956.

Following intermittent operation at power levels up to 61,700 kW_t, the EBWR was modified to increase the power output capability to 100,000 kW_t. In November 1962, the reactor was successfully operated at 100,000 kW_t. Soon thereafter, the boiling-water experimental program at the EBWR was completed, and operation of the plant ceased temporarily.

The EBWR was next loaded with a core containing plutonium and operated in support of the Atomic Energy Commission's Plutonium Recycle Program. The

EBWR's role in this program was completed in July 1967, and the plant was shut down permanently. All nuclear fuel was then removed from the reactor, all liquids were drained from the various process systems, and the plant was placed in a dry lay-up condition.

In 1986, decontamination and decommissioning (D&D) of EBWR was initiated with the following objectives:

-- Removal of all radioactive materials associated with the EBWR facility from the Argonne National Laboratory's Illinois site,

-- Decontamination of the EBWR facility to unrestricted use levels, and

-- Cleanup of the EBWR containment building and its release for unrestricted use.

This study has been performed to aid in the planning for a safe and economical fulfillment of all of the objectives pertaining to the removal and final disposition of the reactor pressure vessel.

Argonne National Laboratory currently occupies a 1,700-acre reservation in DuPage County, Illinois, approximately 22 miles southwest of downtown Chicago. Laboratory structures and support facilities occupy approximately 200 acres of the site, with the remaining 1,500 acres devoted to landscaped areas and forest. Figure 1.1 shows the location of the Laboratory in relation to the Chicago metropolitan area. The location of EBWR, which is in the 300 area, is shown on the ANL site map, Figure 1.2.

The EBWR containment building is a circular, domed structure made of steel plates welded together. The structure originally formed a gas-tight envelope around the power plant. It rises 63 ft above, and extends 56 ft below, ground level and has an inside diameter of approximately 80 ft. Below ground level, the steel envelope, or shell, is 5/8 in. thick. Above ground level, it is 3/8 in. thick. The interior of the steel shell is lined with 2 ft of reinforced concrete below the main floor level. Above the main floor to a height of 26 ft, there is a 1-ft-thick concrete lining. At the 26-ft height, a 1-ft-thick concrete ceiling slab faced with 3/8-in.-thick steel plate completes the concrete envelope surrounding the power plant inside the containment. The main floor area is designed for a uniform allowable floor loading of 2000 lb/ft^2, while the lower levels are designed for loadings of 500 lb/ft^2.

As shown in Figure 1.3, the reactor pressure vessel is contained within a shielded cell that extends from the main floor downward approximately 25 ft to the region of the pump floor. The pressure vessel and its internal arrangement are shown in Figure 1.4. The vessel is made of carbon steel and is clad with stainless steel on those surfaces that were in contact with reactor water or steam. It is approximately 7 ft 5 in. in outside diameter, 24 ft 8 in. in length, and has a nominal wall thickness of 2.5 in. Nine control-rod drive tubes and four forced-circulation inlet pipe stubs extend downward from the bottom of the vessel approximately 7 ft, penetrating the bottom of the cell shielding. Two 12-in.-diameter, forced-circulation outlet pipes also extend from the pressure vessel through the bottom shield. The vessel is closed by a forged-steel cover plate approximately 9 in. thick, which is retained by 44 2.5-in. stud bolts.

The outside of the pressure vessel is covered by a layer of thermal insulation consisting of a 3-in. thickness of stainless steel wool held in place by stainless steel bands and wire mesh. The steel wool is separated from the inner surface of the steel cylinder by 3 in. of dead air space. This cylinder, approximately 8-1/2 ft in diameter and made of 3/4-in.-thick plate, constitutes the inner boundary of the reactor cavity cell. Lead bricks are stacked against the outside of the cylinder to provide a gamma-radiation shield. Shield-cooling coils made of copper tubing are fastened to the steel cylinder beneath the lead. Figure 1.5 shows construction details of the shielded cell.

1.3 Technical Basis and Assumptions

The evaluation of reactor-vessel-cutting techniques is based on the following factors:

-- The EBWR pressure vessel is a 2.5-in.-thick carbon steel vessel with approximately 1/10-in. stainless steel cladding on the inner surface. The ability to cut this vessel wall is the basis for technology assessment. The 9-in.-thick vessel head need not be considered since it may be decontaminated or manually cut.

-- The vessel will be cut into pieces small enough to permit shipment in standard, cylindrical 55-gallon drums.

- The initial vessel cuts will be made in air, while subsequent size-reduction activities may be under water.
- Contamination from reactor-vessel-cutting operations must be controlled to minimize cross contamination of other areas in the reactor building.
- Off-site releases of radioactivity are unacceptable.
- Peak contact radiation exposure levels are in the core region and will not exceed 100 Rem/h.
- Reactor internals will have been removed before vessel cutting.
- The remote manipulator will only be required to make circumferential and vertical cuts.
- The nozzles will be cut out separately.

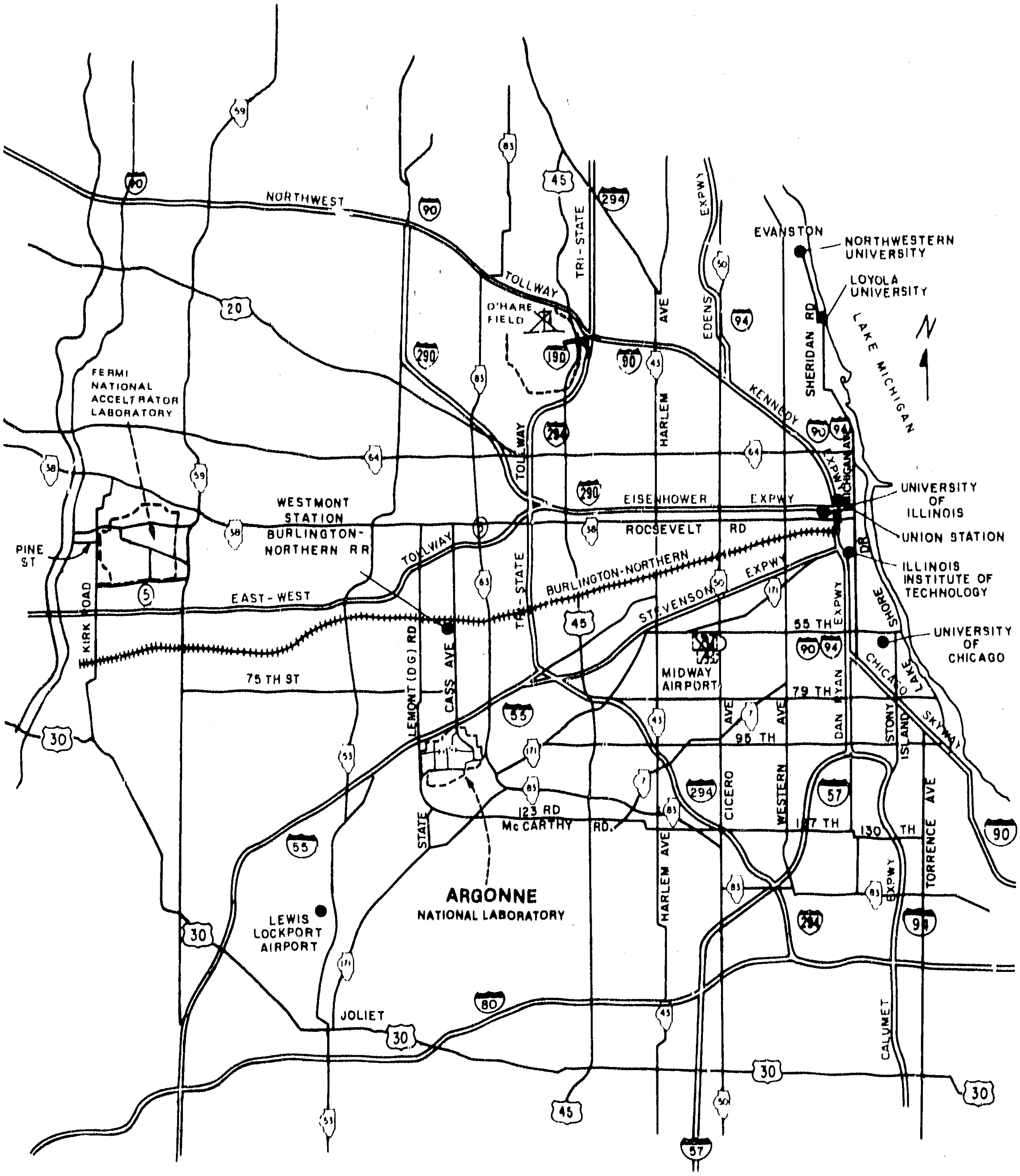

Fig. 1.1 Location of Argonne National Laboratory

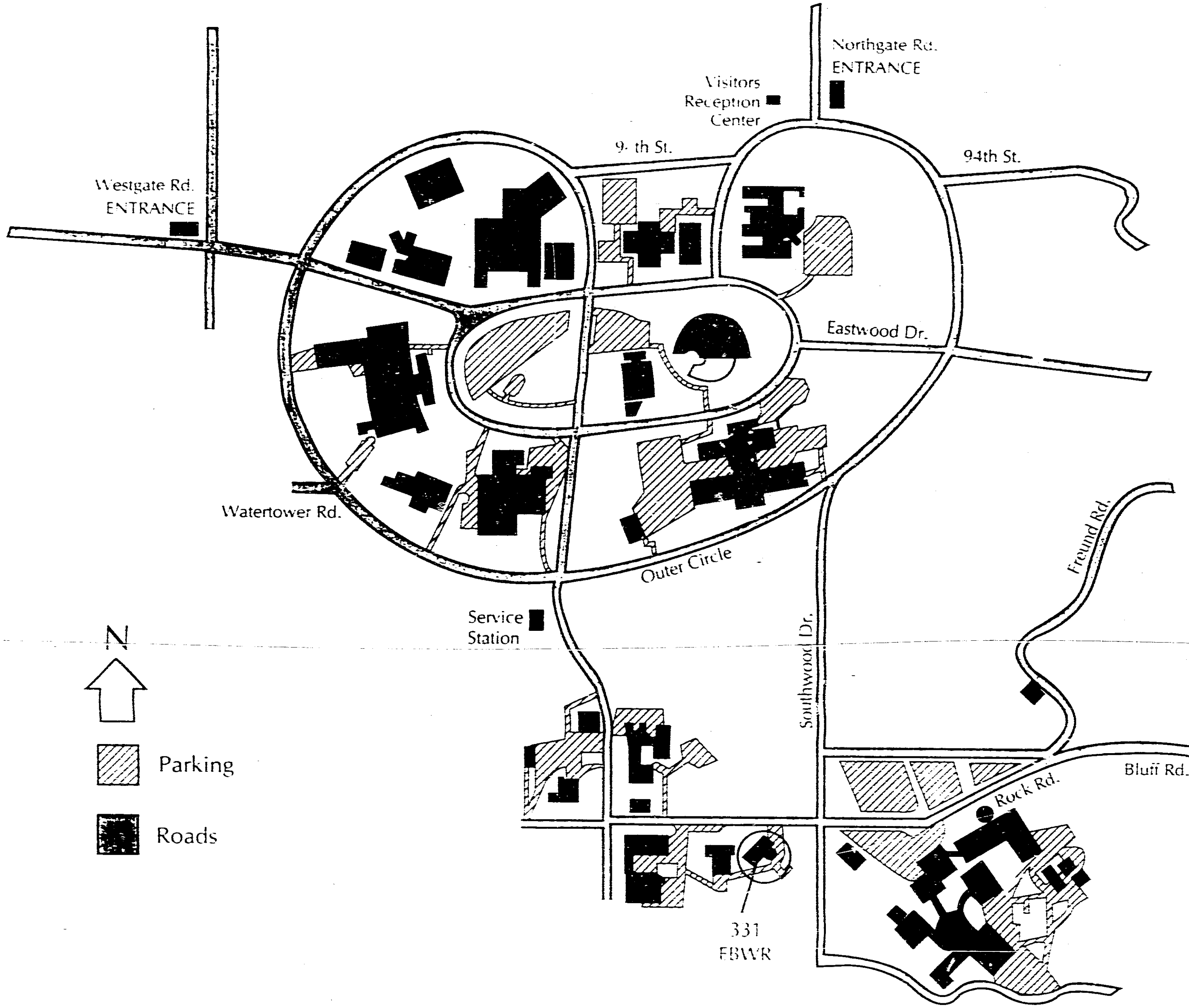

Fig. 1.2 Location of EBWR within the Argonne Site

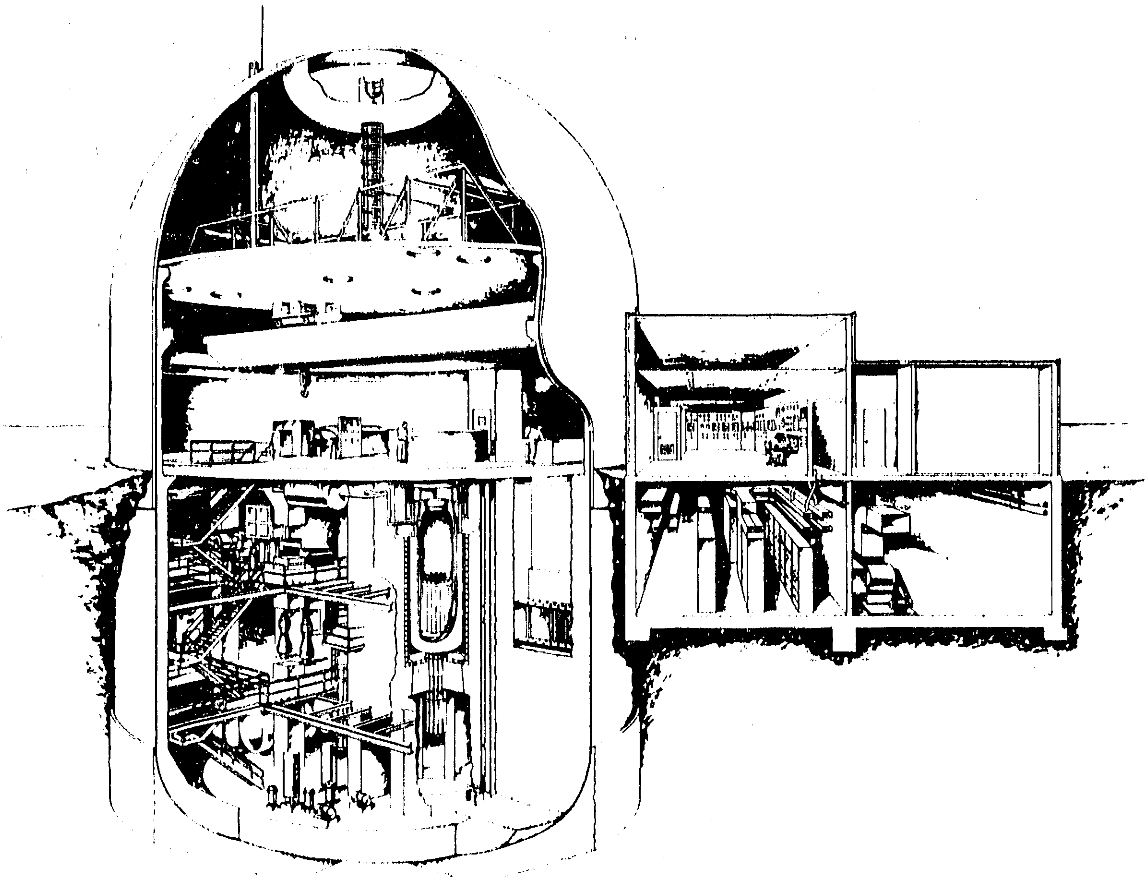

Fig. 1.3 Layout of EBWR Building

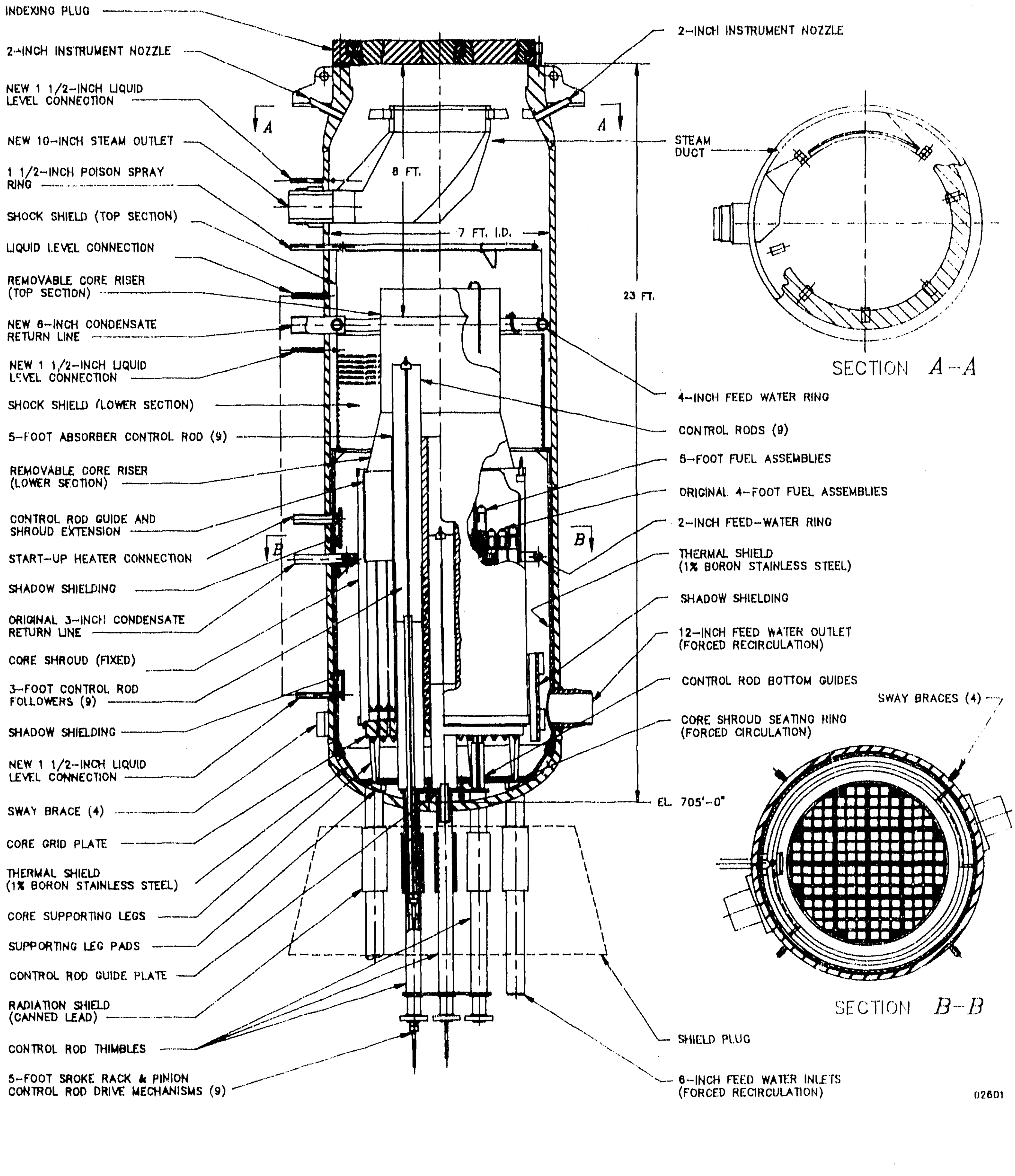

Fig. 1.4 Diagram of EBWR Pressure Vessel and Internals

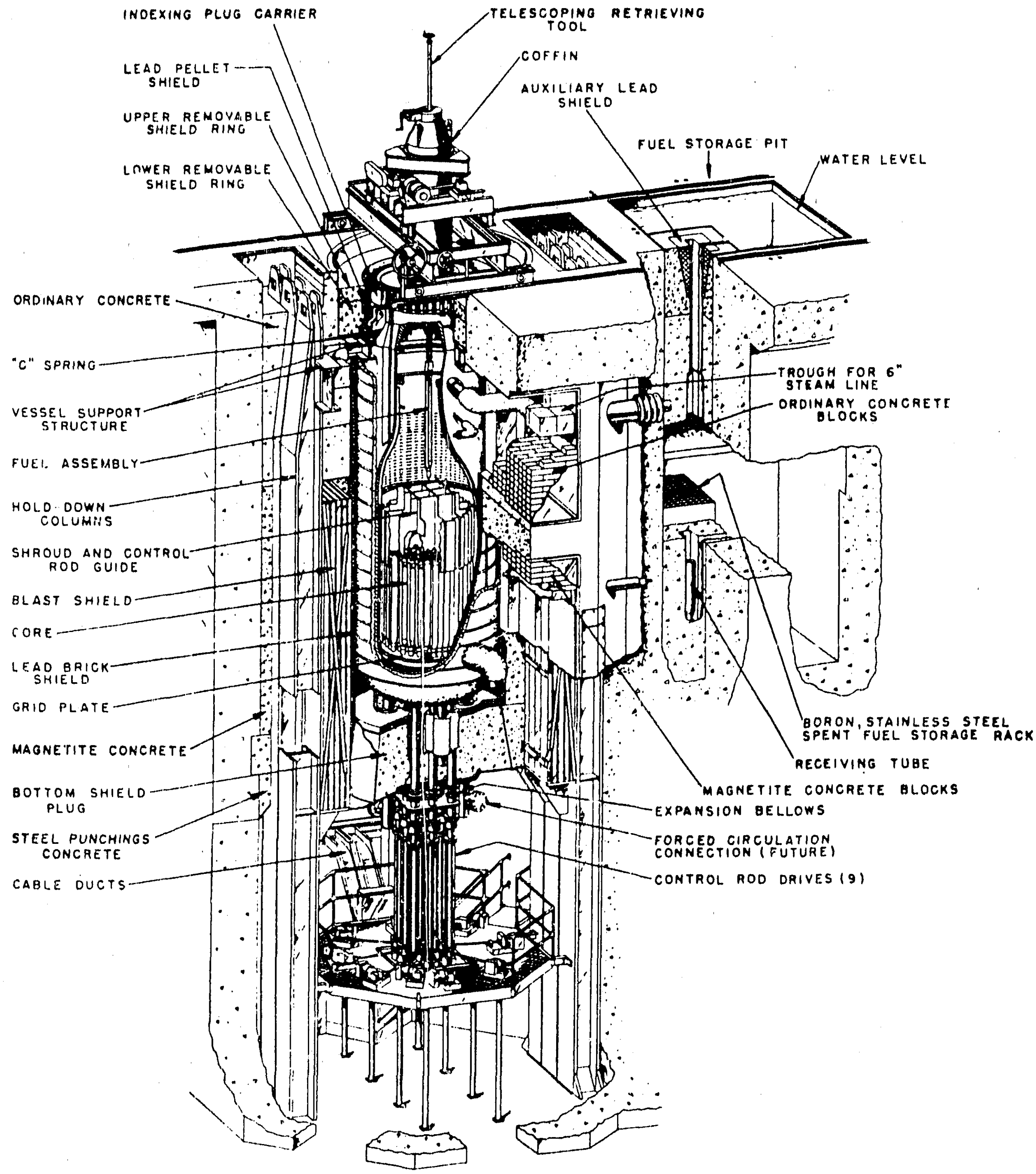

Fig. 1.5 Cutaway Pictorial of EBWR Reactor and Components

2.0 DISCUSSION OF REACTOR-VESSEL-CUTTING PARAMETERS

This section describes the parameters evaluated for each cutting technology.

2.1 Performance and Physical Characteristics

This report describes the performance capabilities of each cutting technology evaluated. The technique's limitations, as well as its favorable aspects, are described. Performance characteristics examined are cutting speed and depth of cut, reliability and maintenance requirements, adaptability of the technique to the cutting operation, and the need to provide a special support mechanism to permit cutting.

Also examined are such physical characteristics as equipment dimensions, weight, the cutting-system layout, and additional factors.

2.2 Site-Specific Impacts and Characteristics

Site-specific characteristics are considered for each cutting technique described. The factors examined include area accessibility, structural obstructions, equipment maneuverability, site resources, and plant system requirements. In general, it was assumed that services such as compressed air, water, and sewers were available, and no cost estimates were made for these items. One special feature of the ANL site is the presence of a facility for disposal of irradiated water. Even though this facility could be used to dispose of any liquid waste generated, the estimates made in this study assumed that all liquid waste was disposed of using an outside vendor.

2.3 Radiological, Safety and Environmental Impacts

The radiological and industrial safety needs associated with each cutting technique also are evaluated.

Radiological requirements such as containment construction, temporary ventilation, and radiologically adapted vacuum cleaner use, are incorporated to identify methods for minimizing potential airborne generation, surface contamination, and waste generation.

Fire, personnel safety, and other industrial safety hazards are considered in addition to occupational radiation exposure.

The potential for environmental releases from the EBWR building and any other off-site impacts are also addressed in this document.

2.4 Schedule and Costs

Scheduling and the time considerations therein have an important impact on work performance and job duration. Various scheduling factors invite analysis since they vary with cutting technique and could affect selection based on ease and flexibility. Among these factors are the following considerations: premobilization, operation, decontamination and demobilization.

Premobilization considerations include equipment availability, procurement, and delivery lead time. Other important considerations are preparations necessary for personnel deployment, training, and testing as required. Technology development or adaptation is another vital consideration for premobilization scheduling. Several of the cutting methods discussed in this document are not readily available for use or have never been used under these conditions. Modifications or further development may be required, increasing premobilization time and ultimately cost.

Operational considerations for scheduling include assembly and setup time, as well as cutting performance (cutting speed and projected downtime).

Decontamination and demobilization scheduling considerations include cutting-equipment disassembly (upon completion of vessel sectioning) and decontamination, as well as radiological survey time and disposition. Scheduling may also include containment-dismantlement time and time for area decontamination and material disposal. Waste-packaging time and temporary-ventilation-system disassembly, decontamination, and disposition are additional considerations.

Costs associated with each cutting technique include capital costs and costs for consumables and manpower requirements to support the vessel-cutting operation.

3.0 REVIEW OF REACTOR-VESSEL-CUTTING TECHNOLOGY

3.1 Plasma-Arc

3.1.1 Cutting Principle and Method

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 nitrogen or a mixture of argon and hydrogen 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 (15,000-24,000°K). 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, although the torch is capable of piercing metal. 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 (Hypertherm, 1989).*

The plasma-arc process may also use 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, high-quality cut surface, and reduced smoke generation (Manion, 1981). Figure 3.1.1 is a schematic of a complete remote plasma-arc cutting system.

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* See reference list in Section 5.0 and list of vendors contacted in Section 6.0.

3.1.2 Performance and Physical Characteristics

The typical cutting speed for the plasma-arc technique applied to thick carbon and stainless steels is 13 in./min (see Table 3.1.1). It can be expected that the EBWR vessel could be cut at a speed greater than 13 in./min, with a plasma-arc system (L-Tech, 1984).

To initiate the plasma-arc process, a starting gas mixture is used, typically argon and nitrogen. A high-frequency generator is energized to establish a pilot arc and cooling-water flow is initiated. Then, 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 to ensure complete penetration of the cut. When the operator is sure that penetration is being made, torch travel speed is increased to the programmed normal speed, and the required cut is made.

When the cut is complete, 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 then is de-energized, and torch travel is stopped.

The plasma-arc cutting technique, developed in the 1950's, uses a proven technology that has undergone continuous improvement over the years. Its successful use in the Elk River Reactor dismantlement was preceded by a development program that advanced the state-of-the-art by a factor of two in achievable cut thickness (Manion, 1981). Plasma-arc cutting at Elk River was a very successful application of this technology.

One potential limitation of the plasma-arc process is the ability of the arc to be maintained with complex geometries, such as layered thermal shields not tightly bonded. The plasma-arc application is limited to the simpler geometries. However, it is quite suitable for most reactor-vessel applications.

As shown on Table 3.1.1, the maximum in-air depth of cut in carbon steel is 7 in. which certainly bounds the EBWR cutting requirement (L-Tech, 1989).

Problems encountered during cutting operations can decrease cutting productivity. As shown in Table 3.1.4, the cutting life of the torch unit is only 1-2 hours. Torch failures require removal of the manipulator from the vessel, evaluation and correction of the problem, and reinstallation of the torch and manipulator. Torch rebuilds could include the replacement of any or all torch consumables, such as tip, electrode, end piece, outer insulator end cap, or collar, depending on torch condition.

During the operation of the plasma-arc system, a phenomenon called "double arcing" can occur. This means that an arc is established between the electrode and the torch nozzle. 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. Double arcing is a leading cause of nozzle damage (Manion, 1981).

Nozzle life is greatly increased with a water-injection technique because the steam boundary layer insulates the nozzle from the intense heat of the arc, and the water cools the nozzle at the point of maximum arc constriction. The protection afforded by the water-steam boundary layer also allows a unique design innovation; the entire lower portion of the nozzle can be ceramic. Consequently, double arcing caused when the nozzle touches the workpiece (the major cause of nozzle destruction) is virtually eliminated (Hypertherm, 1989).

3.1.3 Site-Specific Impacts and Characteristics

The plasma-arc cutting system is composed of several units that would be located in two general areas: inside the reactor vessel and on the containment building work floor. The torch and manipulator would be placed in the reactor vessel similar to the arrangement shown in the conceptual drawing in Figure 3.1.2. The equipment placed on the work floor includes the high-voltage supply, the torch-cooling system, the supply cutting gas, and the control panel. Since these items are rather large, heavy, and sensitive, they require a safe and stable space on the work floor. As shown in Table 3.1.2, the plasma-arc cutting system requires nitrogen, argon, and water supplies.

3.1.4 Radiological, Safety, and Environmental Impacts

A major concern with plasma cutting is the impact of smoke and particulate generation on the local atmosphere. Table 3.1.3 indicates that airborne particulate matter is generated at 4-6 lb/h during cutting operations (L-Tech, 1976).

Use of the plasma-arc for remote cutting of the EBWR vessel would have to be accomplished within the confines of a contamination-control envelope (containment) with a HEPA filtration flow rated at about 1000 ft^3/min, changing the total air volume in the envelope approximately 10 times per hour (Gulf United, 1972).

Since the plasma-arc will be operated remotely, the occupational exposure will become a function of the reliability and maintainability of the torch and manipulators.

Although vendors claim that one or two technicians can operate the system remotely once set up, thus permitting low exposure levels of workers to radioactivity, the crew to operate the plasma-arc at Three Mile Island included eight full-time workers. The staff size was necessitated by the increased maintenance associated with underwater cutting. The presence of such a large crew indicates that more than two operators may be required [Power Cutting Inc. (PCI), 1989].

Manipulators have been used and demonstrated to be dependable, making the torch assembly the major contributor to downtime (PCI, 1989). The operating life of the components of a typical torch assembly is shown in Table 3.1.4. The nozzle can be expected to last only 1-2 hours.

Selection of the location of the control panel and operator could be affected by the noise level. Within 6 ft of the torch, the noise level can reach 105 decibels (dB) (L-Tech 1989). Ultraviolet light, electrical shock, and fire are other hazards associated with plasma-arc cutting.

Liquid waste generated during in-air cutting with the use of water injection is limited to 0.5 gal/h required for stream constriction (Table 3.1.3). The quantity of slag generated with the use of water injection is less than the amount produced by normal in-air cutting because the kerf is smaller. Also, the amount of oxides produced will be reduced by the use of water injection (Hypertherm, 1989). Slag generated from cutting the reactor vessel will not significantly increase the volume of radioactive waste generated.

The plasma-arc torch, along with the manipulator, may be decontaminated and salvaged for future use at another site.

Off-site impacts during metal-cutting operations are not anticipated, because noise, airborne contamination, and waste materials will be confined to the containment building.

3.1.5 Schedule and Costs

As shown in Table 3.1.5, the approximate cost of a plasma-arc cutting system capable of cutting 3-in.-thick stainless steel in air is approximately $40,000 (1989 dollars). The system includes the torch assembly, power supply, control panel, and cooling-water system. The automation of torch positioning, cutting-speed control and automatic arc control and remote viewing will add $148,000-$278,000 to this cost.

Gas consumption during plasma-arc cutting in air is approximately 350 ft^3/h. As shown in Table 3.1.5, the total consumables cost for a 40-hour cutting program would be approximately $1,820.

As mentioned before, some vendors indicate that 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.

A remote plasma-arc manipulator that could control the critical standoff distance between the torch and the workpiece would have to be designed and manufactured (L-Tech, 1984). The lead time required for delivery of a plasma-arc system is estimated to be 6-8 weeks, plus additional time for the design and manufacture of the handling equipment (Hypertherm, 1989).

Table 3.1.1 Plasma-Arc System Performance and Physical Characteristics

Cutting Speed	13 in./min
Cut Water Flow Rate	0.5 gal/min
Operating Current	875 amps
Standoff Distance	0.75 in.
Maximum Cutting Ability in Air	6-7 in.

Table 3.1.2 Site-Specific Factors

Process System Requirements	Nitrogen, argon, water
Plant Process or Structural Modifications	HEPA filtration of airborne emissions, water processing
Access to Building and Vessel	Acceptable

Table 3.1.3 Radiological, Safety and Environmental Impacts

Generation of Airborne Radioactivity	4-6 lb/h iron oxide, nickel oxide, chrome oxide
Liquid Waste Generation	0.5 gal/min water injection
Solid Waste Generation	No increase to inventory
Industrial Safety Hazard	Noise, UV light, electrical shock, fire
Occupational Exposure	Low
Off-site Impacts	No

Table 3.1.4 Planning and Scheduling Considerations

Availability/Lead Time	6-8 weeks[a]
Development Requirements	None
Personnel Requirements	1 person to operate and 2 material handlers
Assembly Time	1 week[a]
Nozzle Cutting Life	1-2 hours[a]
Electrode Cutting Life	2-3 hours[a]

[a]Taken from Hypertherm, 1989.

Table 3.1.5 Costs for the Plasma-Arc System

Cutting System Capital Costs	
Power supply, control panel, torch unit, cooling water	$40,000[a]
Remote Manipulation and Viewing Equipment	
Manipulator and associated hydraulics	$120,000-$250,000
CCTV system	$27,800
Contamination-Control Equipment	
Contamination-containment structure	$13,000-$40,000
HEPA ventilation system	$7,100
Liquid processing	$25,000-$35,000
Consumables	
Gas	$600[b]
Electric power	$120[b]
Electrodes	$100[a]
Nozzle tip and nut	$1000[a]

[a]Taken from Hypertherm, 1989.

[b]Taken from Manion, 1981.

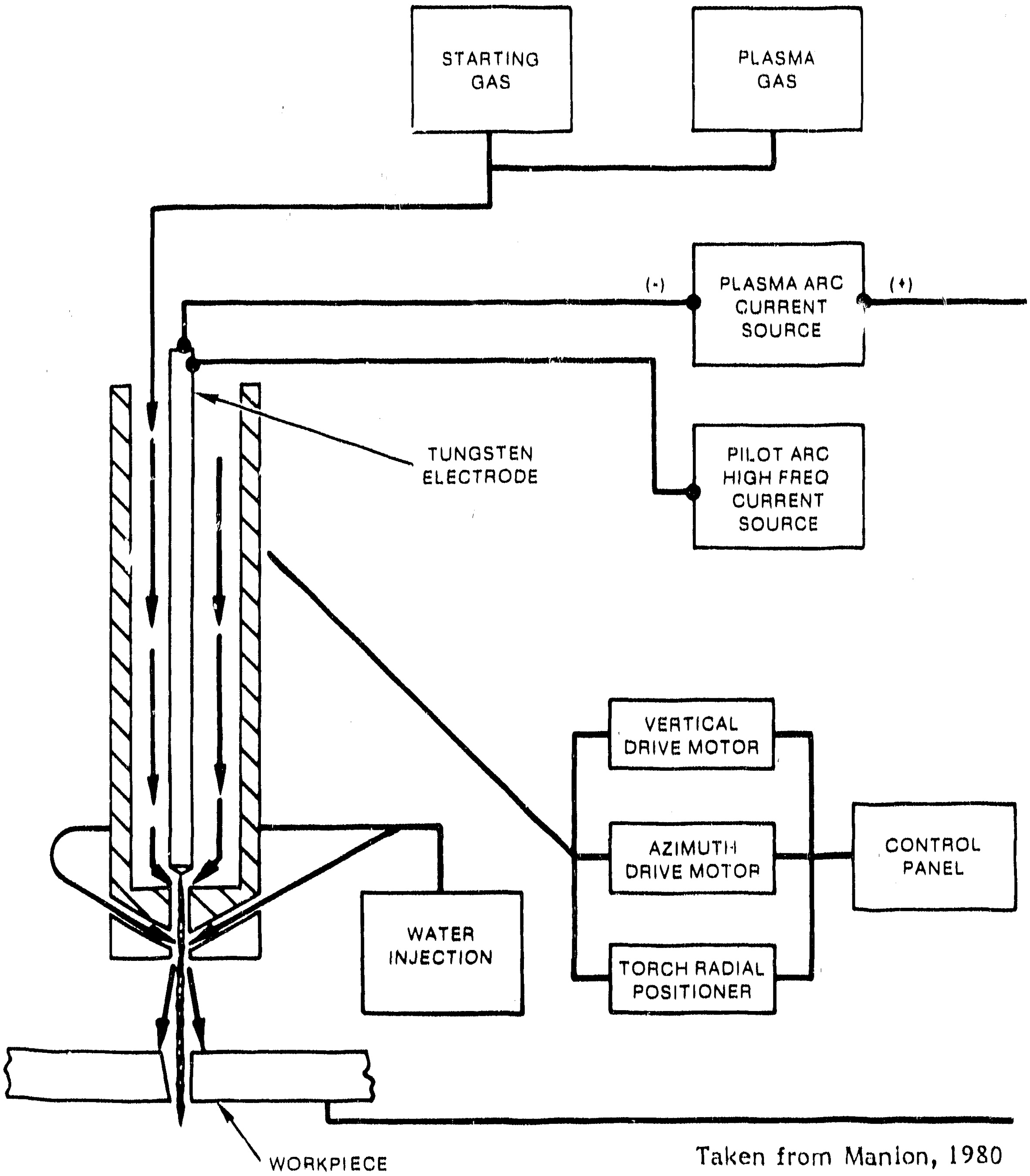


Fig. 3.1.1 Remote Plasma-Arc Cutting System Schematic (Taken from Manion, 1980)

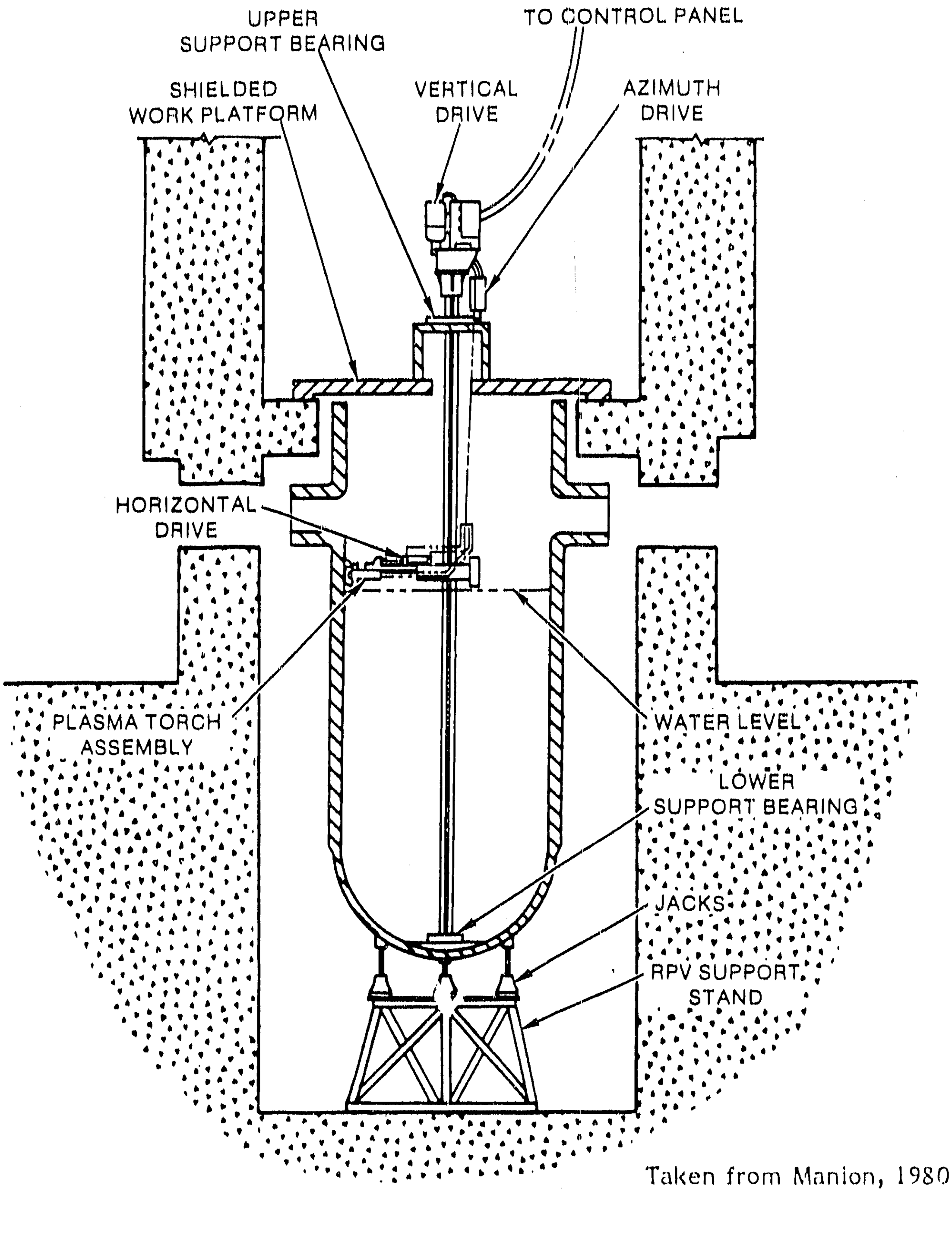


Fig. 3.1.2 Plasma-Torch System for Reactor-Vessel Cutting
(Taken from Manion, 1980)

3.2 Arc-Saw

3.2.1 Cutting Principle and Method

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 maintaining 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. Rotation of the blade is essential to operation, but rotational speed is not a critical parameter. Blade rotation causes 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 the blade and maintaining its structural integrity. The arc-saw can operate under water or in air. The saw blade must be water-cooled for in-air cutting. The depth of cut is limited only by blade diameter (Manion, 1981).

The saw blade is rotationally driven by a conventional electric motor. A fast-response, regulated D.C. power supply maintains a positive potential of 35 to 50 volts from the saw blade to the workpiece. The current passes to the saw blade by means of a slip ring assembly, maintaining a tightly controlled cutting arc. Normally, the amperage required for cutting is set by the operator, and the feed of the saw blade into the workpiece is controlled by a servo mechanism receiving input from the arc-current control network (Retech, 1989).

3.2.2 Performance and Physical Characteristics

The arc-saw achieves significantly faster cutting rates than other contemporary cutting techniques. Since the saw cuts by arc melting rather than friction, cutting speed is determined primarily by the melting point and electrical conductivity of the workpiece. Mechanical properties such as strength, hardness, and ductility are of little consequence.

The system excels at sawing hard-to-cut metals, such as stainless steel and high-temperature alloys. Cutting rates of up to 280 in.^{2} of cross section per minute have been achieved with stainless steels, high-alloy steels, titanium, zirconium, and nickel and cobalt base alloys (Leland, 1989a). Carbon steel cuts are most difficult to make. The current causes a magnetic field that impedes removal of carbon steel, thus causing slag buildup in the kerf. This buildup impedes the cutting rate. Therefore, the cutting rate is reduced by a factor of two for purposes of this study (60 in./min) (Clapper, 1989).

Because there is no physical contact between the blade and the workpiece, angular cuts are made with accurate tracking regardless of the point of entry, and fixturing requirements are minimal. However, the arc-saw is limited to making straight cuts (Leland, 1989a)

Many brittle materials cut cleanly without fracturing or binding, and a variety of materials, thicknesses, and configurations can be cut in a single pass. Since the arc-saw does not make contact with the workpiece, it can be operated remotely (Leland, 1989a).

Blade-wear characteristics are excellent. Average wear ratios are approximately 5 $in.^2$ of material cut to 1 $in.^2$ of blade wear (5 to 1) and can exceed 20 to 1 (Clappier, 1989).

Thin blades (thickness-to-diameter ratio of about 0.001) have greater cutting speeds than thick blades (thickness-to-diameter ratio of about 0.01). However, thick blades are capable of withstanding larger mechanical forces. There is an obvious trade-off that needs to be evaluated for each application. For this application, a thick blade would be recommended (Clappier, 1989).

The blades typically vary from 12 in. to 30 in. in diameter (Leland, 1989b). Thus, there appears to be ample margin beyond the 2.5-in. requirement at EBWR. It should be noted that approximately 9 in. of the blade diameter is prevented from entering the kerf by the head assembly. In addition, for deep cuts (e.g., greater than 3 in.), side arcing is a problem that tends to reduce the effectiveness and speed of cutting. Multipass cutting is recommended for deep cuts (Leland, 1989b).

For 2.5-in.-thick carbon steel with stainless steel cladding, a single-pass cut using a 20-in.-diameter blade is recommended (Leland, 1989b).

In early tests of the arc-saw system, arc initiation was achieved by visually positioning the blade within 0.5-in. of the workpiece, then advancing at slow speed until contact was made, stopping, and proceeding only after arc initiation. This requirement to physically contact the workpiece subjected the blade and saw head to violent collisions that reduced blade and saw life (Beitel, 1981).

Once arc initiation is achieved, it is easily maintained. Some of the arc-saw's advantages over plasma-arc cutting are that the saw keeps operating while waiting to cut, the cutting area is kept clean by the saw blade rotation, and standoff distance has a greater tolerance (Beitel, 1989).

A maximum arc gap tolerance of 0.003 in. to 0.005 in. is required for efficient cutting; however, a tolerance of 0.001 in. is optimal (Leland, 1989b).

3.2.3 Site-Specific Impacts and Characteristics

Since the arc-saw is designed in a modular fashion, the various main components, such as the arc-saw head, power supply, control system, hydraulic unit, and manipulator frame assembly, can be sized to meet the site-specific requirements for the EBWR (Leland, 1989a). Specifically, the arc-saw head assembly, which could weigh up to 400 lb, has approximate dimensions of 3 ft x 3 ft x 3 ft.

Figure 3.2.1 shows a conceptual sketch of a remote setup for arc-saw manipulation. Since the arc-saw is fairly large and heavy, the manipulator and support system would be a steel beam structure. The beam structure would rest on the bottom of the vessel and be anchored both to the building floor and to the vessel below the cutting head.

3.2.4 Radiological, Safety, and Environmental Impacts

Operation of the arc-saw under water provides a smooth, uniform kerf and is the preferred environment. Cutting also may be performed in air. In-air cutting will generate significant amounts of smoke and noise, increase blade wear, and produce a rougher cut surface. These effects can be reduced during in-air cutting by using a water spray. The water spray has a tendency to reduce kerf width, noise, smoke, and blade wear. It also enhances blade cooling. The benefits of water spray must be weighed against the reduction in cutting speed caused by the cooling of the workpiece. Blade cooling is typically accomplished using two nozzles, one on each side of the blade, with a combined operating flow rate between 5 and 20 gal/min (Leland, 1989b).

However, even with a water spray, in-air cutting with an arc-saw generates high noise levels (135 dB) (Beitel, 1981).

Localized containment and filtration of the resulting vapors will be necessary (Manion, 1981). It is estimated that a HEPA filtration system rated for 1000 ft^3/min will be sufficient to control contamination in the reactor building. Since the arc-saw would be operated remotely from a low-radiation area outside the contamination-control envelope, the levels of occupational exposure would be a function of blade wear, machine/manipulator maintenance, and tracking success. The blade wear ratio is in the 20:1 range (Leland, 1989a) and is not expected to be a significant contributor to the downtime of the arc-saw. Since tracking is reported to be extremely successful (Beitel, 1989), the reliability of the manipulator will have the most influence on overall downtime.

Liquid waste generated during in-air cutting would be limited to the 5-20 gal/min required for blade cooling. Solid waste is limited to the metal slag generated during cutting. Since this slag will be composed of the metal from the reactor vessel and depletion of the arc-saw blade, it will not significantly increase the volume of radioactive waste to be disposed. The arc-saw itself, along with its manipulator assembly, may be salvageable for use on another reactor dismantlement.

Off-site impacts during metal-cutting operations are not anticipated because noise, airborne contamination, and waste materials will be confined to the EBWR building.

3.2.5 Schedule and Costs

Delivery of an arc-saw with manipulator from an experienced manufacturer would require a lead time of 8-12 months (Leland, 1989b). Although the arc-saw has been used to segment metal in a radiological environment at Hanford, Washington (Beitel, 1981), at Los Alamos, New Mexico (Deichelbohrer, 1984), and in Japan (Torikai, 1976), the time for development or demonstration must include the preparation of specifications, fabrication, and delivery of the manipulator equipment. An additional month would be required to assemble and test the equipment before operation.

The operation of the unit requires only a single individual at the console (Leland, 1989b). The field application would probably require a three-person team, considering operation of the positioning equipment and handling of the workpiece segments (Manion, 1981).

Table 3.2.6 presents the approximate cost (in 1989 U. S. dollars) of the basic arc-saw head system described above. These components include the arc-saw head, controller console, power supply, and the remote handling and positioning equipment that would be required for application to the segmenting of an irradiated reactor vessel. Costs for the entire system, including the manipulator with associated hydraulics required to apply the arc-saw at the EBWR, are estimated to range from $300,000 to $500,000 (Leland, 1989b). Approximately six saw blades would be required to complete the cutting campaign at an additional cost of $1,200.

Table 3.2.1. Arc-Saw Physical Characteristics

Dimensions of Arc-Saw Head/ Blade Assembly	3 ft x 3 ft x 3 ft
Weight of Arc-Saw Head	400 lb
Cutting Speed	60 in./min
Cycle Limitations	Blade wear ratio = $\frac{\text{Work Piece Cutting}}{\text{Blade Wear}}$ = 50:1

Table 3.2.2 Arc-Saw Models Available[a]

Head Size	Blade Diameter (in.)	Current Rating (amps)
5 in.	7-16	2,000
7 in.	9-34	10,000
V8	10-38	15,000
T12	10-42	22,500

[a]Taken from Retech, 1989.

Table 3.2.3 Site-Specific Factors

Process System Requirements	Requires heavy remote handling system
Plant Process or Structural Modifications	HEPA filtration of airborne effluent; water processing
Access to Building and Vessel	Acceptable

Table 3.2.4 Radiological, Safety and Environmental Impacts

Generation of Airborne Radioactivity	Significant
Liquid Waste Generation	5-20 gal/min water spray
Solid Waste Generation	No
Industrial Safety Hazards	135 dBA noise
Occupational Exposure	Low
Off-site Impacts	No

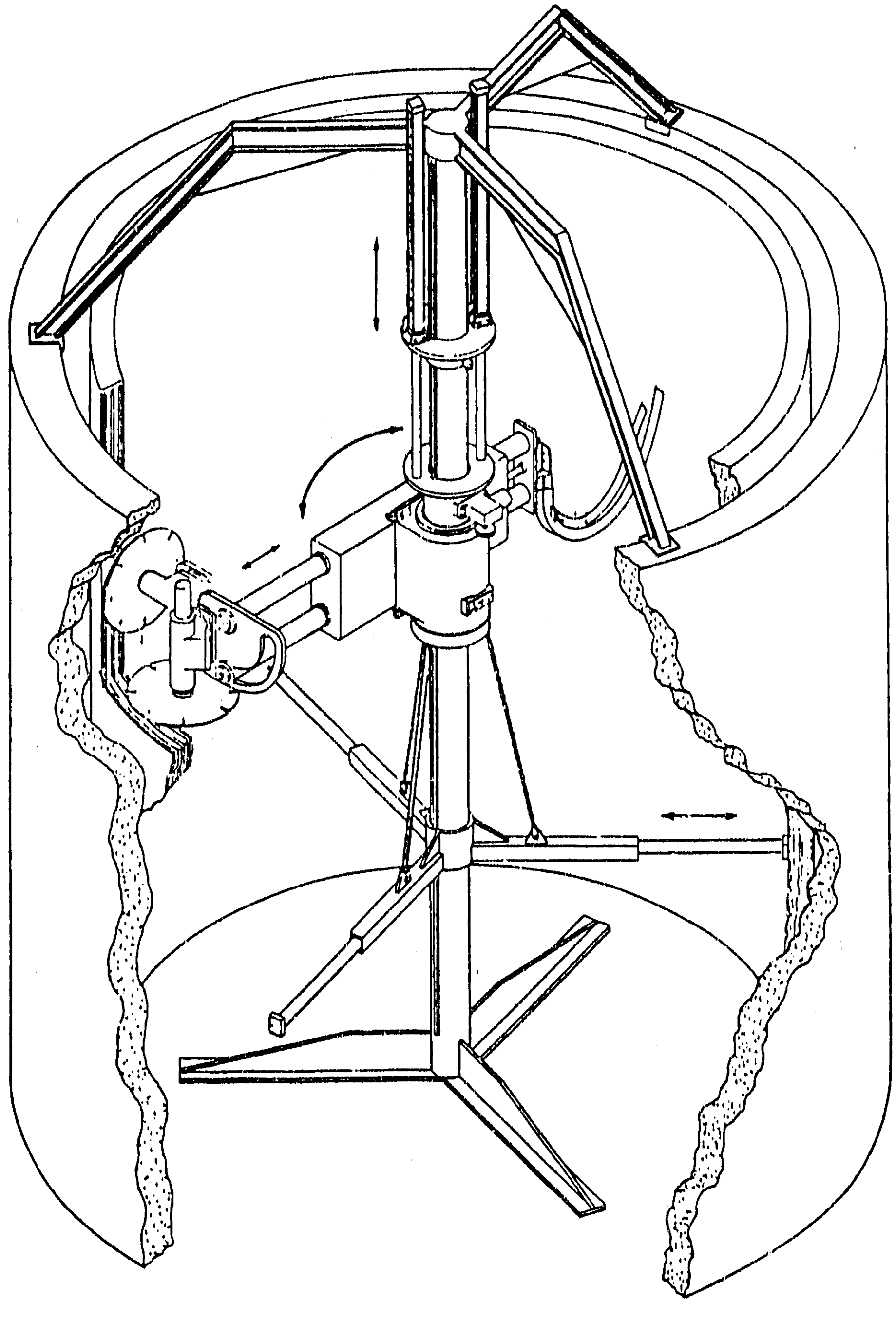
Table 3.2.5 Planning and Scheduling Considerations

Availability/Lead Time	8 to 12 months
Development Requirements	Mast-mounted remote application needs to be demonstrated
Personnel Requirements	1 person to operate and 2 material handlers 4 weeks
Assembly Time	4 weeks
Cutting Blade Life	100-150 ft of cutting per blade

Table. 3.2.6   Arc-Saw System Costs

Cutting System Capital Costs	
Arc-Saw head[a]	$40,000-$60,000
Controller console[a]	$60,000-$70,000
Power supply[a]	$60,000-$150,000
Remote Manipulation and Viewing Equipment	
Manipulator and associated hydraulics	$120,000-$200,000
CCTV system[c]	$27,800
Contamination-Control Equipment	
Contamination-containment structure[b]	$13,000-$40,000
HEPA ventilation system[b]	$7,100
Liquid processing	$25,000-$35,000
Consumables	
20-in. arc-saw blade @ $200 ea.[a]	$1,200

[a]Obtained from L. Leland, Retech, Inc.
[b]Obtained from NPO, 1984.
[c]Obtained from Rees, 1989.



Taken from Retech, 1989

Fig. 3.2.1 Conceptual Schematic of Arc-Saw Remote Manipulation (Taken from Retech, 1989)

3.3 Flame Cutting

3.3.1 Cutting Principle and Method

Flame cutting, also known as oxygen burning or oxyacetylene cutting, uses a flowing mixture of a fuel gas and oxygen that is ignited at the orifice of a torch. The fuel gases most commonly used are acetylene, propane, or hydrogen.

Flame cutting occurs with the rapid exothermic oxidation of the metal to be cut. Therefore, in general only ferrous metals can be cut with this process. It is a very effective process for cutting carbon steels.

Flame cutting can be performed either in air or under the water. Underwater cutting is more difficult to accomplish. In air, flame cutting has performed cuts up to 60 in. thick (Manion, 1981). Cuts up to a maximum thickness of 18 in. have been achieved in underwater applications (Hamasaki, 1987). This disparity is caused by the greater heat loss that occurs during underwater cutting. Underwater cutting generally uses hydrogen as the fuel gas. Acetylene is not used underwater since it becomes explosively unstable at pressures greater than 15 psig (Manion, 1981).

Flame cutting typically is unable to cut nonferrous or ferrous/high-percent alloy metals. This is due to the formation of refractory oxides (e.g., chromium oxide, aluminum oxide) that have high melting-point temperatures and form an insulating coating on the work that hinders progress of the cut. Another factor that prohibits flame cutting of some metals is that the combustion of some alloys does not add sufficient heat to the operation. These metals can be cut if either the torch flame temperature can be increased above the melting point of the refractory oxides or if the formation of these oxides can be prevented. Formation of the refractory oxides can be inhibited by the introduction of a chemical flux into the reaction. One method used to accomplish this is by introducing a powder, either through the oxygen jet or through a separate nozzle. This increases the fluidity of the refractory oxides so they can then be blown from the kerf (Doyle, 1969).

Also, flame temperature can be increased by introducing a fine iron or iron/aluminum powder at the torch nozzle to be injected into the flame and oxygen stream. The powder is introduced by blowing it with compressed air from a dispenser through an extra passage in the torch (L-Tech, 1989). The powder burns and increases the flame temperature sufficiently to melt the refractory oxides formed by the oxygen. This technique also assists the cutting action by producing an increased mass flux in the torch flame, which produces an erosion effect (Doyle, 1969). A larger torch top is required to accommodate the addition of the powder into the flame and oxygen stream.

3.3.2 Performance and Physical Characteristics

Flame cutting equipment is similar to that used in gas welding. A cutting torch may be manipulated either by hand or may be mechanized. Mechanized cutting provides steadier, faster, and more economical results.

Tolerances of ±1/32 in. are considered practical and achievable in cutting plate up to 6 in. thick.

Flame cutting equipment is relatively inexpensive, portable, and adaptable to different sizes of work. For mild steel plate thicknesses from 3 to 6 in., mechanized cutting speeds of 18-30 in./min are attainable (see Table 3.3.1). The cutting speed will depend on the temperature and the carbon content of the steel (L-Tech).

Flame cutting operational characteristics are shown in Figure 3.3.2. For in-air flame cutting of a mild steel plate 2.5 in. thick, cutting speeds of 10-14 in./min are considered optimum. (Many vendors claim to be able to achieve better performance than indicated in Figure 3.3.2.) In this range, 10-20 ft^3 of oxygen and 2-3 ft^3 of acetylene would be required per linear foot of cut. Higher cutting rates are attainable, but the efficiency of the other operational variables would be affected.

3.3.3 Site-Specific Impacts and Characteristics

Flame cutting and related techniques, such as powder cutting and flux injection, could be employed in a variety of circumstances. Conventional flame cutting could be used with electric-arc gouging for cutting from the reactor vessel inside diameter (ID). If used with oxide powder (powder cutting) or flux powder (flux injection), a complete cut could be performed from the reactor ID without preliminary electric-arc gouging or abrasive cladding removal.

If flame cutting (in conjunction with electric-arc gouging), powder cutting, or flux injection were employed from the reactor vessel ID surface, the reactor vessel could be cut in place. Access to the ID surface is adequate to accommodate the required equipment. Flame cutting alone without powder or flux injection is capable of cutting the vessel from the OD.

Flame cutting equipment is rugged, reliable, and versatile. Powder cutting and flux-injection techniques use the same basic equipment as flame cutting but with additional components for introduction of oxide or flux powder to the flame. All components are relatively small and portable.

Positioning equipment would be required for the equipment to traverse either the OD or ID surface of the reactor vessel. If flame cutting were used with either electric-arc gouging or mechanical cladding-removal techniques from the reactor vessel ID, the same positioning equipment could be used for both operations.

3.3.4 Radiological, Safety, and Environmental Impacts

As shown in Table 3.3.3, operation of flame cutting, powder cutting, and flux-injection equipment in air will produce significant amounts of smoke and vapor. Adequate ventilation and filtration would be required to control the spread of radiological contaminants present in these by-products. Noise levels in air are expected to be comparable to those with electric-arc gouging (115-120 dB).

If performed in water, flame cutting would minimize these problems, but a water-filtration system would be required to maintain water clarity for viewing. Powder cutting and flux-injection cutting are not performed in water.

The equipment for flame cutting, powder cutting, and flux-injection can be controlled remotely if used with a mechanized system. Fuel gas, oxygen, powdered oxides, and powdered flux are all supplied remotely through hoses to the torch.

This process does not generate liquid waste. Solid waste will be in the form of slag consisting of the consumed metal from the reactor vessel. Powder cutting and flux-injection techniques will also produce waste from the consumed oxide powders and flux powders.

Off-site impacts are not anticipated since all by-products of the metal-cutting operation will be confined in the EBWR building.

Personnel hazards associated with flame cutting and its associated variations include ultraviolet radiation, hot spatter, and fumes.

3.3.5 Schedule and Costs

Flame cutting, powder cutting, and flux-injection processes all utilize equipment that is readily available and relatively inexpensive. A typical flame cutting system costs approximately $500. This cost has been increased by a factor of 3 to account for control of gas and ignition systems from a remote location (Hamey, 1989).

Since flame cutting cannot perform a complete cut of the reactor vessel wall from the ID without preliminary removal of the stainless steel cladding, the additional cost of either vessel jacking or a preliminary process must be considered.

Powder cutting and flux-injection processes eliminate the need for preliminary removal of the stainless steel cladding. Cutting speeds are comparable to flame cutting, but these processes cost about twice as much because to the additional cost of powder (Doyle, 1969).

Components of a mechanized flame cutting system include a cutting torch, fuel gas, oxygen, counterweight, heat shield, and gas lines. Approximate prices in 1989 U. S. dollars are shown in Table 3.3.5.

Table 3.3.1 Flame Cutting Performance and Physical Characteristics

Cutting Speed	10-14 in./min
Limitations	Unable to cut stainless steel
Oxygen Consumption Rate	10-20 ft^3/min
Acetylene Consumption Rate	2-3 ft^3/min

Table 3.3.2 Site-Specific Factors

Process System Requirements	Oxygen, acetylene
Plant Process or Structural Modifications	HEPA filtration of airborne effluent
Access to Building and Vessel	Requires access to vessel OD or cladding removal system

Table 3.3.3 Radiological, Safety, and Environmental Impacts

Generation of Airborne Radioactivity	Significant
Liquid Waste Generation	No
Solid Waste Generation	No
Industrial Safety Hazards	115-120 dBA noise
Occupational Exposure	Low
Off-site Impacts	No

Table 3.3.4 Planning and Scheduling Considerations

Availability/Lead Time	1-2 weeks
Development Requirements	None
Personnel Requirements	1 person to operate and 2 material handlers
Assembly Time	1 day

Table 3.3.5 Cost and Availability of Flame Cutting Equipment

Cutting System Capital Costs	
Cutting torch	$1,500
Counterweight	$75
Heat shield	$55
Remote Manipulation and Viewing Equipment	
Manipulator equipment	$120,000-$200,000
CCTV system	$27,800
Contamination-Control Equipment	
Contamination-containment structure	$13,000-$40,000
HEPA ventilation system	$7,100
Consumables	
Acetylene @ $0.43/ft^3	$500-$800
Oxygen @ $0.08/ft^3	$450-$900

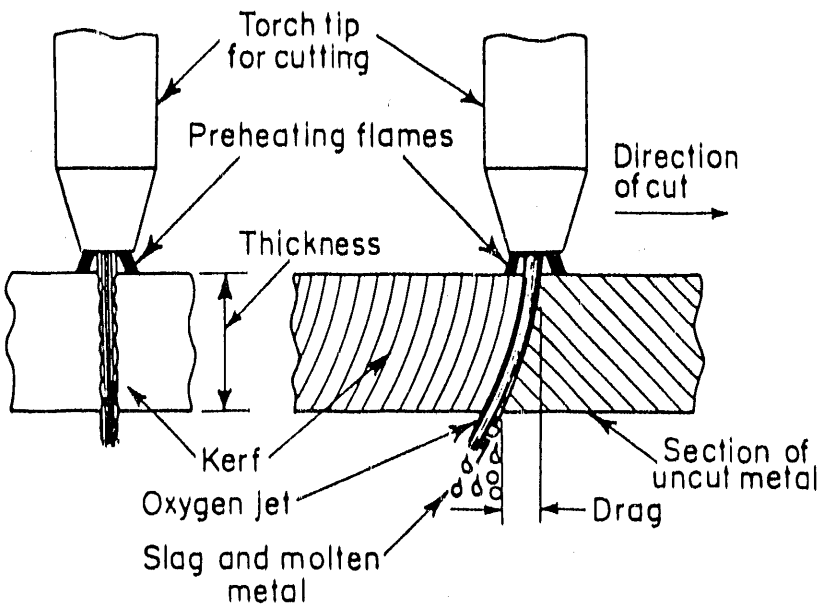
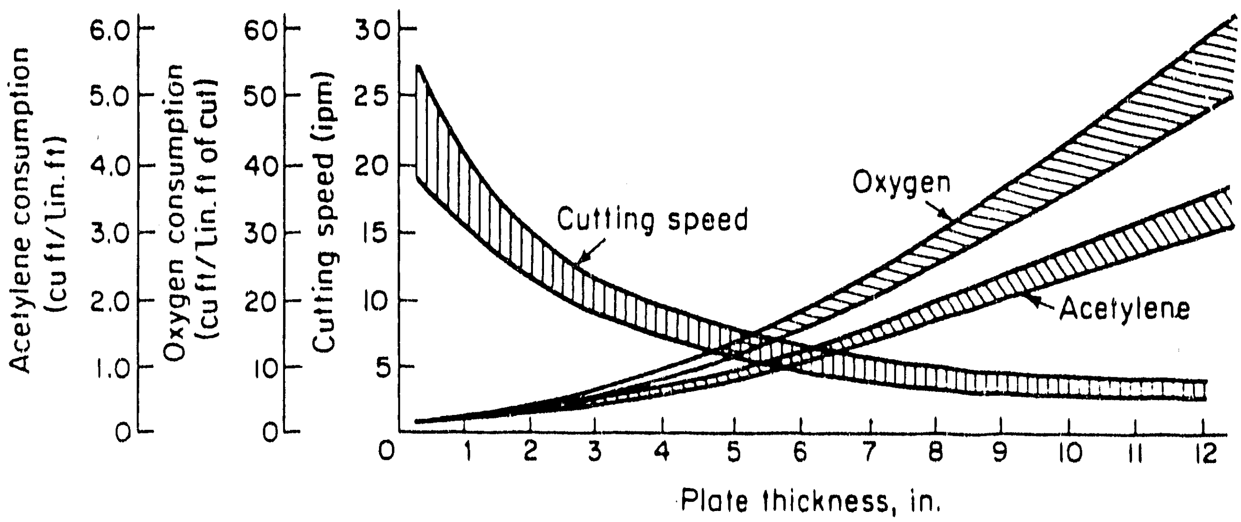


Fig. 3.3.1 Principles of Flame Cutting



Taken from Doyle, 1969

Fig. 3.3.2 Performance Data for Machine Flame Cutting of Mild Steel Not Preheated

3.4 Electric-Arc Gouging/Flame Cutting

3.4.1 Cutting Principle and Method

Electric-arc gouging would be useful in cutting the pressure vessel only when used in conjunction with a secondary cutting technique. As a preliminary operation, electric-arc cutting is a suitable method for removing the stainless steel clad surface from the carbon steel plate. To completely penetrate the carbon steel, flame cutting would be used for the final cut. The result would be a complete cut of the stainless steel cladding and carbon steel plate.

Electric-arc gouging uses a physical rather than a chemical means of metal removal. Unlike flame cutting, which utilizes the chemical oxidation process as the method of metal removal, electric-arc gouging uses the intense heat from the arc to melt a portion of the workpiece. An arc is drawn between the workpiece and the electrode. The electrode may be composed of graphite, carbon, flux coated, or mild steel. As the workpiece is made molten, a jet of air is passed through the arc; the jet is of sufficient velocity and volume to blow away the molten material. This exposes solid metal, which in turn is melted by the arc, and the process continues.

Because the electric-arc gouging technique removes metal by arc melting rather than oxidation, this technique is effective on both ferrous and nonferrous alloys. Arc gouging is typically performed in air with carbon or graphite electrodes. It has been performed in water with mild steel electrodes. When performed in water, the molten metal produced by the arc is blown away by a water jet rather than compressed air (Hamasaki, 1987).

3.4.2 Performance and Physical Characteristics

Electric-arc gouging for metal removal is a versatile technique that has been in use since the late 1940's. Its primary use in industry is to remove defective welds or to prepare joints for welding. Equipment is available that can provide manual (hand-held), semiautomatic (operator controlled), and automatically controlled (operator assisted) gouging. Automatic gouging is five times faster than manual gouging (Arcair, 1985).

The combination of electric-arc gouge and flame cutting utilizes two separate metal-removal operations to cut through carbon steel plate with stainless steel cladding. When the cutting is performed from the clad surface of the plate, the arc gouge technique is used to remove a strip of the stainless steel cladding. This exposes the carbon steel plate beneath for the flame cutting process. The cladding must be removed to a minimum width of 8 mm (0.32 in.) to accommodate subsequent flame cutting (Hamasaki, 1987)

Electric-arc gouging equipment for use in air consists of electrodes (typically carbon), electrode holder, power supply, and compressed air.

Three basic types of carbon electrodes exist: pointed, jointed, and flat. Pointed electrodes are pointed at one end. Approximately 3 in. of each pointed electrode is lost as stub. Jointed electrodes are designed to allow connecting electrodes for continuous gouging. Flat electrodes are designed to provide broader, flatter gouges. Electrodes range in diameters from 5/32-1 in. and in lengths from 12-in. Electrodes used with A.C.-powered systems require arc stabilizers to reduce arc outages caused by polarity changes. These stabilizers cause a reduction in metal volume removed as compared to D.C.-powered systems using electrodes of the same size. The D.C.-powered carbon electrode systems produce a smoother arc and increased metal-removal volume (Arcair, 1985).

As shown in Table 3.4.1, electric-arc gouging in air can achieve travel speeds of 20 in./min for removal of 1/4-in.-thick stainless steel cladding (Lundgren, 1981).

In water, complete cuts of stainless steel cladding and carbon steel plate were performed at speeds of 8 in./min and 5 in./min on plate thicknesses of 7 in. and 12 in., respectively (Hamasaki, 1987). These results were achieved with an automated system of unitary electric-arc gouging/flame cutting equipment.

Power for electric-arc gouging is supplied by standard welding power supplies. Manual gouging can utilize A.C. or D.C. power supplies. Automated gouging requires the use of a DC power supply (variable or constant voltage). Automatic systems require that the power supply be 100% duty cycle for the current required (based on electrode diameter). Three-phase DC power supplies provide smoother current output than single phase DC power supplies or combination AC/DC machines and improve the ease of operation (Arcair, 1985).

Compressed air for electric-arc gouging should be supplied at pressures of 60-100 psi when using carbon electrodes (see Table 3.4.2). The volume of air is determined by electrode size and type. The recommended air pressure for automated systems is 80 psi, with a minimum volume of 46 ft^3/min (Arcair, 1985). Adequate volume is more critical than pressure. The air provided should be clean and dry for optimum results.

One of the limitations of typical electric-arc gouge operations is the amount of work that can be performed per electrode. Since the standard electrode length is rather small (12-20 in. length for carbon electrodes), the work would be interrupted frequently to replace or attach new electrodes.

For removal of 1/4-in. stainless steel cladding at 20 in./min, the feed rate of a carbon electrode would be 1-2 in./min (Lundgren, 1981). Thus, the vessel cutting rate would be limited by the flame cutting rate of 10-14 in./min.

The Japanese have successfully used a mild steel strip electrode to perform underwater arc gouging. This electrode can be fed continuously during the gouging operation since sections can be welded on as needed. There, the electrodes were made long enough to allow welding to take place above the reactor pool to minimize exposure and contamination (Hamasaki, 1987). Mild steel strip electrodes could also be used in air.

3.4.3 Site-Specific Impacts and Characteristics

Electric-arc gouge equipment would be required only if gouging of the reactor vessel was to be performed from the clad inner surface in conjunction with flame cutting. Electric-arc gouging would be employed to remove a portion of the stainless steel cladding to allow completion of the cut with standard flame cutting techniques. If cutting were to be performed in this manner, the reactor vessel could be cut in place since access to this surface is adequate to accommodate the required equipment.

The available equipment for electric-arc gouging is rugged, reliable, and versatile. All components are relatively small and portable.

3.4.4 Radiological, Safety, and Environmental Impacts

As shown in Table 3.4.3, operation of the electric-arc gouge equipment in air would produce significant amounts of smoke, vapor, and, therefore, airborne radioactivity. Adequate ventilation and filtration would be required to control the spread of radiological contaminants present in this smoke and vapor. Noise levels in air of 115-120 dB are also to be expected. Operation in water would minimize these concerns, but a water-filtration system would be required to maintain water clarity for viewing.

Use of standard carbon electrodes would require frequent shutdowns to replace electrodes as they are consumed. Use of a mild steel strip electrode as described in Section 3.4.2 would allow electrodes to be replaced away from high radiation areas where the equipment would be operating.

This process does not generate liquid waste. Solid waste would be in the form of slag consisting of the consumed electrodes and metal from the reactor vessel.

Off-site impacts are not anticipated since all by-products of the metal-cutting operation will be confined to the EBWR building.

As with any metal-removal system that uses an electric arc, UV light, electrical shock, and hot spatter are potential hazards.

3.4.5 Schedule and Costs

Electric-arc gouging involves standard equipment used widely in numerous industries. As shown in Table 3.4.5, it is available for delivery from many suppliers within 2 months.

Components of a mechanized electric-arc gouge system include a gouging torch, counterweight, heat shield, DC power supply, electrode feed system, compressed air supply, welding cables, and electrodes (carbon, mild steel). Approximate prices in 1989 U. S. dollars are shown in Table 3.4.5. The capital and consumable costs for flame cutting are included in the costs of using this system to effect a complete cut of the vessel wall.

Table 3.4.1 Arc Gouge Performance and Physical Characteristics

Cladding Removal Rate in Air	20 in./min for 1/4-in. cladding
Electrode Consumption Rate	1-2 in./min
Power Requirements for Automated System	100% duty, 3-phase D.C.
Compressed Air Requirements	60-100 psi; 46 ft^3/min minimum

Table 3.4.2 Site-Specific Factors

Process System Requirements	60-100 psi air; 46 ft^3/min minimum
Plant Process or Structural Modifications	HEPA filtration of airborne effluent
Access to Building and Vessel	Acceptable

Table 3.4.3 Radiological, Safety, and Environmental Impacts

Generation of Airborne Radioactivity	Significant
Liquid Waste Generation	No
Solid Waste Generation	Electrodes are consumed
Industrial Safety Hazard	120 dBA noise, UV light, electrical shock
Occupational Exposure	Low
Off-site Impacts	No

Table 3.4.4 Planning and Scheduling Considerations

Availability/Lead Time	2 months
Development Requirements	Need to mount arc gouge and flame cutter on one manipulator
Personnel Requirements	1 person to operate and 2 material handlers

Table. 3.4.5 Electric Arc Gouge System Costs[a]

<u>Cutting System Capital Costs</u>	
Gouging torch unit w/automated electrode feed	\$5,500
Counterweight[b]	\$75
Heat shield[b]	\$55
Air compressor and air lines[b]	\$7,000
Power supply[a]	\$16,800
<u>Remote Manipulation and Viewing Equipment</u>	
Manipulator and associated hydraulics	\$120,000-\$200,000
CCTV system	\$27,800
<u>Contamination-Control Equipment</u>	
Contamination containment structure	\$13,000-\$40,000
HEPA ventilation system	\$7,100
<u>Consumables</u>	
Carbon electrodes @ 0.43/ft^3	\$150
Acetylene @ 0.43/ft^3	\$500-\$800
Oxygen @ 0.08/ft^3	\$450-\$900

[a]Obtained from T. Stump, Arcair
[b]Obtained from W. Donaldson, L-Tech

3.5 Mechanical Cladding Removal/Flame Cutting

3.5.1 Cutting Principle and Method

Should the flame cutting system be chosen for reactor-vessel sectioning from inside the vessel, it first will be necessary to remove the stainless steel cladding that protects the inner wall surface of the vessel. Mechanical removal and cladding along the proposed section lines will enable efficient penetration of the cutting flame through the exposed carbon steel base metal. Mechanical cladding removal is not necessary if the vessel wall can be cut from the outside, since the inward direction of the oxyacetylene flame will remove the cladding incidentally during the cutting process by literally "blowing" the cladding material away from the base metal.

Two principal methods for mechanical removal of surface metal were considered for this application -- machine cutting and abrasive cutting. Machine cutting techniques include milling, boring, drilling, surfacing, shaping, shaving, and planing. Abrasive cutting techniques include grinding, honing, polishing, lapping, filing, and particulate bombardment.

Machine Cutting

In all types of machine cutting, the effectiveness of the tool is governed by the precision of engagement with respect to the depth and angle of cut and the consistency with which the metal being cut is fed to the tool. This is generally a result of the overall size of the typical machine tools, which by virtue of their tremendous weight, rigidity, and strength facilitate high cutting speeds and engagements with extreme degrees of accuracy. In the case of machining the inner wall surface of the reactor vessel, the normal application of feeding material into a machine is reversed. Instead, a cutting head is traveled over the material being machined. To keep such a portable machine tool rigid, it would be necessary to design a tracking device of sufficient stability to enable consistent material engagement depth, angle, and travel speed. (See Section 3.10 for a further discussion of mechanical machining or cutting.)

Abrasive Cutting

Abrasive cutting types include grinding, sanding, honing, lapping, and particulate bombardment (sand blasting). Honing, lapping, and particulate bombardment are primarily surface-preparation techniques and are not considered suitable for the subject application. Grinding and sanding are commonly utilized in industrial and manufacturing processes and are considered effective and expedient metal-removal methods. Additionally, an exceptionally wide selection of sizes, shapes, and compositions are commercially available through literally hundreds of manufacturers and thousands of distributors worldwide. This highly competitive market provides the consumer with high quality and reasonable cost for these products. Moreover, the tooling required for the operation of grinding wheels and/or sanding discs/belts is light weight, small, and reliable thus facilitating technically straight-forward adaptation to use of remotely controlled manipulators.

Abrasive cutting is accomplished by the continuous abrading of a metal surface by a stone, disc, or belt roughly impregnated, bonded, manufactured, or coated with a granular substance or combination of substances with a hardness greater than that of the metal being worked. Unlike machine cutting, abrasive cutting media contact only 10-50% of the material surface at any given moment. This irregular cutting pattern allows for efficient thermal dissipation, which helps to retain the structural integrity of the abrasive material. Operating temperatures may also be controlled by increasing the size of the grindstone or disc or by lengthening the sanding belt. This effectively increases the time interval for heat dissipation from any given point of contact of the abrasive material. Finally, if desired, heat may be further controlled by the use of a coolant (generally water) that will retard the degradation of the abrasive material being used. However, because of the problems posed by the generation of liquid radioactive waste, this report assumes that no coolant would be used, and wear calculations are based accordingly.

As stated above, abrasives and their associated tooling are easily adapted to commercially available basic robotic/manipulator systems. This technology is currently utilized with demonstrated success in numerous automated manufacturing applications. No apparent technological obstacles exist to removal of stainless steel cladding by abrasive methods. Once this cladding is removed, the vessel wall may be flame cut with an oxyacetylene torch as described in Section 3.3.

Abrasive wheels are available "off the shelf" in a variety of grades, ranging in size up to 36 in. in diameter and 10 in. wide. Wheels can be custom-made but this generally requires 45 days lead time for delivery. Since literally thousands of sizes, shapes, and abrasive grades are offered as standard products, the need for specially manufactured wheels is unlikely.

An abrasive wheel is a self-sharpening cutting tool consisting of two basic elements -- the abrasive cutting grain and the bonding agent that holds the grain together. The abrasive wheel is designed for a particular application by selecting the appropriate combination of grain and bond for optimum metal removal and wheel life. The two types of bonding processes used universally are vitrified and resin bonding. Vitrified bonding, which literally means "changed into glass," produces a strong, rigid, yet relatively brittle bond support for the abrasive grain, making this type of bond most suitable for precise, tight tolerance metal removal when high surface finish is a requirement. Resin-bond abrasive wheels are best suited to removal of stainless steel cladding. Phenolic resins are used to produce resin-bond wheels that are extremely tough and strong. They are well suited to grinding operations involving severe stresses and normally operate at very high speeds [up to 17,500 surface feet per minute (SFPM)]. Resin bonds are commonly used in rough grinding applications called "snagging." Large-diameter snagging wheels are very effective for fast removal of large amounts of metal. Reinforced snagging wheels are commonly available in diameters up to 30 in. and are engineered for rotation in all planes of operation. A full range of abrasive grades, including zirconia, is readily available.

3.5.2 Performance and Physical Characteristics

Table 3.5.1 summarizes the performance and physical characteristics of the coated abrasive belt system. A conservative estimate of cladding removal to a depth of 0.1 in. by abrasive belt methods is 12 ft/hr, 2.4 in./min, 1 in. wide at a rotational cutting speed of 7200 SFPM. This is achievable using abrasive belts coated with 40-grit mixed granular zirconia crystals with an applied pressure of 10 lb to the workpiece surface during cutting operations. It is estimated that a belt 78 in. long is capable of removing stainless steel cladding to the prescribed minimum depth and width over a length of 1200 in. before the belt must be replaced (Hermes, 1989).

A grinding disc used with a standard industrial-grade grinding tool can not perform as efficiently or last as long as a belt with comparable abrasive qualities due to constraints on the size of abrasion working area available and the comparatively short disc life. A disc will also work a much wider surface area than is required for this application, leaving a surface with feathered edges and thus making depth gaging more difficult.

An abrasive wheel is capable of removing the cladding to a sufficient depth and width but would require constant fluid cooling to minimize degradation and maximize stone life. Typically, such a wheel is driven by a right-angle industrial-grade tool (pneumatic is preferable over electric). Such tooling is easily adapted to robotic applications and is readily available at competitive prices. Table 3.5.2 summarizes the performance and physical characteristics of the resin-bonded scarfing-wheel equipment.

To reduce the potential for fragmentation or shattering at high rotational speeds, fiberglass-reinforced wheels can be used. Slower rotation causes chattering, which results in excessive wear on the equipment, ineffective cutting, and potential shattering. The abrasive material commonly adapted to operation at 10,000-12,500 SFPM is mixed zirconia. As shown in Table 3.5.2, an abrasion wheel 16 in. in diameter will cut an estimated 20 linear feet of cladding per hour (4 in./min).

Thus, for either method described, the metal-cutting rate will be limited by the cladding removal rate.

3.5.3 Site-Specific Impacts and Characteristics

Implementation of abrasive methods for cladding removal may be simply accomplished utilizing the same remotely controlled manipulator that would be used for subsequent flame cutting. Little or no modification of the manipulator would be needed. The equipment is generally compact and lightweight posing no special problems in setup, movement, maintenance, or repair. The equipment is most efficient and reliable when operated pneumatically; however, 110 or 220 VAC electric drive motors are available. Typically, 90 psig constant air supply is adequate for satisfactory pneumatic operation. The air supply must be filtered through a moisture separator, and the tool must have an in-line oiler to ensure uninterrupted reliability.

3.5.4 Radiological, Safety, and Environmental Impacts

Radiological concerns are primarily involved with the control of airborne contaminants in the form of fine dust generated by the abrasion process. Since abrasion methods are commonly used throughout industry, most notably in welding preparations, efficient collection systems are readily available. High-volume suction vacuums are used to collect 80% of the abrasion by-products as they are generated. The balance of airborne material is typically controlled by area HEPA filtration systems. Nonairborne particulate material generated by the abrasion process may be collected by HEPA vacuuming equipment. The grinding methods discussed herein pose no unusual toxic atmospheric conditions, although a minimal amount of dust and smoke is generated. Assuming uninterrupted HEPA operation during grinding, no radiological, safety, or environmental impacts are expected beyond the vessel contamination-control envelope.

3.5.5 Schedule and Costs

Scarfing Wheel System

Equipment for the scarfing-wheel abrasive system consists of the pneumatic drive motor, air compressor and associated equipment, and the consumable resin-bonded zirconia grinding wheels. Additional equipment includes the remote manipulator required for application. The total equipment costs, excluding the remote manipulator and the air compressor system (it is assumed that ANL will provide a compressed air delivery system), is $1,300. This cost includes the consumption of eight scarfing wheels required for 600 linear feet of cutting. The remote manipulator, which would be used for the flame cutting process as well, is estimated to cost $120,000-$250,000.

Table 3.5.7 summarizes the equipment and consumable costs for scarfing-wheel abrasive system components. Since the equipment and consumable costs for the flame cutting system would also be required, they are included in the table. Manpower requirements for operation of scarfing wheel abrasive system used in conjunction with the flame cutting process would be one operator and two material handlers for optimum efficiency. Time required for assembly of the flame cutting/cladding removal operation performed with remote manipulation equipment is estimated to be 80 person hours. Downtime is expected to be limited to material handling and consumable replacements.

Coated Abrasive-Belt System

Equipment associated with the abrasive-belt system is the electric belt drive and the consumable zirconia-coated abrasive belts. Additional equipment includes the remote manipulator required for application of the system to the EBWR vessel. Equipment costs, including six consumable abrasive belts, is estimated to be $5,000. The estimated cost for a remote manipulator is $120-000-$250,000. Table 3.5.6 summarized these equipment and consumable costs.

Manpower requirements for operation of the coated abrasive-belt cladding-removal system used in conjunction with the flame cutting system for the sectioning of the EBWR vessel is estimated at one operator and two material handlers for optimum efficiency.

The time required for assembly of the remote manipulation equipment is estimated to be 80 person hours. Downtime is expected to be limited to material handling and consumable replacements.

Table 3.5.1 Performance and Physical Characteristics of Coated Abrasive Belt

Cladding Removal Rate	2.4 in./min (2400 grams/h)
Minimum Power Requirement	Electric, 6 hp, variable speed
Contact Wheel Hardness	50 shore
Wheel Seration Ratio	1:1 (45^{o})
Drive Tool Size	24 in. x 36 in. x 36 in.
Drive Tool Weight	75-200 lb
Optimum Cutting Speed	7,200 SFPM[a]
Wear Ratio[b]	20:1

[a]SFPM = Surface Feet Per Minute

[b]Wear Ratio = $\frac{\text{Volume of Metal Removed}}{\text{Volume of Abrasive Removed}}$

Table 3.5.2 Performance and Physical Characteristics of the Resin-Bonded Scarfing Wheel

Cladding Removal Rate	4 in./min (4000 grams/h)
Minimum Power Requirement	Pneumatic, 2.5 hp, variable speed
Minimum Arbor Size	5/8 in. for 16-in. wheel
Drive Tool Size	24 in. x 10 in. x 12 in.
Drive Tool Weight	20-40 lb
Optimum Cutting Speed	10,000 SFPM[a]
Wear Ratio[b]	15:1

[a]SFPM = Surface Feet Per Minute

[b]Wear Ratio = $\frac{\text{Volume of Metal Removed}}{\text{Volume of Abrasive Removed}}$ with water cooling

Table 3.5.3 Site-Specific Factors for Mechanical Cladding Removal/Flame Cutting

Process System Requirements	Manipulator must accommodate flame cutting
Plant Process or Structural Modifications	HEPA filtration of airborne effluent, vacuum for dust
Access to Building and Vessel	Acceptable

Table 3.5.4 Radiological, Safety, and Environmental Impacts

Generation of Airborne Radioactivity	Significant
Liquid Waste Generation	No
Solid Waste Generation	Cladding dust and slag from flame cutting
Industrial Safety Hazard	Noise
Occupational Exposure	Low
Off-site Impacts	No

Table 3.5.5 Planning and Scheduling Considerations

Coated Abrasive Belt	
Availability/Lead time	2-3 Weeks
Development requirements	No
Personnel requirements	1 person to operate and 2 material handlers
Number of belts to complete job	6
Resin-Bonded Scarfing Wheel	
Availability/lead time	2-3 Weeks
Development requirements	No
Personnel requirements	1 person to operate and 2 material handlers
Number of belts to complete job	8

Table 3.5.6 System Costs Using Coated Abrasive Belt

Cutting System Capital Costs	
Electric belt drive	\$750-\$3,000
Flame cutting equipment	\$1,500
Remote Manipulation and Viewing Equipment	
Remote manipulator	\$120,000-\$200,000
CCTV system	\$27,800
Contamination Control Equipment	
Contamination containment structure	\$13,000-\$40,000
HEPA ventilation system	\$7,100
HEPA vacuum system	\$3,000
Consumables	
Coated abrasive belts (78 in. x 1 in., 40 grit mixed zirconia with heat ablative) @ \$275 ea.	\$1,650
Oxygen for flame cutting	\$450-\$900
Acetylene for flame cutting	\$500-\$800

Table. 3.5.7 System Costs Using Resin-Bonded Scarfing Wheel

Cutting System Capital Costs	
Pneumatic drive	\$275-\$575
Flame cutting equipment	\$1,500
Remote Manipulation and Viewing Equipment	
Remote manipulator	\$120,000-\$250,000
CCTV system	\$27,800
Contamination Control Equipment	
Contamination-containment structure	\$13,000-\$40,000
HEPA ventilation system	\$7,100
HEPA vacuum system	\$3,000
Consumables	
Resin-bonded scarfing wheels (16-in. dia., 1-in. width, 50-grit mixed zirconia) @ \$85 ea.	\$700
Oxygen for flame cutting	\$450-\$900
Acetylene for flame cutting	\$500-\$800

3.6 Exothermic-Reaction Cutting

3.6.1 Cutting Principle and Method

The exothermic reaction produced from the combustion of carbon steel (or carbon steel combined with other metals) in the presence of oxygen produces an extremely high temperature (6,000-10,000°F). This high temperature, when concentrated on a small area, is capable of burning, melting, or vaporizing almost any material including stainless steel or mineral aggregates.

Equipment adopting this exothermic reaction for gross cutting purposes is commercially available in several hand-held systems. Two of these cutting systems are referred to as the exothermic cutting rod and the thermite-reaction lance.

Exothermic Cutting Rod

The exothermic cutting-rod system uses consumable, small diameter (1/4-in. and 3/8 in.), carbon steel rods with a maximum length of 44 in. These rods are fabricated to allow a supply of industrial oxygen (regulated to 80 psi) to flow through the rod (at 7-9 ft^3/min) to the tip of the rod, where the high-temperature combustion (6,000-7,000°F) occurs. The exothermic cutting rod is ignited by the generation of an electrical arc. The arc is supplied from a minimum 100-ampere source, such as a 12-volt battery. The exothermic cutting-rod system may also be supplemented by an electrical source (maximum 200 amperes), such as a welding machine, used in conjunction with flux-coated cutting rods to maintain a continuous arc with conductive materials. This arc produces a higher burn temperature (over 10,000°F) and allows for faster cutting speeds (Arcair, 1988a; Henderson, 1989).

The exothermic cutting-rod system is not designed for use in underwater cutting. This system is operated by one person. The operator, with the torch handle/cutting rod in hand, actuates the torch handle trigger to supply oxygen to the exothermic cutting rod. The operator then grounds (strikes) the rod to the workpiece or striker plate and the arc produced ignites the cutting rod. The operator then applies the end of the rod to the workpiece to perform the cut, continually feeding the rod into the kerf as the consumable rod burns away. When the cutting rod has been entirely consumed, the operator replaces it with a new rod and continues until the cut is complete.

Thermite-Reaction Lance

The thermite reaction lance consists of a 10.5-ft-long of iron pipe small diameter (available in 3/8 in., 1/2 in., 5/8 in., and 11/16 in. OD) that is packed with wires of magnesium, aluminum, and steel. Industrial oxygen from a supply tank (70-120 psi) flows through this pipe (at approximately 15 ft^{3}/min) and when ignited produces an exothermic reaction that produces an extremely high temperature (up to 10,000°F). The exothermic reaction caused by the combustion of iron, aluminum, magnesium, and steel is referred to as a "thermite reaction" (Thermolance, 1988).

Figure 3.6.1 illustrates the basic system for a thermite-reaction "thermal" torch. Figure 3.6.2 illustrates a specific holder/oxygen supply valve for a thermite-reaction lance.

The thermite-reaction lance is generally ignited with an oxyacetylene torch or electrical-arc source. There is no provision for the supplement of an electrical cutting arc. The thermite-reaction lance can be used in underwater cutting tasks, and when it is used at depths greater than the surface, oxygen delivery pressures must be adjusted accordingly (Thermolance, 1988).

The lance is operated by one operator and an assistant. The cutting lance is inserted into a holder that controls the flow of oxygen to the lance. The operator partially opens the control valve on the holder to allow a small amount of oxygen to flow through the lance, and the assistant ignites the end with an oxyacetylene torch. The end of the lance will begin a sparkling action. The operator then completely opens the oxygen-control valve to produce a vigorous burning reaction. Application of the lance to a concrete workpiece must be done with a slight pressure combined with a circular movement to prevent jamming. If the workpiece to be cut is metal, the operator must maintain a short gap and manipulate the lance in a downward direction to wash the molten metal out of the kerf and keep the kerf wide enough to prevent jamming. The consumable lance can be extinguished by closing the oxygen supply valve and can be used again when required. When the lance is consumed, another lance is attached directly to the old one with a special friction-fit swage end to continue the cut. The new lance is ignited, and the cutting process continues (Thermolance, 1988).

3.6.2 Performance and Physical Characteristics

The exothermic-reaction systems, described in this section are versatile, hand-held, portable cutting systems designed for use in field applications where general maintenance or gross cutting is required. The exothermic cutting processes have not been designed for, or adapted to, performance of remote manipulation cutting tasks (Henderson, 1989).

Components of the exothermic cutting-rod system consist of the following:

-- A regulated oxygen supply (typically 80 psi),

-- Exothermic cutting rods (uncoated or flux coated),

-- 100-ampere ignition source (12-volt battery),

-- 200-ampere ignition/constant arc source (welding machine),

-- Hand-held torch handle (integral oxygen supply trigger),

-- Oxygen supply hose,

-- Electrical supply cable, and

-- Safety equipment.

The components listed here (exclusive of the oxygen supply bottles, 200-amp welding machine, and safety equipment) are contained within a storage box of 23 in. x 17 in. x 7 in., and a shipment weight of 42 lb. (Arcair, 1988a).

The exothermic reaction cutting rods (uncoated for normal usage or flux coated for use with an electrical arc) are consumed during the cutting process. A 36-in. cutting rod with a diameter of 3/8 in. is consumed in approximately 1.5 min. This "burn time" will, however, produce a cut of 8-10 in. in a 2.5-in. thick carbon steel plate (Henderson, 1989).

Table 3.6.1 shows that the cutting speed for the exothermic rod (1/4-in. diameter) is approximately 6 in./min.

Oxygen supplied to the exothermic cutting rod at 80-100 psi is consumed at the rate of 7 ft^3/min for the 1/4-in.-diameter rod and up to 12 ft^3/min for the 3/8-in. diameter cutting rod (Henderson, 1989).

The principal thermite-reaction lance equipment consists of the following:

-- A thermite-reaction lance holder (oxygen supply valve), and

-- A 10-ft 6-in. thermite reaction lance (3/8, 1/2, 5/8, or 11/16 in. OD),

Additional equipment required to complete the system, available through most welding supply wholesalers, consists of the following:

-- A regulated oxygen supply (70-120 psi typ.),

-- Oxygen supply hose (3/8-in. ID minimum),

-- Ignition source (oxyacetylene torch), and

-- Safety equipment.

Figure 3.6.1 illustrates a basic setup for a two thermite lance system. Figure 3.6.2 illustrates a specific holder for the thermite reaction lance.

The 10.5-ft thermite-reaction lance is also consumed during the cutting process. Burning time for the lance is approximately 4 min, consumption of oxygen during this time is 60 ft^3 at 80-120 psi delivery pressure (Burning Bar, 1968).

The thermite reaction lance will penetrate 12 in. of a metal workpiece in approximately 1 min., consuming 6-12 in. of the lance and 15-20 ft^3 of oxygen at 80 - 100 psi. The diameter of hole produced will vary with the metal being cut (Burning Bar, 1968).

3.6.3 Site-Specific Impacts and Considerations

The exothermic-reaction cutting equipment is designed for use as a portable, manually operated, gross-cutting system. Since this equipment is manually operated, equipment access is predicated on personnel access. The exothermic-reaction equipment is not readily adapted for use with remote manipulation systems. As shown on Table 3.6.2, even if remote manipulation of the thermite-reaction lance were feasible, the lance is about 3 ft longer than the diameter of the reactor vessel.

3.6.4 Radiological, Safety, and Environmental Impacts

Radiological concerns for the exothermic-reaction cutting process include methods of containing airborne radionuclides that may be generated. The exothermic-reaction cutting process produces significant amounts of airborne gaseous emissions that are potentially toxic in high concentrations.

Personnel breathing apparatus will need to be evaluated accordingly. An atmospheric-containment system equipped with HEPA ventilation equipment would be required to filter airborne contamination from personnel breathing areas.

Safety measures to be taken while using exothermic-reaction cutting processes include adequate ventilation for personnel breathing; eye protection from arc rays; heat rays; and spatter; and personnel body protection through the use of protective clothing and gloves. Hearing protection also is recommended because the process produces approximately 80-100 dBA of noise in the immediate vicinity. Special safety equipment included with the exothermic cutting rods includes a shield fitted onto the handle of the cutting rod to deflect hot spatter.

Oxygen supports and vigorously accelerates fire. Personnel involved in the use of oxygen-supplied combustion should be well trained in the correct use of such systems. Fire hazards can be reduced by eliminating nearby combustibles, making fire extinguishers available, and ensuring that properly trained fire fighting/prevention personnel.

Radiological, industrial, and environmental hazards associated with the use of the exothermic reaction cutting processes would be limited to the interior of the EBWR building; no off-site impacts would be anticipated.

3.6.5 Schedule and Costs

The cost of the basic exothermic cutting-rod system equipment is $1,000, excluding oxygen and the optional 200-ampere electrical source (Arcair, 1988c).

The basic equipment consists of:

-- A cutting rod handle,

-- Oxygen regulator,

-- 40 ft^3 oxygen tank,

-- 100 ampere rechargeable battery,

-- Supply hoses and cables, and

-- Striker "ground" plate.

As shown on Table 3.6.6, the exothermic cutting rods are available in carton prices of $124 per 100. Assuming 600 ft of cutting is required to complete the job, approximately 800 cutting rods would be consumed.

As shown in Table 3.6.5, delivery time for the exothermic cutting rod system is expected to be 5-7 days since this equipment is a stocked, "off the shelf" item.

The thermite reaction lance is available in 10.5-ft length in two "in stock" diameters of 5/8 in. and 11/16 in.. Other sizes are made to order. The price for each lance is approximately $5. Approximately 320 lances would be required to complete the job. The thermite-reaction lance holder/oxygen supply valve is available at $55 each (see Table 3.6.7). Additional equipment required to complete the system must be purchased through a welding supply wholesaler. Delivery time for the thermite reaction lance and holder is approximately 5-7 days.

Table 3.6.1 Performance and Physical Characteristics of Exothermic-Reaction Cutting Processes

Exothermic Cutting Rod	
Material-cutting capability	Any metal, composite, or mineral aggregate material
Cutting speed	6 in./min for 2.5-in. carbon steel
Length of rod	36 in.
Rod burn time	1.5 min
Oxygen-consumption rate	7-12 ft^3/min
Thermite-Reaction Lance	
Material-cutting capability	Any metal, composite, or mineral aggregate material
Cutting speed	5 in./min for 2.5-in. carbon steel
Length of rod	10 ft-6 in.
Rod burn time	4.5 min
Oxygen-consumption Rate:	15 ft^3/min

Table 3.6.2 Site-Specific Factors

Process System Requirements	Manual gross-cutting techniques, not adaptable to remote manipulation applications
Plant Process or Structural Modifications	None required
Access to Building and Vessel	Thermite reaction lance is longer than vessel diameter

Table 3.6.3 Radiological, Safety, and Environmental Impacts

Generation of Airborne Radioactivity	Significant amounts of gaseous emissions (smoke) that includes airborne radioactivity
Liquid Waste Generation	No
Solid Waste Generation	Slag includes consumed rods
Industrial Safety Hazards	Toxic emissions Airborne radioactivity Noise - 80-100 dBA Eye protection and protective clothing required
Occupational Exposure	High -- not a remote technique
Off-site Impacts	No

Table 3.6.4 Planning and Scheduling Considerations for Exothermic-Reaction Cutting Processes

Availability/Lead Time	5-7 days delivery time for basic components
Demonstration/Development Requirements	Not adaptable to remote manipulator applications
Personnel Requirements	1 operator, 1 assistant/fire watch, 2 material handlers
Assembly Time	Less than 2-h
Downtime/Performance Time	
Exothermic cutting rod	1 1/2 min burn time
Thermite-reaction lance	4 1/2 min burn time

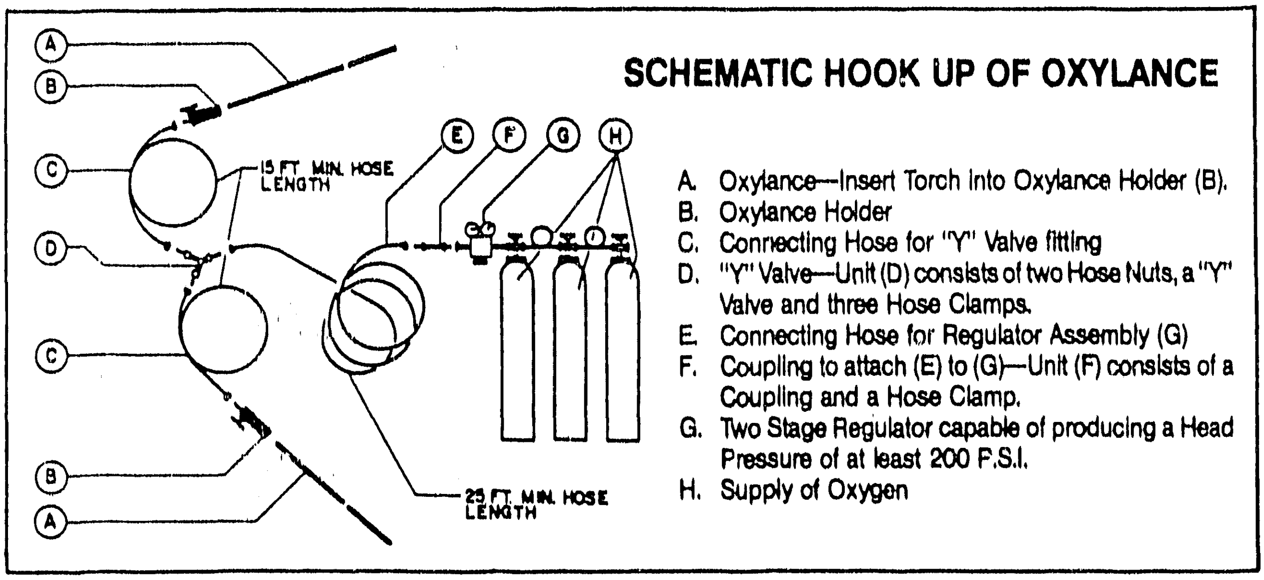
Table. 3.6.5 Costs of Exothermic-Reaction Cutting-Rod System

Cutting System Capital Costs	
Exothermic-cutting-rod system equipment	$1,000
Remote Manipulation and Viewing Equipment	
Manipulator equipment	Not feasible
CCTV system	Not required
Contamination-Control Equipment	
Contamination-containment structure	$13,000-$40,000
HEPA ventilation system	$7,100
Consumables[a]	
Industrial oxygen	$650-$1,100
800 flux-coated rods (1/4 in. x 22 in.) @$124/100	$1,000

[a]Taken from Arcair, 1988c.

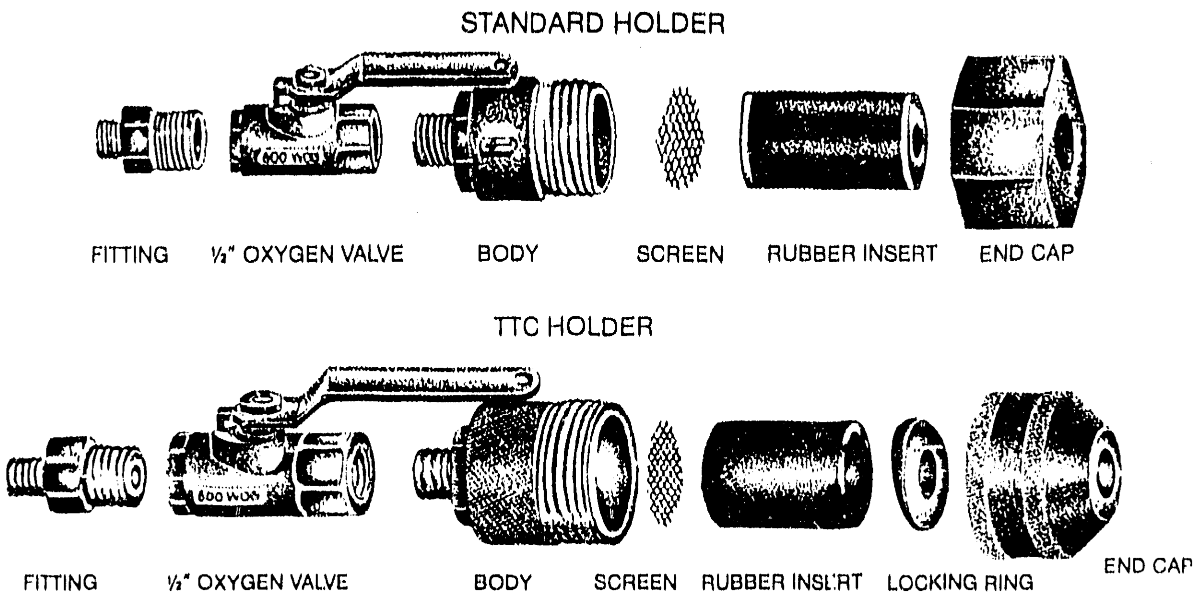
Table. 3.6.6 Costs of Thermite-Reaction Lance System

Cutting System Capital Costs	
Thermite-reaction lance holder	$55
Supplementary manual flame cutting equipment	$500
Remote Manipulation and Viewing Equipment	
Manipulator equipment	Not feasible
CCTV system	Not required
Contamination-Control Equipment	
Contamination-containment structure	$13,000-$40,000
HEPA ventilation system	$7,100
Consumables	
320 thermite-reaction lances @ $5 ea.	$1,600
Oxygen	$1,600



(American Oxylance, 1988)

Fig. 3.6.1 Basic System Hookup for a Two Thermite-Reaction Lance System (Taken from American Oxylance, 1988)



(American Oxylance, 1988)

Fig. 3.6.2 Standard Holder/Oxygen Supply Valve for a Thermite-Reaction Lance (Taken from American Oxylance, 1988)

3.7 Diamond-Wire Cutting

3.7.1 Cutting Principle and Method

Diamond-wire cutting is a relatively new method typically employed to cut concrete and stone. A 10-mm steel wire with abrasive cutting diamonds bonded to it is driven around a series of pulleys in a continuous loop. The cutting action of diamond wire is mechanical, and water is used to flush the debris from the cut.

As shown on Figure 3.7.1, a 25-hp electric motor or a 30-hp diesel engine drives a hydraulic pump system that in turn supplies a hydraulic motor. The hydraulic motor is connected through a spindle to a flywheel that provides motion to the diamond wire. Tension is applied to the wire through a hydraulic cylinder, gear, and rack.

Access to both sides of the material being cut is necessary, and pilot holes are drilled through the material with a diamond boring tool. One equipment operator is needed to guide the wire through the workpiece. The equipment can be operated remotely from the workpiece simply by lengthening the diamond wire loop and pulley system. Diamond wire loops are available in "off the shelf" lengths of 2, 5, 10, 15, and 20 meters. Longer or shorter lengths are custom made. The wire loops are connected at the ends with special threaded couplings. It is recommended that the number of couplings be kept to a minimum because this is the weak area of the loop. High-tensile-strength wires impregnated with diamonds are also available. The wires typically range in size from 0.003 to 0.015 in. These wires are capable of very precise cuts with very little waste. They have been used to cut metals, laminates, frozen foods, leather, paper goods, and glass.

3.7.2 Performance and Physical Characteristics

Application of this type of diamond cutting system is limited in its ability to cut metals such as carbon steel. Experimentation has shown that the life of the wire is very short when attempting to cut carbon steel (Bollander, 1989). This is caused primarily by the thermal breakdown of the electroplated nickel bonding of the diamond abrasive to the wire. The diamond abrasive itself is also subject to fracturing. Cutting speeds of 1-2 in./min in 2-in. carbon steel plate has been reported (Tuttle, 1989).

The cutting rate for high-tensile-strength wire impregnated with diamonds is predicted to be very low. However, work is underway to determine if the cutting rate can be increased through the use of small amounts of acid.

3.7.3 Site-Specific Impacts and Characteristics

The diamond-wire system designed for cutting concrete and stone is not ideally suited to cutting ferritic or austenitic steel other than rebar present in concrete. The diamond-wire cutting of rebar is possible because the concrete aggregate tends to resharpen the diamonds that have been blunted by the cutting of the steel rebar. This cleaning and sharpening action does not occur when cutting metal alone.

The approximate weight of this system is 2000 lb for the hydraulic driving system and an additional 500 lb for the flywheel. Figure 3.7.1 shows a schematic illustration of the equipment.

As shown on Table 3.7.2, a there must be room around the outside of the reactor vessel to accommodate a pulley system.

For the high-tensile-strength wires, a system of pulleys resistant to acid would be required. Also, a sufficiently long wire would have to be fabricated. With either of these systems, the kerf tends to narrow as the cut progresses. Therefore, it is important that a single wire lasts until the cut is completed.

3.7.4 Radiological, Safety, and Environmental Impacts

Diamond-wire cutting works best as a wet cutting technique using 3-5 gallons of water per minute to flush debris from the cut and to limit the amount of airborne particulates generated or using a small amount of acid. While the liquid limits the amount of airborne particulate radionuclides, it requires a system to collect, contain, and process the potentially contaminated fluid. Generation of solid waste is limited to the debris from the cutting action.

As shown in Table 3.7.3, safety hazards inherent in this system include possible eye injury from material ejected from the cutting action. Eye protection (safety goggles) is recommended. If the delivering system includes a diesel engine, ear protection also is recommended, because diesel engine noise levels may exceed 100 dB.

Off-site impacts during diamond wire cutting operations are not anticipated because noise, airborne contamination, and waste materials will be confined to the EBWR building.

3.7.5 Schedule and Costs

Since the conventional, concrete-cutting equipment is an off-the-shelf item, delivery time for a diamond-wire cutting system from an experienced manufacturer/vendor would take approximately 5-7 days via motor freight.

The vendor provides personnel training of approximately 2 days at no additional cost above the basic capital cost.

Assembly time and setup time for the equipment is an hour or less for the machine and approximately 2 hours for an eight-pulley configuration. (High-tensile steel wire impregnated with diamonds is also commercially available. This wire is expensive and delivery time is usually a month or more.)

This cutting technology requires further development in order to successfully make the number of cuts in 2.5 in. of metal as required for the EBWR vessel-sectioning project. Development work should focus on methods to reduce wear on the wire when cutting metal. It is possible that a cleaning/sharpening system could be developed to produce the same effect as that experienced when cutting reinforced concrete.

The operation of the diamond-wire cutting system requires only one equipment operator at the unit. The field application would probably require three people to facilitate handling of the workpieces and positioning of the equipment.

Extensive downtime is expected because of the frequent need to change the diamond wire. Diamond wire has an average ratio of 2-5 ft^2 of concrete cut per foot of diamond wire consumed, and in carbon steel the average ratio if 2-3 $in.^2$ per foot. Replacement diamond wire costs $110 per foot. Assuming 600 ft of cutting, diamond wire would cost approximately $660,000 - $990,000.

Capital cost for the diamond-wire cutting equipment is $35,000. A replacement spare parts inventory is also available at additional cost.

Table. 3.7.1 Performance and Physical Characteristics of the Diamond Wire Cutting System

Dimensions	
Power unit	203 x 105 x 950 cm
Drive unit	285 x 120 x 108 cm
Weight	
Power unit	630 kg
Drive Unit	380 kg
Cutting Speed	
Concrete	20-40 $in.^2$/min
Carbon steel	2-4 $in.^2$/min (1-2in./min)
Cycle Limitations	Very low wire life for cutting carbon steel
Maintainability	Requires regular maintenance of hydraulic system and frequent replacement of wire

Table 3.7.2 Site-Specific Factors

Process System Requirements	Water source of 3-5 gal/min
Plant Structural Modifications	None
Access Acceptability	Clearance on OD of reactor vessel required

Table 3.7.3 Radiological, Safety, and Environmental Impacts

Generation of Airborne Radioactivity	Moderate
Liquid Waste Generation	3-5 gal/min water
Solid Waste Generation	Material debris
Industrial Safety Hazards	Potential eye and ear hazard
Occupational Exposure	Low
Off-site-impacts	No

Table 3.7.4 Planning and Scheduling Considerations for Diamond-Wire Cutting

Availability/Lead Time	5-7 days
Training Requirements	2-day personnel training
Demonstration/Development Requirements	Metal cutting needs to be further developed to reduce wire wear
Personnel Requirements	1 trained person to operate and 2 material handlers
Setup Time	2-3 hours
Consumables	Diamond wire, water
Downtime	Frequent replacement of worn wire

Table. 3.7.5 Costs for Diamond-Wire Cutting System

Cutting System Capital Costs	
Diamond-wire cutting equipment	\$40,000-\$60,000
Remote Manipulation and Viewing Equipment	
Remote manipulator	\$70,000-\$150,000
CCTV system	\$27,800
Contamination-Control Equipment	
Contamination-containment structure	\$13,000
HEPA ventilation system	\$7,100
Liquid processing	\$25,000-\$35,000
Consumables	
Diamond-wire @ \$110/ft	\$660,000-\$990,000

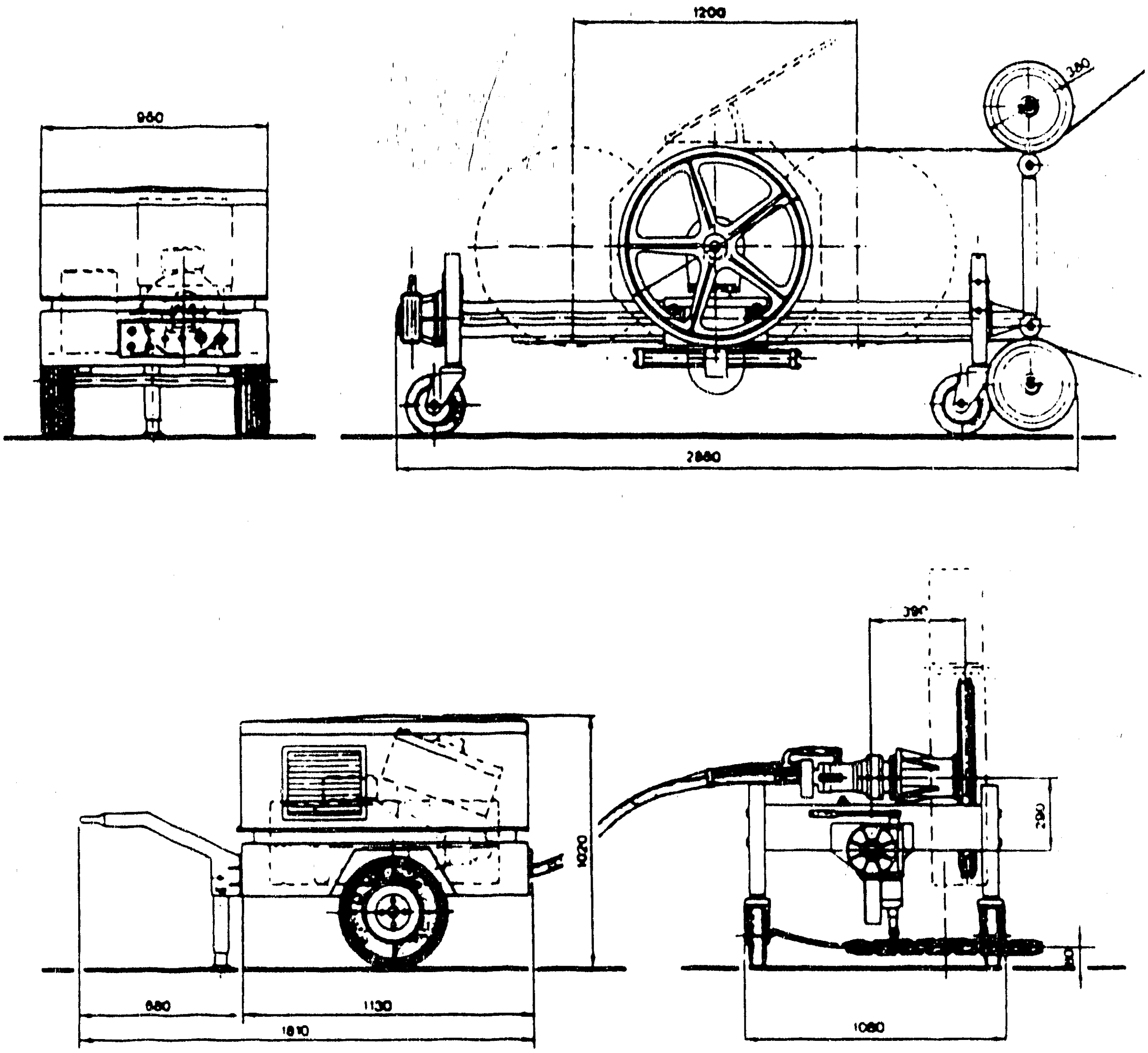


Fig. 3.7.1 Diamond-Wire Cutting Equipment (Taken from Diamant Borat, 1987)

3.8 Water-Jet Cutting System

3.8.1 Cutting Principle and Method

The water-jet cutting system uses highly pressurized water (up to 55,000 psi) that passes through a mixing chamber where an abrasive (such as crushed garnet crystals) is injected into the water stream (Carden, 1989). This water and abrasive mixture then passes through a short tungsten carbide nozzle that guides the mixture until it impacts the workpiece at a terminal velocity greater than the speed of sound. The resulting impact produces a cutting erosion force of up to 55 hp leaving a narrow kerf in the workpiece. The water jet is effective in cutting both stainless and carbon steels without altering the physical characteristics of the material. One of the water jet's advantages over plasma cutting techniques is its effectiveness in cutting a thick workpiece without appreciable generation of gaseous or airborne by-products.

As shown in Figure 3.8.1, the water-jet system consists of the following:

-- A booster pump that raises the supply water pressure to 200 psi,

-- A filtration system to remove solid particulates from the water supply,

-- A hydraulically driven water intensifier that provides a predesignated water pressure up to 55,000 psi,

-- A supply system to supply abrasives to the water-jet nozzle through an electronically controlled metering device,

-- An abrasive nozzle that provides a mixture area for the "slurry" of water and abrasives,

-- A water orifice (jewel), which is a consumable metered orifice to allow water into the abrasive nozzle (the orifice is made either of sapphire or diamond), and

-- A tungsten carbide tube, which is a consumable tube that guides the water/abrasive mixture onto the workpiece.

3.8.2 Performance and Physical Characteristics

Conventional applications of the water-jet cutting system are designed to be integrated and/or retrofitted into most current machine manipulators, such as computer numerically controlled (CNC) robots, with x-y-z axes. Field-cutting operations are also possible with a portable unit.

The water-jet cutting system is a proven cutting system for ferritic and austenitic steel up to 9 in. thick (Romano, 1989a). The water jet combined with an abrasive such as garnet can achieve cutting speeds of 1 in. linear travel per minute in steels up to 9 in. thick. Cutting speed through 2.5-in. carbon steel will be approximately 3-4 in./min. Abrasives such as silica carbide can also be used, but cutting speed is reduced and abrasive consumption is increased. Faster travel speeds with multiple passes are also possible with the added benefit of reduced water and abrasive requirements. The water-jet system utilizing a 0.010-in. water orifice and a 0.018-in. tungsten carbide nozzle tube offers the optimum performance characteristics with approximately 55 hp of cutting force available.

The consumable materials used in this cutting technique include water, abrasives, the water orifice (jewel), and the tungsten carbide nozzle tube. The system requirement for water with a 0.018-in. orifice is approximately 1.4 gal/min or 84 gal/h. The system requires an abrasive supply of crushed crystals, or other abrasives such as silica carbide, at a rate of approximately 1.5-2 lb/min for garnet and 2-5 lb/min for other abrasives. The garnet is presently available at $0.30/lb (Romano, 1989a).

The jewel water orifice is presently available in either sapphire or diamond. The life of each sapphire orifice is approximately 20-30 hours, and the replacement cost is $16. The life of the diamond orifice is approximately 200-300 hours, and the replacement cost is $500. The tungsten carbide nozzle tube has a life expectancy of 2-5 hours and a replacement cost of $400 (Romano, 1989b).

The hydraulically driven water-intensifier pump, which provides water at a pressure of 55,000 psi, requires maintenance after every 500 hours of operation. Maintenance includes replacement of seals and rings, which are included in a spare parts to build kit.

3.8.3 Site-Specific Impacts and Characteristics

Use of the water-jet cutting system for sectioning of the EBWR vessel dissection, could be accomplished remotely. The water-jet pumps, filters, supply hoppers, and controls would be located in a low-dose area. They would be connected by hose, piping, and electrical connections to the nozzle assembly. The nozzle assembly could be mounted on the main level on a circular track. The track could be mounted directly on the EBWR vessel or on the floor. However, using this method would require that the vessel be raised up for cutting. The focusing distance between the carbide nozzle tube and the workpiece is not a critical tolerance. If a standoff distance of up to 1.5 in. is maintained, the cutting operation would be satisfactory. Therefore, the tracking system need not be extremely accurate.

The liquids generated by the system operating at approximately 1.4 gal/min would be largely confined to the inside of the reactor vessel. This water could be pumped out, filtered, and recirculated to the system.

3.8.4 Radiological, Safety, and Environmental Impacts

The low probability of gaseous emissions or airborne generation is an attractive feature of using the water-jet cutting system to segment the EBWR vessel. An atmosphere-containment tent and HEPA filters would be used to mitigate any potential problems. The low probability of contamination spreading would facilitate containment disassembly and disposal.

Containment of the majority of liquid (water) and solid (spent abrasives, steel particles) wastes within the confines of the reactor is a desirable feature of cutting from outside into the vessel. This waste mixture could then be pumped out of the vessel for processing or the water could be filtered for recirculation.

Since the wastes generated would not escape the EBWR building confines, off-site environmental impacts are not anticipated.

There are no inherent safety concerns in this system other than physical contact with the cutting stream, which would be minimized by using a remote operating system. The noise produced during system operation (100-110 dB at the water intensifier unit) would require ear protection.

3.8.5 Schedule and Costs

As shown on Table 3.8.5, the capital cost for a complete water-jet system capable of cutting the EBWR vessel is approximately $90,000. This system comprises the intensifier pump, abrasive supply system, interface kit for use with a manipulator, piping, and a 1-year supply of spare parts. Not included in this price are consumables, used such as the jewel orifice and carbide nozzles. In addition, the manipulator system is expected to cost $120,000-$200,000, and a water-processing system would cost $25,000-$35,000. A contamination-control envelope and HEPA ventilation system would be required, but would cost only $20,000 since the envelope would not have to be flameproof.

Downtime would be limited mainly to replacing the consumable components in the nozzle head assembly (the water orifice and carbide nozzle tube). If a tungsten carbide nozzle were used, this maintenance would have to be performed approximately every 2-5 hours of operation. A spare nozzle-head assembly would expedite this operation because replacement of the assembly would require less than 54 minutes (Romano, 1989b).

Operation of the water-jet system equipment requires only one operator at the control panel (Romano, 1989b). To facilitate handling and maintenance of the equipment, as well as handling of the workpiece segments, a three-person crew is suggested.

Table 3.8.1 Physical Characteristics of the Water-Jet Cutting System

Dimensions of Pumps	70 in. x 45 in. x 44 in.
Pump Output at Orifice	55,000 psi at 1 gal/min
Cutting Speed	3 in./min for 2.5-in. carbon steel
Cycle Limitations	Requires replacement of consumables every 1-5 hours
Maintainability	Every 500 hours of pump operation

Table 3.8.2 Site-Specific Impacts

Process System Requirements	1.5 gal/min water at 40 psig, 2 lb/min abrasives
Plant Structural Modifications	May require water collection under reactor vessel
Access to Building and Vessel	Requires 18 ft x 5 ft floor space

Table 3.8.3 Radiological, Safety, and Environmental Impacts

Generation of Airborne Radioactivity	None
Liquid Waste Generation	1.4 gal/min water
Solid Waste Generation	2 lb/min abrasives
Industrial Safety Hazards	Extremely powerful jet
Occupational Exposure	Low
Off-site Impacts	No

Table 3.8.4 Planning and Scheduling Considerations for Water-Jet System

Availability/Lead Time	18 weeks
Development Requirements	No
Personnel Requirements	1 operator, 2 material handlers
Training Requirements	Basic instruction system operation - 2-3 hours, video training tapes available
Assembly Time	2-3 hours
Consumables	Water, abrasives, water orifice, carbide nozzle tube
Downtime	5 minutes every 2-5 hours

Table 3.8.5 Costs for Water-Jet Cutting System

Cutting System Capital Costs	
Water jet system[a]	$150,000
Remote Manipulation and Viewing Equipment	
Remote manipulator	$16,000
CCTV system	$27,800
Contamination-Control Equipment	
Contamination-containment structure	$13,000
HEPA ventilation system	$7,100
Water processing	$25,000-$35,000
Consumables	
4799 lb of garnet	$1,500
Sapphire orifices @ $16 ea.	$32
Carbide nozzles @ $10 ea.	$200

[a] Inclusive of intensifier pump, abrasive supply system, manipulator interface, motor starter panel, piping and a 1-year supply of spare parts.

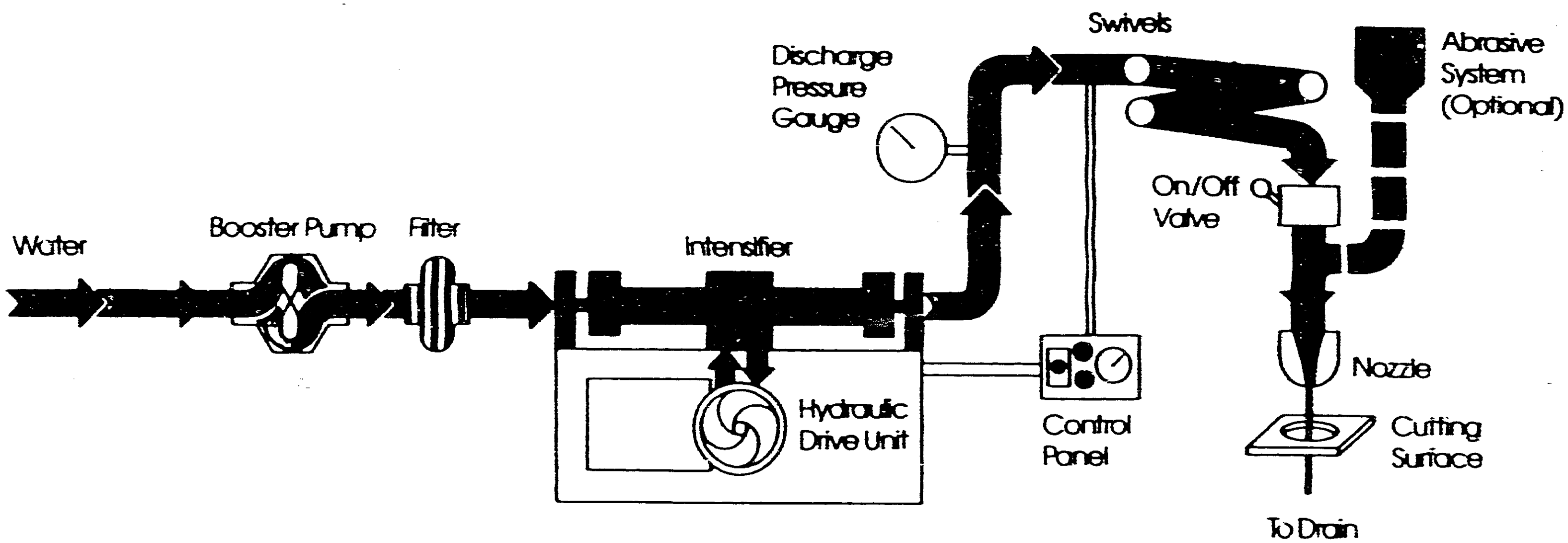


Fig. 3.8.1 Simplified Illustration of Ingersoll-Rand Streamline Water-Jet Cutting System

back and forth between precisely aligned mirrors, thus creating a laser beam. The beam passes through the resonator until it is transmitted through the partially reflective output mirror. External mirrors can direct the laser beam to a work area without reducing the intensity of the beam.

In the larger, more powerful lasers, such as 20- or 25-kW systems, only reflective optical components are used. The output of the high power laser is too high to be handled safely by lenses and other transmissive optical components. The laser beam is directed to the focusing elements via water-cooled copper or molybdenum mirrors, and the beam is focused by means of a spherical or parabolic mirror. In such a system, the amount of laser power that can be handled is very high, but the minimum focused spot is larger than that generated by a lower powered CO_2 laser. Thus, thicker material can be cut but at the expense of a larger kerf and a rougher finish. The material edge finish in the thicker metals is not uniform because of the dissipation of assist gases when entering the kerf. The result generally is a tapered kerf with an input diameter of 0.070 in. and an output diameter of 0.150 in. The cleaning action of the assist gas is critical. If the assist gas disperses before completely blowing out the molten metal, the metal will freeze and resolidify, preventing a complete cut.

The cutting speed expected for 2.5-in. carbon steel plate with the 25-kW laser-beam system is 5-10 in./min.

3.9.3 Site-Specific Impacts and Characteristics

The CO_2 laser system consists of the following components: a laser-beam generator with associated controls, pumps, high voltage supplies, gas supply, and cooling system; beam-handling optics; focusing optics, and cutting-nozzle assembly. The larger laser systems, such as the 20- or 25-kW lasers, require a 460-kVA, 3-phase, 600-amp power supply; cooling water; helium, nitrogen, carbon dioxide, and carbon monoxide lasing gas mixture; cutting assist gas; optics cooling; and ventilation (Manion, 1981; Brown, 1989).

The laser components may be mounted on a skid or trailer. The beams can be transmitted over appreciable distances to a focusing and cutting head. The operator control panel may be easily adapted for remote use up to 30 ft away.

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The laser components may be mounted on a skid or trailer. The beams can be transmitted over appreciable distances to a focusing and cutting head. The operator control panel may be easily adapted for remote use up to 30 ft away.

The modular units for the 25-kW laser beam cutting system require an 8-ft x 26-ft floor space, and the total weight of these units is 30,000 lb, including the power supply. Table 3.9.1 summarizes the physical characteristics of this system.

3.9.4 Radiological, Safety, and Environmental Impacts

As shown in Table 3.9.3, use of the laser to section the EBWR vessel has very low inherent radiological or industrial safety hazards. The amount of airborne contamination generated during cutting would be low compared with other conventional cutting techniques. A HEPA-filtered vacuum unit that follows the cutting nozzle would further reduce the airborne contamination level. Since the laser is such a quiet method of cutting, noise is not a concern. Hazards associated with the laser itself would be minimized by the use of remote manipulation. The laser system generates very little slag and no liquid waste.

Environmental impacts outside of the EBWR vessel containment building are not anticipated since the effects of operatimg the laser-beam cutting system would be limited to the inside of the containment building.

3.9.5 Schedule and Costs

A 25-kW laser cutting system is available from a commercial vendor at a capital cost of approximately $1,200,000, excluding the required remote manipulation system, which would cost an additional $200,000-$350,000. It is suggested by the vendor that a specific laser cutting system could be developed for the applied task for an estimated $50,000 additional. Delivery time for the laser-beam cutting equipment is expected to be 6-9 months. A 2- to 3-week course is offered by the vendor for instruction on the specific laser beam system. If requested, the vendor will supply equipment operators and a field service engineer for operation of the laser system (Brown, 1989).

Consumable costs associated with the laser beam cutting system as applied to the EBWR vessel dissection would include an assist gas requirement of 30 ft^3/h at $5-$10 per hour for a total estimated cost of $250. The estimated total cost of a 25-kW laser-beam cutting system, including a remote manipulator, development costs, and consumables, is approximately $1,450,000-$1,600,000. Actual setup time is limited to wiring, piping, and integrating the manipulation system with laser system and is expected not to exceed 120 person hours (Brown, 1989). Table 3.9.5 summarizes the capital and consumable costs for this system.

Table 3.9.1 Performance and Physical Characteristics of the 25-kW CO_2 Laser-Beam System

Cutting Speed for 1.5-in. Carbon Steel Plate	5-10 in./min
Maximum Depth of Cut for Carbon Steel Plate	4 in. (one pass)
Laser Gas Utilization (He, H_2 CO_2)	30 standard ft^3/h
Electrical Service	480 VAC, 3-Phase, 60-Hz, 600A
Cooling Water at 10°C for Heat Removal	90 gal/min at 60 psig, 400 kW
Shop Air	80 psig
Compressed Air Clean and Dry (0.1 μm and DP - 10°C)	4 in. (one pass) 100 psig, 150 standard ft^3/min
Approximate System Weight	30,000 lbs

Table 3.9.2 Site-Specific Factors

Process System Requirements	Assist gas, cooling water, shop air supply, HEPA ventilation
Plant Structural Modifications	None
Access to Building and Vessel	Acceptable

Table 3.9.3 Radiological, Safety, and Environmental Impacts

Generation of Airborne Radioactivity	Low
Liquid Waste Generation	No
Solid Waste Generation	Very little slag
Industrial Safety Hazards	High energy in the beam path
Operational Exposure	Low
Off-site Impacts	No

Table 3.9.4 Planning and Scheduling Considerations

Availability/Lead Time	6-9 Months
Development Requirements	Specific laser-beam system development
Personnel Requirements	1 person to operate and 2 material handlers
Assembly Time	Approximately 120 person hours
Set-up Time	Requires 30 minutes to warm up

Table 3.9.5 Costs of Laser Cutting System

Cutting System Capital Costs	
Laser, resonator, and control cabinet	\$1,000,000
Aerodynamic window, air supply (compressor) and chiller unit (for cooling)	\$200,000
Remote Manipulation and Viewing Equipment	
Remote manipulator	\$200,000-\$350,000
CCTV system	\$27,800
Contamination-Control Equipment	
Contamination-containment structure	\$13,000
HEPA ventilation system	\$7,100
Consumables	
Laser-assist gas (He, N_2, CO_2, CO)	\$250

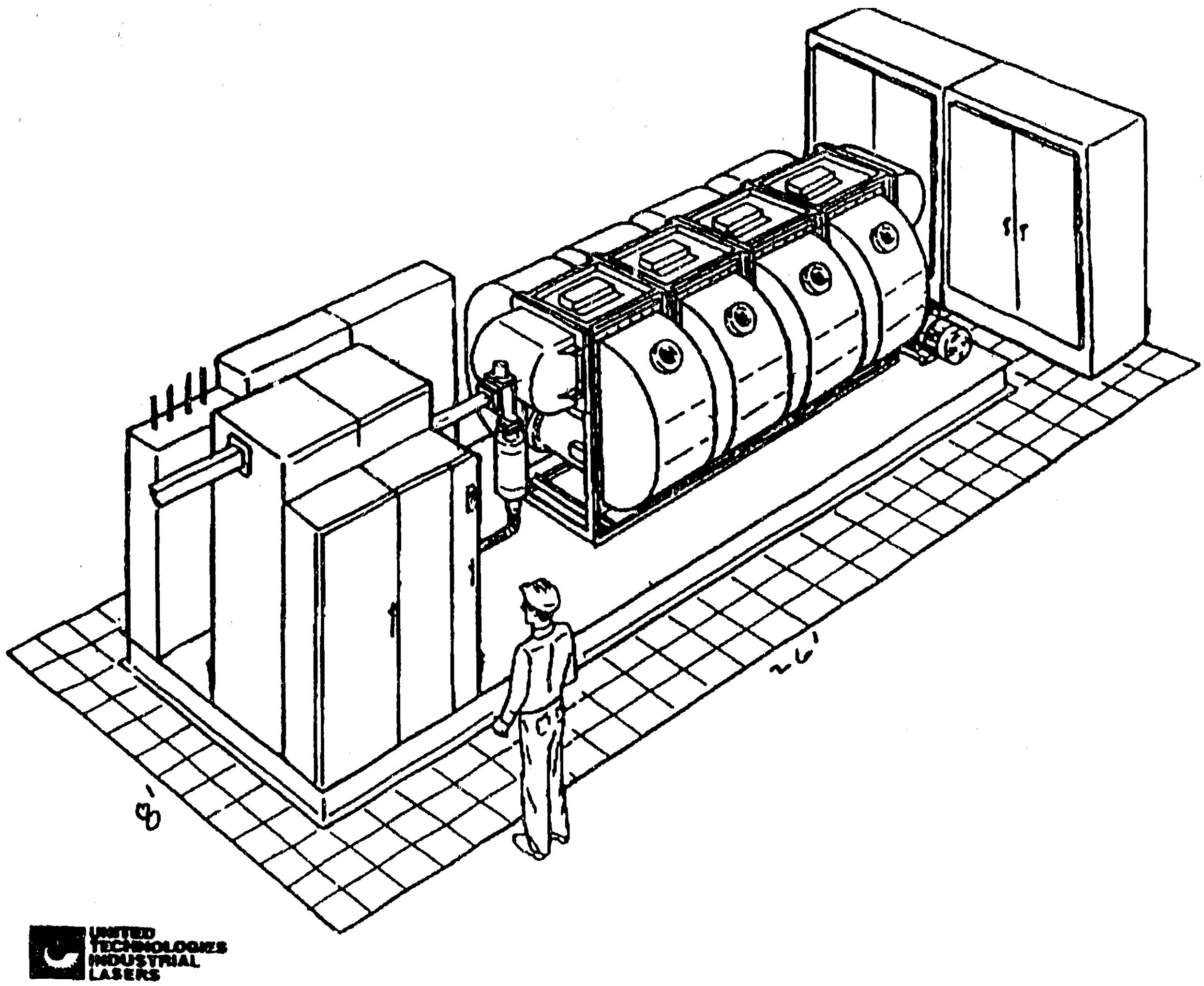


Fig. 3.9.1 Schematic Drawing of a Four-Module, 25-kW, Co_2 Laser System

3.10 Mechanical Milling

3.10.1 Cutting Principle and Method

The outside diameter (OD) milling-machine equipment consists of a portable hydraulically powered unit designed to be strapped onto a pipe or vessel with twin mounting chains (see Figure 3.10.1). Hydraulic motors move the portable unit around the outside of the pipe or vessel. For a vertical cut, the unit travels on a guide track. This guide track must be modified for workpieces that are larger than 5 ft. in diameter. The twin hydraulic motors are equipped with an automatic load-sensing feed system that prevents over-feeding or blade stalling. The dual motor drive is adjustable and will supply a constant horsepower flow to the cutting spindle. As shown on Figure 3.10.2, the blade is simply a rotating, multiple-tooth, circular cutter designed to remove metal from a workpiece. The mill machine is can be operated either in air or in water and will safely cold-cut pipes or vessels with diameters greater than 14 in.. For use under the water, the machine is designed with a gearbox sealed to withstand depths up to 800 ft (E. H. Wachs Co., 1989).

Inside diameter (ID) milling-machine equipment could be designed to produce circumferential cutting from inside a pipe or vessel (Earney, 1989). Since the OD of the EBWR vessel has limited access, ID milling may be attractive.

3.10.2 Performance and Physical Characteristics

The OD milling machine requires a 13-in. clearance on the outside of a pipe or vessel with diameters of 14 in. or greater. As shown on Table 3.10.1, this machine is capable of traveling 3 in./min from stainless steel that is 3 in. thick. The cutter will cut all pipe schedules (wall thickness) up to 5 in. thick. The quality of the cut is comparable to that of a machined finish and does not change the physical properties of the pipe or vessel. The accuracy of the cut is within ± 0.005 in.

The mill cutter is a self-lubricating, hydraulically powered machine. The cutter drive is operated by an 8-hp governed motor. The cutter speed is adjustable from 0-60 revolution per minute. The feed method for OD cutting is the nonslip, twin-stabilizing, chain drive guided by the metal tracks. The feed is powered by a 2-hp hydraulic motor. The hydraulic requirements are 18 gal/min at 1500 psi. The remote-control unit can be manifold mounted with an auto-feed, on/off cutter feed control valve, and forward/reverse directional control valve that permits the machine to be backed up. The hydraulic power source can be electric, gasoline, or diesel engine driven. The actual setup consists of pinning together the adjustable drive chains and tensioning them around the pipe or vessel (Golich, 1989).

The cutting blades (Figure 3.10.2) are made from a high-speed steel. A carbide-tipped blade may be used for pipes lined with concrete. The blade sizes vary from 5 to 8 in. for cutting thicknesses up to 2.25 in. A 9-in. blade would be used for cutting the EBWR vessel. The blades can be changed without removing the entire track assembly from the vessel, which will reduce exposure and downtime caused by a damaged or worn blade. The blade, assisted by the vibration-free, rigid cutter-drive system is expected to last for at least 25 ft of continuous cutting (Keaney, 1989). Blade life would be longer if a cutting fluid was used.

The cutting fluid used in the cutting of stainless steel is a water-soluble, halogen-free base delivered in the form of a spray. Delivery is either automatic or manual on an as-needed basis. The delivery rate for the cutting fluid is approximately 10 gal/h of cutting.

Vibration was a major problem in the use of a mill cutter for reactor sectioning at other decommissioning projects. This problem was encountered at the Trino Vercellese reactor vessel in Italy. Modifications made since 1969 include additional chain tensioners designed to provide the necessary rigidity and stability to prevent excessive vibration. The machine incorporates a heavy-duty gear box that features large double-tapered roller bearings that support the cutter shaft and has a 1.2-gal oil capacity to provide cooling and reduce friction for the thrust bearings and large worm gears.

3.10.3 Site-Specific Impacts and Characteristics

As shown in Table 3.10.1, the OD mill cutter is a portable unit mill that weighs 350 lb and has physical dimensions of 24-in. x 19-in. x 10-in.

Figure 3.10.1 shows a picture of the portable OD cutter as it would look mounted on a horizontal pipe. To accommodate the OD cutter on the EBWR, the vessel would have to be jacked up from its normal position. Since the EBWR vessel has a diameter in excess of 5 ft, the guide track would have to be custom made (e.g., tack welded together to circle the larger diameter) (Bauer, 1989). A radial clearance of 13 in. is required to accommodate the OD cutter.

Use of an ID cutting/milling process would allow sectioning of the EBWR vessel without the need to jack or raise the vessel. However, a rigid manipulator would be needed to support the cutter.

3.10.4 Radiological, Safety, and Environmental Impacts

As shown in Table 3.10.3, the primary radiological hazard of concern is flying chips. A closed containment with HEPA ventilation would be required to avoid the spread of contamination. In addition, it may be advantageous to use a HEPA vacuum to follow the cut to clean the chips as they are generated. The flying metal chips also constitute an industrial safety hazard. Steps must be taken to ensure personnel protection from the chips. Protective measures include a chip guard installed on the machine and use of a respirator, safety goggles, and protective coveralls by the operators. Operation of the milling cutter generates a significant amount of noise.

3.10.5 Schedule and Costs

As shown on Table 3.10.4, the delivery time for the milling machine is estimated at 3-4 weeks (E. H. Wachs Co., 1989). The assembly time is estimated at 3 days, with actual setup time of approximately 4 hours, depending on the positioning of the mounting chains. One person would be needed to operate the control valve, and two to three people would be needed to strap the unit onto the vessel to be cut. Training by the vendor would take about 3 days (Bauer, 1989). Anticipated downtime of the mill cutter should be limited to cutter blade replacement. Approximately 12 blades would be required to complete the job. As shown on Table 3.10.5, the OD milling machine would cost approximately $60,000, plus the cost of blades. The development of an ID cutter was estimated by a vendor to cost an additional $20,000 (Earney, 1989).

Table 3.10.1 Performance and Physical Characteristics of the OD Milling Machine

Dimensions	24 in. x 19 in. x 10 in.
Weight	350 lb
Cutting Speed	3 in./min for 3-in. steel

Table 3.10.2 Site-Specific Factors

Process System Requirements	HEPA ventilation
Plant Structural Modifications	None
Access to Building and Vessel	Requires 13-in. clearance on OD or ID

Table 3.10.3 Radiological, Safety, and Environmental Impacts

Generation of Airborne Radioactivity	Significant
Liquid Waste Generation	10 gal/min cutting fluid
Solid Waste Generation	Significant (chips)
Industrial Safety Hazards	High noise level
Occupational Exposure	Low
Off-site Impacts	No

Table 3.10.4 Planning and Scheduling Considerations

Availability/Lead Time	3-4 weeks
Development Requirements	Larger guide track needs to be demonstrated for OD cutting; ID cutting requires further development
Personnel Requirements	1 person to operate and 2 material handlers
Assembly Time	3 days
Training Time	3 days

Table 3.10.5 System Costs for Mechanical Milling

Cutting System Capital Costs	
Milling machine and track	$60,000
Development for ID cutting	$20,000
Viewing Equipment	
CCTV system	$27,800
Contamination-Control Equipment	
Contamination-containment structure	$13,000
HEPA ventilation system	$7,100
Liquid processing	$25,000-$35,000
Consumables	
9-in. cutting blades	$2,400-$6,000

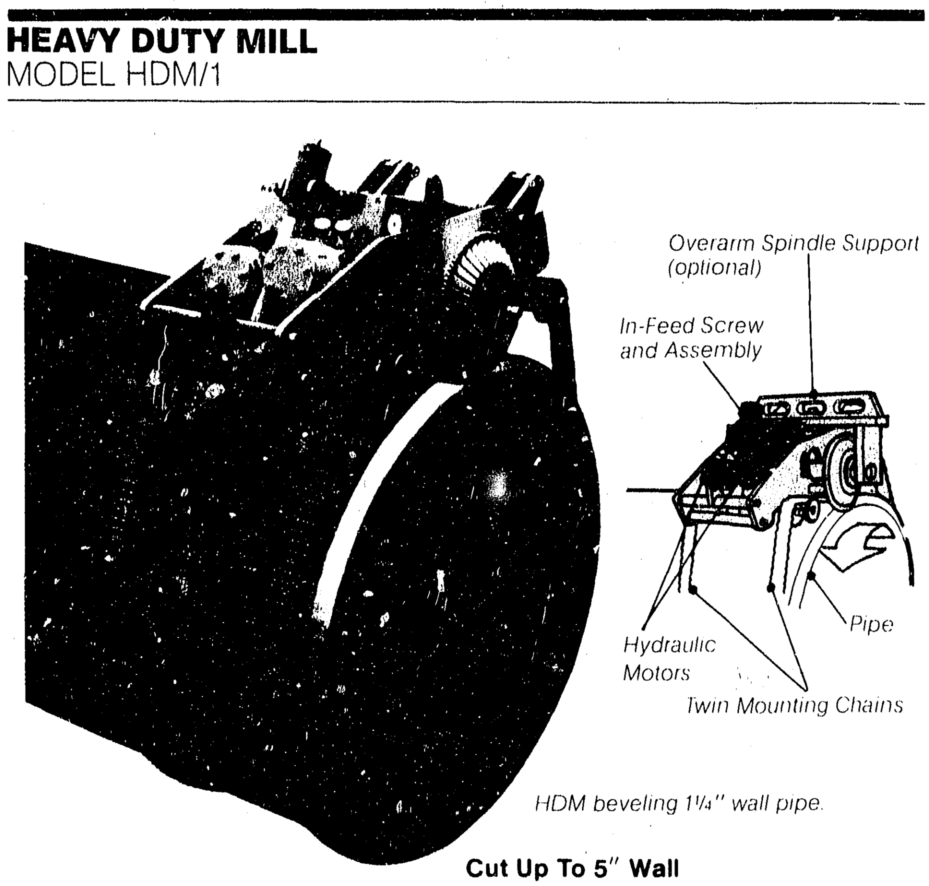
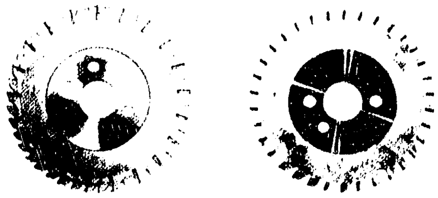


Fig. 3.10.1 Outside-Diameter Cutting Mill Strapped on Workpiece (Taken from E. H. Wachs, 1989)

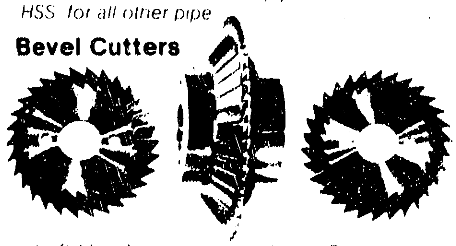
Slitting Saws



High Speed Steel — Carbide Tipped

Carbide for concrete lined pipe
HSS for all other pipe

Bevel Cutters



Left Hand Bevel Cutter	Gang of Cutters*	Right Hand Bevel Cutter

Cutter Dia	for use with wall thicknesses up to
6″	1¼″ (31.7 mm)
7″	1¾″ (44.4 mm)
8″	2¼″ (53.9 mm)

Cutter Dia.	Bevel Angle	Max. Wall Penetration
5″	37½°	⅝″ (15.8 mm)
6″	37½°	⅞″ (20.9 mm)
7″	37½°	1¾″ (44.4 mm)
5″	30°	¾″ (19.0 mm)
6″	30°	1″ (25.4 mm)
7″	20°J	1¾″ (44.4 mm)
6″	10°	1″ (25.4 mm)
7″	10°	1¾″ (44.4 mm)

Gang of Cutters For Beveling Pipe
1 R.H. Bevel, 1 Slitting Saw, and 1 L.H. Bevel

Fig. 3.10.2 Milling Blades Available for Metal Cutting (Taken from E. H. Wachs, 1989)

3.11 Controlled Explosive Cutting

3.11.1 Cutting Principle and Method

Explosive cutting is a method of segmenting metal or other materials by the use of an explosive that is formed in a geometric shape especially designed and sized to produce the desired separation of the workpiece.

An explosive cutter consists of an explosive core, such as cyclotrimethylenetrinitramine (RDX) or PETN, surrounded by a casing of lead, aluminum, copper, or silver. Hard plastic casings also are being developed. The cutter is chevron shaped, with the apex pointing away from the material to be cut, and acts as a hollow charge. When detonated, the explosive core generates a shock wave that fractures the casing inside the chevron and propels the molten casing into the material to be cut. Cutting is accomplished by a high-explosive jet consisting of the detonation products of combustion and the molten casing metal (IAEA, 1988). The jet forms a directed shock wave that cuts the target material. This technique may be applied either in air or in water with equal success (Motley, 1989).

3.11.2 Performance and Physical Characteristics

Controlled explosive cutting is typically used as a means to cut materials in environments where it is difficult or impossible for workers to use conventional cutting procedures, or where two or more cuts must be made simultaneously. Explosive cutting can be used on any material and is not limited by configuration. The technology has been developed and successfully applied to the dismantlement of off-shore oil platforms and bridges (Motley, 1989a).

Since the cutting occurs instantaneously, cutting speed is a function of the speed at which the charges can be placed. It is estimated that with several hours of planning, about 10 minutes would be required to place one 25-ft vertical charge on the inside of the EBWR. Actual setup time would probably be 4 hours (Motley, 1989b).

To cut 2-in. metal, approximately 0.5 lb of explosives would be required per foot of cut (4000 grains/ft). This translates to an approximate materials cost of between $55/ft (Motley, 1989a) and $150/ft (Richards, 1989). Since detonation creates an extremely loud noise in air, the preferred cutting environment is in water.

It has been reported that explosive cutters have been used for metals greater than 6 in. thick (Manion, 1981).

3.11.3 Site-Specific Impacts and Characteristics

The magnitude of the shock wave caused by controlled explosive cutting would require mitigating measures.. Since it is assumed that the EBWR vessel would be cut in air (Section 1.3), the use of water flooding to buffer the shock wave is not feasible. Therefore, either some other type of buffering or muffling system would need to be used, or administrative controls would have to be implemented to prevent personnel from entering the reactor building during detonations.

A contamination-control envelope with HEPA filtration would be needed to process the airborne radioactivity generated by the detonations. It is estimated that about 4 liters of gas are produced by a 2-in. pipe-shaped charge using 100 grains of explosive per foot (Hazelton, 1981). Thus, for a circumferential cut of the EBWR vessel, approximately 7000 liters (250 ft^3) of gas would be generated using 4000 grains of explosive per foot (0.5 lb/ft).

3.11.4 Radiological, Safety, and Environmental Impacts

Although controlled explosive cutting necessitates manual placement of the majority of the charges, it is anticipated that some charges can be placed remotely. An articulating inside circular support could be lowered into the EBWR vessel to the proper elevation for cutting and monitored by closed-circuit television to assure proper positioning. Thus, the vertical charges could be placed remotely.

Since the charges would be placed and detonated in air, no liquid radioactive waste would be generated. Solid radioactive waste generated would be limited to the remains of the charge housings and skeletons.

As mentioned previously, this cutting technique makes use of a shock wave to cut the metal, and this shock wave makes an extremely loud noise. Muffling or other precautionary measures must be taken to protect personnel hearing during detonation. In addition, it might be necessary to monitor seismicity during detonation to ensure that the structural integrity of the EBWR building was not compromised.

3.11.5 Schedule and Costs

As noted in Table 3.11.4, the technology of cutting small metal pipes using shaped charges is well developed (JRC, 1989; Explosive Technology, 1978). This technique was successfully used in the underwater segmenting of a 3/4-in.-thick stainless steel core tank liner attachment in the reactor vessel of the Sodium Reactor Experiment (Manion, 1981). Also, a technology demonstration was carried out by Pacific Northwest Laboratory for the DOE for two hypothetical sectioning cases: a series of 2-in.-diameter pipes, and a 1/4-in.-thick stainless steel plate (Hazelton, 1981). To cut something the size of the EBWR vessel, an appreciable amount of development might be required. Obviously a large amount of energy would be required to fracture the entire periphery of the vessel. If, however, a band of material was cooled to below the null ductility temperature, the amount of energy required could be reduced by several orders of magnitude. This would require a development program to determine the amount of charge required for various temperatures.

It is estimated that the required cuts could be accomplished using a 2-person crew with specialized skills. With approximately 4 hours of proper planning, this crew could set the charges for each detonation in approximately 10 minutes (Motley, 1989b).

The shaped charges with 0.5 lb of explosives per linear foot cost approximately $150/ft. The cost of an electric fire box is negligible (less than $100) (Motley, 1989b). Assuming that approximately 600 linear feet of explosives are set, the total cost would be $90,000 for explosives. Articulating inside cutters could be supplied for approximately $7,000-$8,000 each (Motely, 1989b). Assuming that 12 circumferential cuts are required, this could add up to $96,000 to the cost. To place all the charges remotely, a remote manipulator could be developed for an additional $70,000-$150,000. If radiation exposure during manual placement of the vertical charges is tolerable, the articulating inside cutters could be used for the circumferential cuts and a manipulator would not be required.

Table 3.11.1 Performance and Physical Characteristics of Controlled Explosive Cutting

Cutting Speed	Instantaneous
Density of Explosives Required	0.5 lb/ft (4000 grains/ft)
Maximum Cutting Capability	6-in. metal

Table 3.11.2 Site-Specific Factors

Process System Requirements	Contamination-control envelope required
Plant Structural Modifications	None required
Access Acceptability to Building and Vessel	Acceptable

Table 3.11.3 Radiological, Safety, and Environmental Impacts

Generation of Airborne Radioactivity	7000 liters of gas per circumferential cut, and dust
Liquid Waste Generation	None
Solid Waste Generation	None
Industrial Safety Hazards	Explosion, Noise
Occupational Exposure	Acceptable -- charges placed Semi-remotely
Off-site Impacts	Noise

Table 3.11.4 Planning and Scheduling Considerations

Availability/Lead Time	Materials readily available
Demonstration/Development Requirements	Technology developed for small metal pipes
Personnel Requirements	2-person crew with specialized skills
Setup Time	4 hours to plan, 10 minutes to set charge

Table 3.11.5 System Costs for Controlled Explosive Cutting

Cutting System Capital Costs	
Ignition fire box	$100
Remote Manipulation and Viewing Equipment	
Remote manipulator	$70,000-$150,000
CCTV system	$27,800
Contamination-Control Equipment	
Contamination-containment/structure	$13,000 - $440,000
HEPA ventilation system	$7,100
Consumables	
Linear-shaped charges @ $150/ft	$90,000
12 articulating inside cutters @ $8,000 ea. (optional)	$ [illegible]6,000

3.12 Electrical-Discharge Machining

3.12.1 Cutting Principle and Method

Electrical-discharge machining (EDM) is a precision metal-removal process using a fine, accurately controlled electrical discharge (spark) to cause thermo-mechanical erosion in metal. The EDM process will machine any conductive metal regardless of its hardness (Elox, 1984).

EDM equipment consists of two major components: a machine tool and a power supply. The machine tool places a shaped electrode (graphite, copper, copper tungsten, or other electrically conducted material) in position to the workpiece. The electrode can be as small as 0.002-in. diameter or as large as 10-to 15-in. diameter, depending on the material removal and surface finish requirements. The power supply produces high-frequency pulses (1,000-10,000 Hz) of electrical arc discharges between the electrode and the workpiece to remove metal from the workpiece.

Integral to the EDM power supply is a computer numerically controlled (CNC) control computer programmed to effect the desired machining operations. This includes electrode movement on x-y-z axes, pulse times, amperage control, and other required programmable settings.

Two basic types of industrial EDM machines are available -- one utilizing a "ram" electrode and the other a "traveling wire" electrode (Hynes, 1989).

Figure 3.12.1 illustrates the components of a typical ram-type EDM system. A workpiece is mounted on the EDM machine. The electrode is attached to the ram of the machine, and a D.C. servo unit or hydraulic cylinder actuates the ram in a vertical plane to maintain proper positioning of the electrode in relation to the workpiece. During normal cutting, the electrode does not touch the workpiece but is separated from it by a small gap. The spark gap is controlled to as close as 0.0005 in. for the smallest diameter electrode to 0.002 in. for the largest diameter electrode (Hynes, 1989). Because of these close tolerances, the manipulator for an EDM system must be extremely accurate and stable, and, therefore, is relatively expensive. Both the workpiece and the electrode are immersed in a dielectric oil (hydrocarbon oil). The oil acts as an electrical insulator to help control the arc discharge, as a coolant. In addition the oil is pumped through the arc gap to flush away the eroded metal particles (swarf).

In operation, the ram moves the electrode toward the workpiece until the voltage in the gap produces an ionized column in the dielectric fluid. The electrical discharge then passes from the electrode through the ionized column to the workpiece. This discharge continues during the pulse, or on-time of the cycle, and stops at the pause or off-time. During the off-time, the oil regains its insulating properties and remains in this state until reionized by the next pulse. The process repeats continuously. Each discharge melts a small area of the workpiece surface. This molten metal then cools and solidifies into a small, spherical, hollow particle that is washed away by the flushing motion of the dielectric oil. The impact of each pulse is confined to a very small area. The arc always travels the shortest distance provided by the inequalities of the two surfaces (electrode and workpiece). With the gap setting held constant, the process gradually erodes the surface, first "leveling" the most prominent points and eventually those areas that were originally least prominent. With the gap setting constant, the surface becomes "level". Then the gap is reduced by a servo mechanism, and the process continues until a shaped cavity (reverse image of the electrode) is produced (Elox, 1984; POCO Graphite, 1977).

The principles of wire cut EDM are essentially the same as for the ram-type EDM. Metal is eroded from the workpiece by electrical sparks protected from the environment by a dielectric. The wire EDM equipment utilizes an electrode in the form of a traveling wire of 0.002-0.012 in. diameter to machine "through the hole" where access to both sides of the workpiece is possible. The wire follows a horizontal path through the workpiece much like a bandsaw. As with the ram-type electrodes, the wire electrode wears as it cuts and must be continually replaced. To accomplish this, the wire is in constant motion vertically as it moves horizontally into the cut (Elox, 1984).

3.12.2 Performance and Physical Characteristics

Industrial applications of the EDM process have been generally confined to precise machining of small parts at a fixed work station (Hynes, 1989).

The EDM process has been used, however, in very specialized applications in nuclear power plants, such as to remotely (underwater) machine small flow holes. The major benefits of utilizing EDM are that (1) no material chips, slag, or other large particles are generated, as is common with other cutting techniques, and (2) EDM are performed at low temperatures. This is especially important when it is necessary to cut components inside a serviceable nuclear pressure vessel. This specialized application of EDM was used in several Westinghouse pressurized-water reactor units: Portland General Electric Company, Trojan Nuclear Generating Station; Wisconsin Michigan Company, Point Beach Units 1 and 2; and Duquesne Light Company, Beaver Valley Unit 1. At these plants, EDM was used to perform underwater modifications to the plates in the lower core plate assembly. This "upflow conversion process" eliminated "baffle plate jetting" from impinging on the fuel elements (T. Litka, 1989).

In this specialized application of EDM technology, a power supply was connected to an electrode by means of a long specially designed 50-ft power supply cable. The electrode was positioned (with electrical cannister-type DC servo mechanisms) on a manipulator arm. The dielectric fluid, in this case reactor coolant, was used with a vacuum system and a specially designed filter system to flush and collect the fine talc-like cutting debris. Approximately 2 hours were required to machine one 2-in. diameter hole in 3-in. thick steel (T. Litka, 1989).

The fastest metal removal rate from a commercial/industrial wire EDM is reported to be 28 in.^{2}/h (Hitachi America LTD, 1989). A more reasonable approximation of removal rate for continuous operation is 10 in.^{2}/h (Waites, 1989). This translates to 4 in/h for a 2.5-in. metal thickness, which is comparatively slow.

Modular components for the EDM process equipment includes: a power supply, a machine tool, and a dielectric filtration system. One specific EDM power supply including the integral CNC unit, for example, requires 220 volts, 3-phase, 60-Hz input and supplies to the electrode 0.5-30.0 amps in 0.5-amp increments with two working voltages of 80 volt/gap for regular work and 200 volt/gap for fine surface finishing work. Digital on-off times for regulation of pulse/pause cycles are in 1-microsecond increments; DC-arc protection, a built-in capacitor box, a completely enclosed lighted membrane keyboard, dual analog voltmeter, and analog ammeter are standard features. Dimensions of this unit are 24 in. x 28 in. x 72 in. The unit weights 655 lb. Other power supply units are available for specific applications with control parameters, such as voltage and amperage, designed for the electrode size, material removal rate, and surface finish requirements (Eltee Pulsitron, 1989).

A photograph of a specific machine tool is shown in Figure 3.12.2. This tool is designed to machine small parts. It features a programmable "Z" axis with a travel of a maximum of 12 in. Vacuum and pressure flushing of the workpiece are standard features in the 19.75 in. x 14.75 in. x 12 in. work tank. The electro-magnetic chuck on the ram will accept up to a 22-lb electrode. Overall dimensions for this unit is 50 in. x 47 in. x 86 in. and the weight is 2440 lb.

3.12.3 Site-Specific Impacts and Characteristics

Commercially available industrial EDM equipment is designed primarily to machine small parts. To adapt the EDM technology to the dissection of the EBWR vessel, a specific implementation design would be required, which may require flooding of the cutting area with a dielectric fluid. Up to 6 months of engineering time would be needed to produce such a design (Rigan, 1989).

Access to both sides of the reactor vessel would be required, with at least 1-in. clearance to accommodate a traveling wire electrode. The traveling wire electrode, as opposed to the electrode EDM, would best be suited to the EBWR task. This would alleviate some of the problems, such as D.C. arcing compounded when the dielectric fluid is required to be sprayed onto the workpiece instead of submerging it into the dielectric fluid. Development of a feasible system would still require engineering application studies.

3.12.4 Radiological, Safety, and Environmental Impacts

The EDM process requires a dielectric fluid for flushing and arc control. This dielectric fluid, (hydrocarbon oil or deionized water) is contained in a work tank in commercially available EDM machine tools. If an EDM system were designed to disassemble the EBWR vessel, it would have to include a means of supplying the dielectric fluid onto the workpiece (EBWR vessel) and a method of collecting the fluid. Since the dielectric fluid is used to flush the cutting debris (swarf) from the kerf of the workpiece, the swarf would be kept wet, and there would be no airborne waste hazard (Table 3.12.4). The swarf produced in the EDM process is a very fine talc-like substance. Since the EDM process is performed remotely with no noise, there are no inherent safety hazards.

Environmental impacts would be minimized because the EDM system and process effluents would be contained within the EBWR vessel and associated building.

3.12.5 Schedule and Costs

At the present time, no commercially available system exists that would allow the EDM technology to be applied to remote cutting of the EBWR vessel. As indicated in Table 3.12.4, if it were necessary to apply this technology to this task, development of a specifically designed system would require at least 6 months (Rigan, 1989). Table 3.12.5 shows the capital costs, for the EDM equipment. EDM equipment that is commercially available (small-parts machining) costs $61,000 for the power supply, machine tool, and dielectric filter illustrated in Figure 3.12.2 (Hynes, 1989).

Zinc-coated brass wire electrodes are available from a commercial source at $321 for the 75,000 ft that would be required to complete 600 ft of cutting (POCO Graphite, 1989).

The complexity of a developed remote application system for EDM would determine how many operators would be required. Generally however, only one operator would be required, and two people would be needed to assist in material handling.

Table 3.12.1 Electrical-Discharge-Machining Performance and Physical Characteristics

Material Cutting Capability	Any conductive metal
Cutting Speed	4 in./hr for 2.5-in. metal
Application to EBWR Vessel	Requires development of remote application and dielectric
Capability	6-in. metal

Table 3.12.2 Site-Specific Factors

Process System Requirements	Requires filtering/processing of dielectric fluid
Plant Structural Modifications	Vessel needs to be flooded, with at least 1 in. access to both sides of the reactor vessel
Access to Building and Vessel	Acceptable

Table 3.12.3 Radiological, Safety, and Environmental Impacts

Generation of Airborne Radioactivity	Cutting under dielectric fluid produces no airborne particulates
Liquid Waste Generation	Dielectric fluid (hydrocarbon oil or deionized water)
Solid Waste Generation	No
Industrial Safety Hazards	No inherent safety hazards
Off-site Impacts	No

Table 3.12.4 Planning and Scheduling Considerations for EDM System

Availability/Lead Time	5-7 days delivery time for basic components
Demonstration/Development Requirements	Remote application requires at least 6 months engineering development
Personnel Requirements	1 operator, 1 material handler
Assembly Time	To be determined by complexity of developed system
Downtime/Performance Time	To be determined by complexity of developed system

Table 3.12.5 Costs for EDM Equipment

<u>Cutting System Capital Costs</u>	
Specific EDM system (small parts machining)	$37,000
Power supply unit	$23,000
2-50 ft power supply cables	$600
<u>Remote Manipulation and Viewing Equipment</u>	
Remote manipulator	$200,000-$350,000
CCTV system	$27,800
<u>Contamination-Control Equipment</u>	
Liquid processing system	$25,000-$35,000
<u>Consumables</u>	
75,000 ft. zinc-coated brass electrode wire	$321

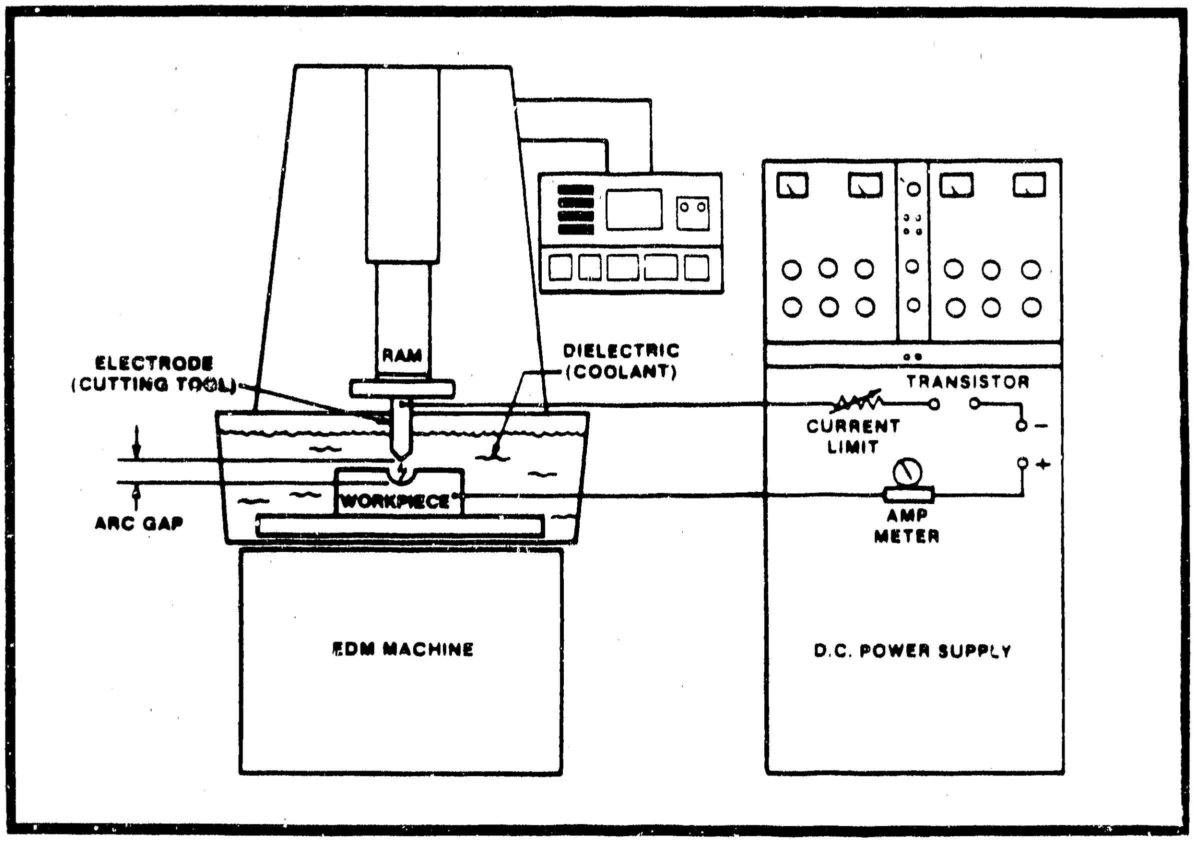
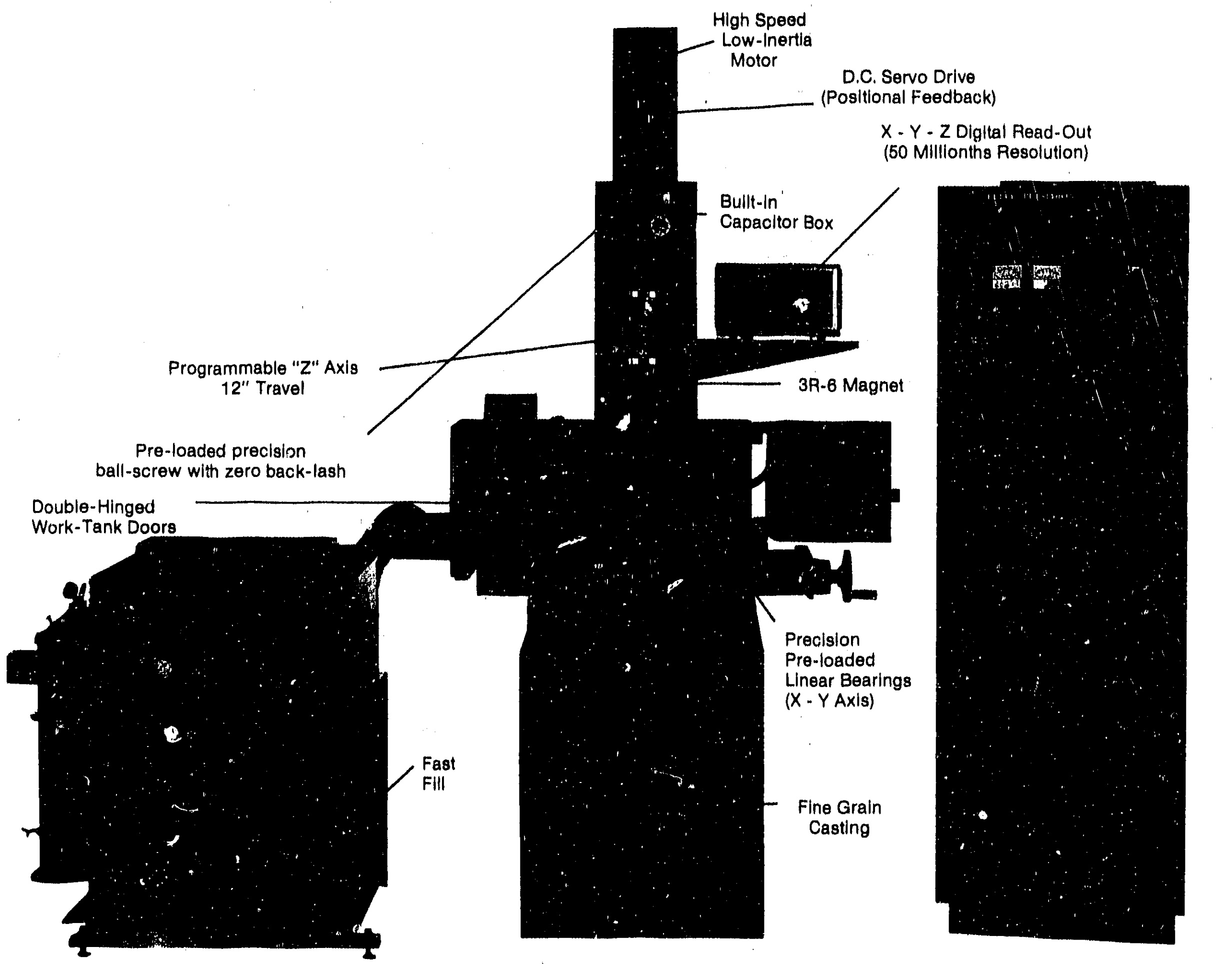


Fig. 3.12.1 A Typical Ram EDM System (The electrode is held by the ram, and the workpiece is immersed in the dielectric fluid on the EDM machine (left). The power supply (right) controls the electrical discharge and movement of the electrode in relation to the workpiece.) (Taken from ELOX EDM Systems, Fundamentals of EDM)



Eltee Pulistron, 1988

Fig. 3.12.2 Photograph if a Specific EDM Equipment System
(Taken from Eltee Pulsitron, 1988)

3.13 Other Cutting Techniques

3.13.1 Intergranular Fissuration Cutting

The fissuration procedure is a method by which a molten material is added to the workpiece, thereby embrittling the base metal and cracking it as it cools. The addition of molten material produces a controlled, intergranular fissure in the heated area of the workpiece. Tension stress created by the thermal gradient induced during local heating causes brittle failure of the component. Since the process is performed at a relatively low temperature (800°C), intergranular fissuration induces metal failure without appreciable aerosol or smoke generation (Cregut, 1986; IAEA, 1988).

Because relatively little information could be gathered about this process, which is under development in Europe, no further analysis could be performed.

3.13.2 Electron-Beam Cutting

Electron-beam cutting is not a recognized metal-cutting process within the welding/cutting industry. Electron-beam drilling (as opposed to cutting) has been performed under laboratory conditions. In a vacuum, high-frequency pulses of electrons impact a workpiece and create a molten keyhole. A backing material, which off-gasses violently above the melting temperature of the material, is employed to remove the molten material.

The electron beam is currently in an experimental stage of development. Insufficient information is available to perform further analysis for the EBWR application.

3.14 Positioning of Remote Cutting Equipment

All vessel-cutting methods require structuring and fixturing of a cutting-tool-handling device with control cables and hoses tended to a remote operating station. This study assumes that an internal handling device or manipulator is required to provide dynamic positioning of the cutting tool with all internal surfaces of the vessel. Depending on the cutting method employed, additional in-vessel equipment may include shielding, ventilation, waste handling, and remote viewing systems.

3.14.1 Cutting Tool Manipulator

Reliable positioning of the cutting tool to the work surface is the critical factor for efficient vessel dismantling. Positioning accuracy requirements vary significantly with cutting method; however, the basic manipulator design should address all of the following performance parameters (see Table 3.14.1 for comparison of manipulator designs and cutting methods):

-- Positioning accuracy - This parameter is derived directly from the required tool-to-work surface tolerance of the selected cutting method. The work of the manipulator involves dynamic actions in maneuvering the cutting tool at a predefined speed, maintaining the tool to the work surface at the correct attitude, and progressing in linear and nonlinear motions in any plane.

-- Force/payload capacity - This parameter is defined by the weight of the cutting tool components and the reaction forces induced by the cutting process. Attention must be given to manipulator dynamics and the ability to maintain position accuracy and repeatability. Moreover, additional tasks (waste handling, remote viewing) may add requirements to this parameter.

-- Force-control capabilities - For cutting operations involving direct contact with the vessel surface, manipulator design must address applied forces that can be measured and controlled, in addition to reaction forces.

-- Cutting speed - Achieving a stable cutting speed can be as demanding as maintaining position accuracy. Some cutting processes require accurate, consistent speed regulation while others do not. These characteristics must be considered in the controls selection for a particular cutting method.

-- Range of motion - The range of motion of the manipulator is defined by the vessel geometry (cylinder and half-sphere). The system must be capable of maintaining the other parameters while accessing all surfaces without gravity affecting manipulator motion or the cutting process.

-- Inherent protection against mechanical shock - This protection is important to consider because collisions with obstructions are unavoidable during dismantling operations. Rigid structures, actuating mechanisms, and control devices must be capable of withstanding intermittent shocks and vibrations.

-- Versatility - The manipulator may be required to permit change toolings for different surface geometries. This parameter may or may not be a consideration, depending on the selected cutting method.

-- Total weight - The weight of the manipulator is a critical parameter in the design of its support structure, which usually weighs many times the manipulator's weight. Size (volumes) and weight may also be a consideration for access to the work area through entry ports or doors.

-- Control lines - The control lines to the manipulator must be as small and simple as possible. The cable or umbilical tending problem influences support-structure design and manipulator operation.

-- Resistance to the environment - Careful consideration must be given to manipulator design and materials that resist radiation, corrosive fluids, heat, dust, and grit. Considering possible decontaminability problems, watertight components and enclosures may be the preferred designs.

-- Maintainability - The ability of service technicians to work on the manipulator with gloved hands and protective clothing is an important consideration. Design objectives should include large enough fastening devices for the limited dexterity of gloved hands and to minimize as much as possible unsealed joints and crevices where contamination cannot be removed.

3.14.2 Manipulator Support Structure

Features to structurally support and control the cutting-tool manipulator within the reactor vessel can generate a variety of designs; however, three basic concepts involving a central mast appear to be best suited for the dismantling project. Each concept has advantages and disadvantages, depending on which cutting method is selected. Therefore, in evaluating a support-structure design, all of the manipulator performance parameters must be considered, including the addition of other systems such as shielding, ventilation, waste handling, and remote viewing systems.

Criteria important to all support structure designs include installation and removal of equipment with respect to personnel exposure, number of fixture changes required for cutting different vessel elevations and geometries (cylindrical vs. spherical sections), interfacing with a waste handling system and costs. The following sections describe three basic mast design concepts.

3.14.2.1 Gantry-Mounted Mast

The gantry-mounted mast design involves a gantry (x-axis and z-axis) erected over the vessel on the main floor (elevation 730 ft, - 0 in.), possibly utilizing rails for the existing fuel coffin/transfer carriage (see Figure 3.14.1). The manipulator is attached to the bottom of the mast (y-axis), which is fixed to an x or z carriage traversing the top of the vessel.

This system allows for simple manipulator design because the x, y and z axis positioning and cutting operations are accomplished with the mast-support-structure movements. Manipulator motion has only to provide for cutting the lower head (half-sphere). However, close positioning tolerances required in some cutting methods will cause high resolution demands on the mast x-y-z-axis controls. The elaboration of these controls will depend on the mass dynamics of the mast and its x-z-axis carriages.

Cutting processes that produce high reaction forces may require a mast stabilizer bar to transmit loads generated into the manipulator back into the vessel. This bar may only be necessary when cutting the lower reaches of the vessel (23-ft inside height). However, it would add complexity to the system, especially for cutting methods requiring close (0.001-0.003 in.) positioning tolerances where it might require its own remotely controlled extension and retraction system. On the other hand, the mast x-y-z-axis positioning mechanisms could be designed to resist cutting reaction forces, thus eliminating the need for a stabilizer bar. Clearly this approach requires a trade-off between simplicity and resolution demands (and cost) to the mast control systems.

3.14.2.2 Stationary Mast

The stationary mast design involves placing a fixed platform over the top of the vessel to which the mast is attached and located on the vessel centerline (see Figure 3.14.2). The first advantage is the simple, inexpensive structure on the main floor, where only mast y-axis (rotational and vertical motion) control has to be provided. Another advantage is the simple shielding arrangement the platform provides.

The manipulator in this concept has to provide much more dexterity than in the gantry-mounted design. The x- and z-axis positioning, as well as pitch rotation for the lower head, must be provided. It would be easier to control the mask deflections caused by the cutting forces without using a stabilizer bar if using the Stationary Mask design. The mast vertical (extend and retract) and rotational motion can be accomplished through telescoping sections or by a jack screw (rack and pinion) design, all of which permits closer mast structure positioning tolerances without concern for the x- and z-axis travel taken care of by the manipulator.

3.14.2.3 Rotating Platform

A rotating platform assembled over the vessel provides shielding and a rotating mast (see Figure 3.14.3). The mast provides the same y-axis rotation and vertical motions as in the stationary design, but also uses the rotating platform for positioning around the inside diameter of the vessel. This allows for simpler manipulator functions, especially for cutting processes that do not require close tolerances. However, if reaction forces of the cutting processes are high, design of the mast-to-platform structure and actuating mechanisms must be more elaborate, because use of a stabilizing bar is not practical.

With the mast providing y-axis motions and the rotating platform providing positioning close to the vessel wall, the manipulator has only to perform fine position adjustments for both the cylindrical and spherical geometries of the vessel. This would allow for smaller, lighter, and less expensive actuating mechanisms and controls.

3.14.3 Control

The work of the cutting-tool manipulator and mast support structure involves dynamic actions in maneuvering the tool at a predefined speed, maintaining the tool to the work surface at a predetermined angle, and defining the geometry of the surface being cut in linear and nonlinear motions in any plane. To achieve these requirements, the position of the tool tip needs to be known at all times within an accuracy that can range from quarters to thousandths of an in., depending on the cutting process. This information needs to be know either in the form of position coordinates or axis positions.

Microprocessor-based controls can provide the ability to maintain small position tolerances with limited operator input and the ability to perform teach and repeat functions. This enables the operator to manually drive the manipulator through a chosen route and teach the machine to follow that path. During the teach operation, geometry can be defined, tool position and angle maintained, and obstacles avoided that might not otherwise be visible through the viewing system during the actual cutting process because of debris and smoke generation.

Available at slightly less cost and with much less complexity are manual controls that rely more on operator skill and knowledge of surface geometries and obstacles. These types of controls can be especially effective and reliable if the cutting process does not obstruct the view of the camera system. The operator would physically drive the machine to the cutting area, initiate the cutting process, and manually control its progress. This type of control would also substantially reduce operator training and maintenance required by the severe environment.

3.14.4 Cost of Remote Manipulator Equipment

Because of a number of variables, there is a broad range of costs associated with positioning a remotely controlled cutting process. Lower costs can be achieved by the use of manual control systems which significantly reduce design and engineering efforts. Table 3.14.2 compares for costs of the different cutting methods and positioning equipment.

Three discernible groups of cutting methods appear in the manipulator cost evaluation table. The first group includes plasma-arc, arc-saw, arc gouging, flame cutting, water-jet, and abrasive cutting. Positioning of these processes appears to be best suited to the central-mast-mounted manipulator designs, which are tolerant of vessel irregularities and can access all inside geometries.

The second group of cutting methods would include diamond wire, mechanical milling, and explosive cutting. These processes would not include mast-mounted manipulators, but would involve positioning equipment that is unique to each cutting method. Except for explosive cutting, diamond wire, and mechanical milling, the manipulators would require several specially designed fixtures (or track systems) to cover the different vessel geometries. Significant increases in handling and exposure time will further increase overall project costs.

The third group consists of laser-cutting and electrical-discharge machining systems. While these processes are attractive relative to radiological, safety, and environmental concerns, each system has limitations due to complex fixturing designs, control equipment, and a general incompatibility with a vessel dismantling application.

It must be noted that when costs for positioning equipment designs are evaluated, consideration should be given to associated systems, such as ventilation, waste handling, shielding, and remote viewing which ultimately are incorporated into the entire package.

Table 3.14.1 Cutting Took Positioning Manipulator Evaluation Table

Manipulator Performance Parameters	Cutting Methods[a] Plasma-Arc Cutting [b]	Arc-Saw Cutting [b]	Electric-Arc Cutting [b]	Flame Cutting [b]	Exothermic-Reaction Cutting [b]	Water-Jet Cutting [c]	Diamond-Wire Cutting [c]	Mech. Cladding Removal (abrasive cutting) [b]	Laser Cutting [b]	Mechanical Milling [d]	Controlled Explosive Cutting [e]	Electronic-Discharge Machining [e]
Required Positioning Accuracy	H	H	M	M	M	L	L	L	L	L	L	H
Force/Payload Capacity	L	H	L	L	L	M	M	H	H	H	L	M
Required Applied Force Control	-	-	-	-	-	-	H	H	-	M	L	-
Manipulator Speed	M	H	M	M	M	L	M	L	M	L	H	L
Required Range of Motion	M	L	M	H	M	H	L	H	H	L	H	M
Required Resistance to Mechanical Shock	H	H	H	M	M	M	L	L	L	L	L	M
Required Versatility	H	M	M	L	M	M	H	H	L	M	H	L
Total Weight of Manipulator	L	H	L	L	L	L	H	H	M	H	L	M
Required Number of Control Lines	M	M	M	M	M	M	H	M	H	M	L	M
Required Resistance to Environment	H	H	M	L	M	H	H	H	L	H	L	M
Required Degree of Maintenance	L	H	L	L	L	M	M	H	M	H	L	M

[a] H = high; M = medium; L = low.

[b] Electric-arc gouging and abrasive grinding are preliminary cutting methods for removing stainless steel cladding prior to flame cutting the carbon steel walls.

[c] Diamond-wire cutting requires access to both sides of the vessel with unique fixturing compared with the manipulator requirements of other cutting processes. As a result, performance parameters should be used only for cutting method evaluation.

[d] The mechanical milling method can only be used on the outside diameter of the vessel, therefore, manipulator performance parameters apply only to equipment necessary to achieve this particular setup.

[e] Controlled explosive cutting requires a unique manipulator application as compared with the other cutting processes, and as a result, performance parameters should be used only for cutting method evaluation.

Table 3.14.2 Manipulator Cost Evaluation Table

Method	Cost[a] ($1000)
Plasma-Arc Cutting	120-250
Arc-Saw Cutting	120-200
Flame Cutting from OD	120-200[b]
Electric-Arc Gouging/Flame Cutting	120-200[b]
Mechanical/Abrasive Cutting/Flame Cutting	120-250[b]
Exothermic-Reaction Cutting	Not now feasible
Water-Jet Cutting	120-200
Diamond-Wire Cutting	70-150
Laser Cutting	200-350
Mechanical Milling	70-150
Controlled Explosive Cutting	70-150
Electronic-Discharge Machining	200-350

[a]The range in each price reflects the difference in prices for manual manipulators versus fully automated manipulators.

[b]Electric-arc gouging and mechanical/abrasive cutting methods are used as a preliminary process to remove the the stainless steel cladding before flame cutting the carbon steel vessel wall.

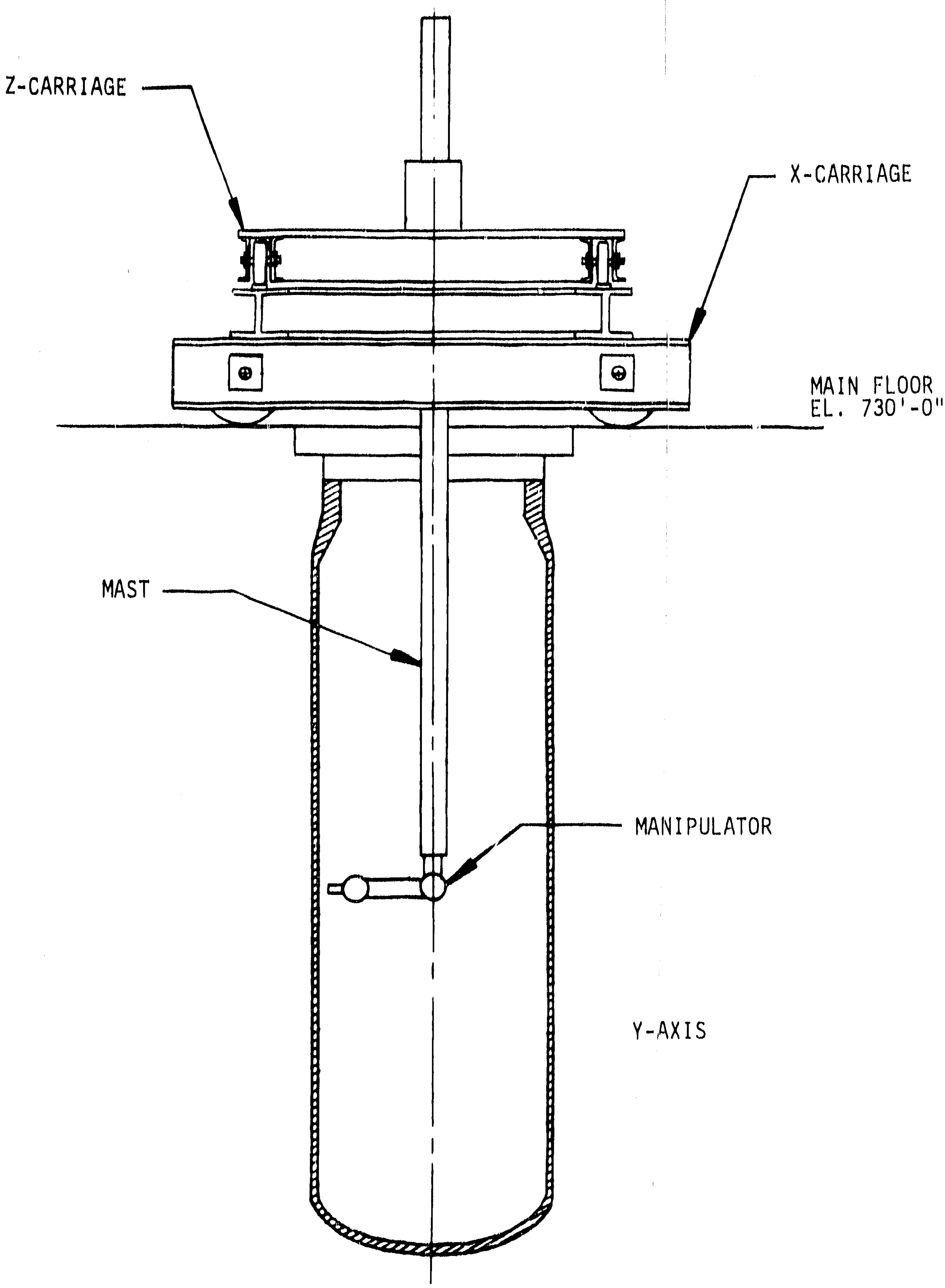


Fig. 3.14.1 Gantry-Mounted Mast Arrangement

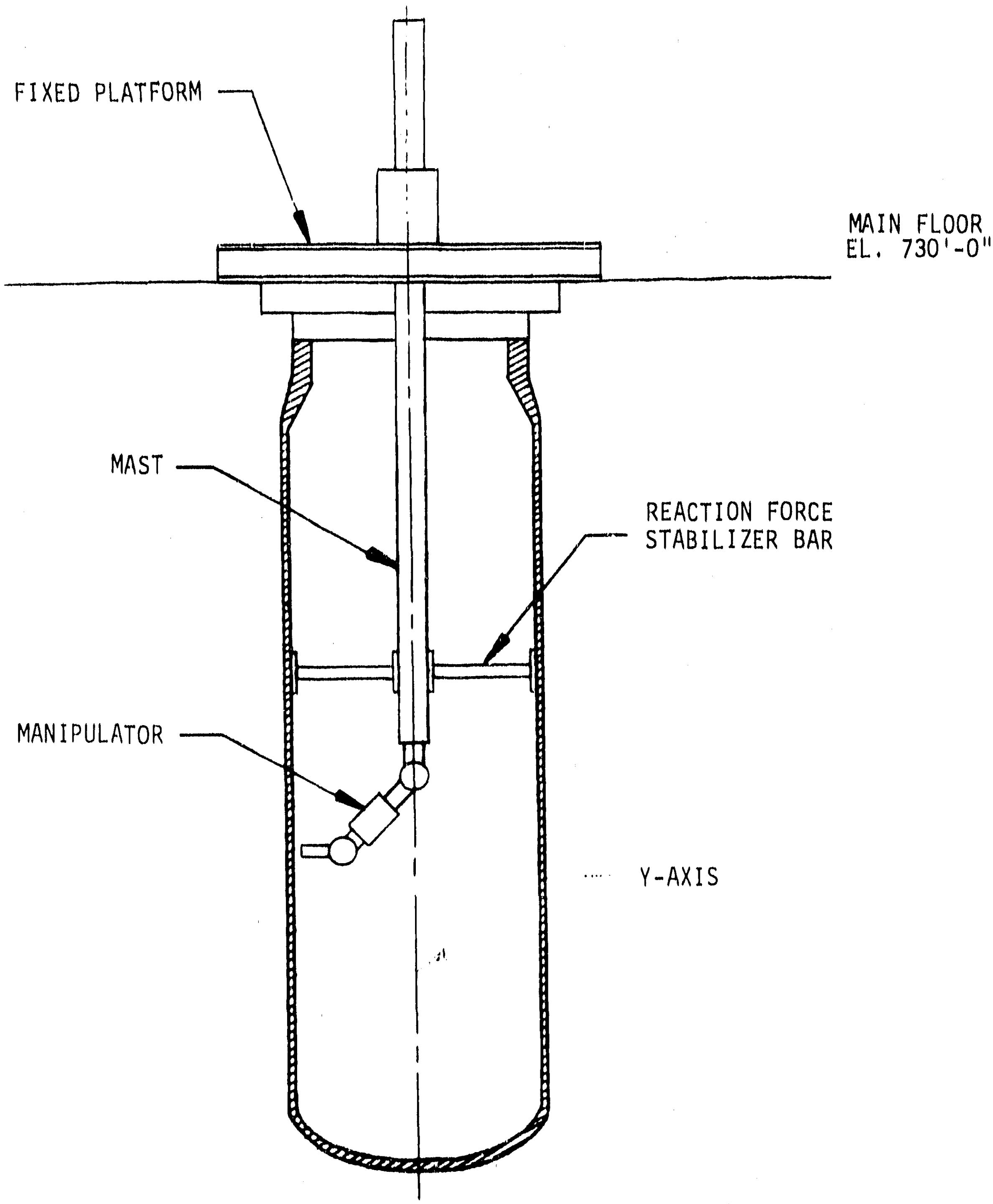


Fig. 3.14.2 Stationary Mast Arrangement

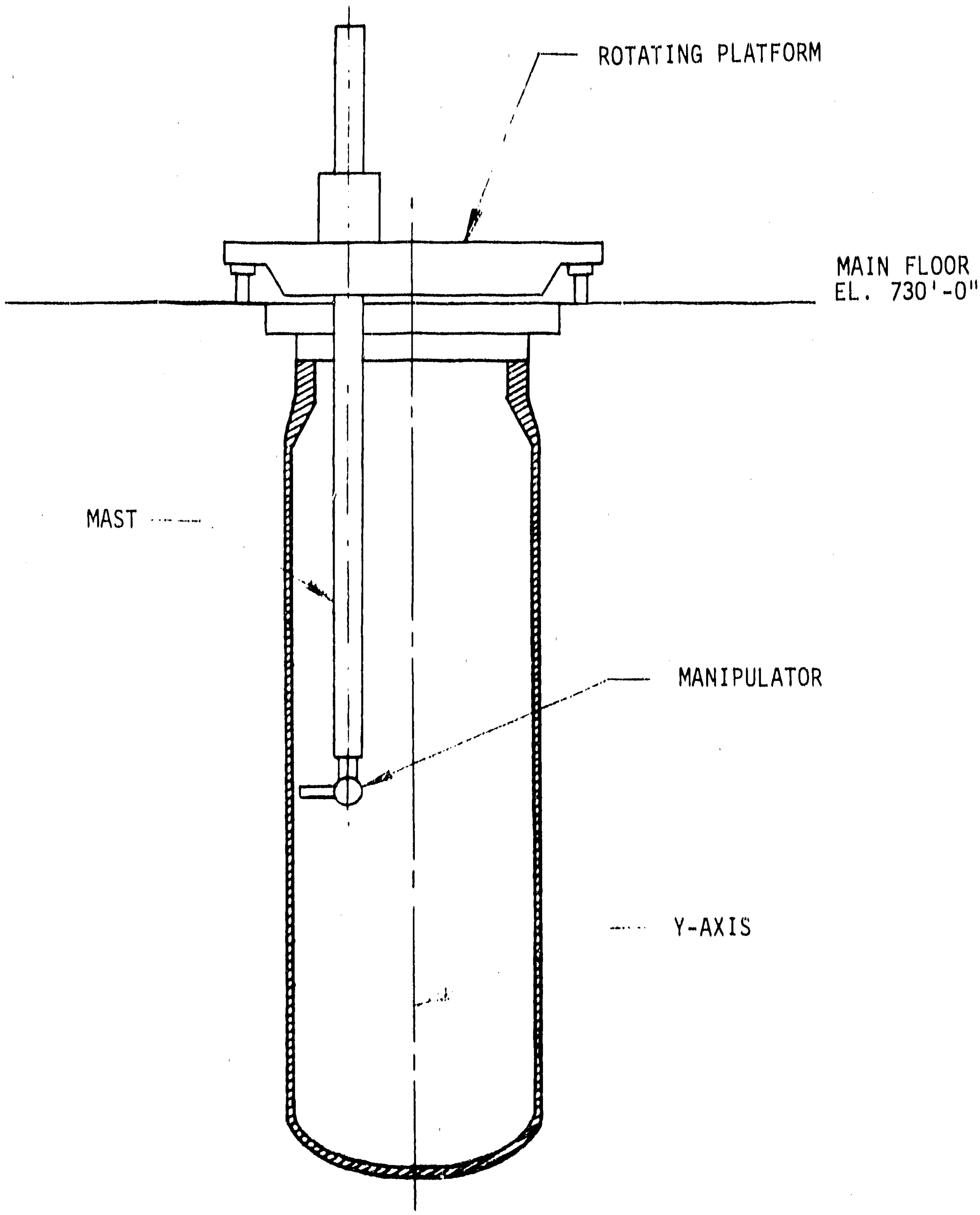


Fig. 3.14.3 Rotating Platform Arrangement

3.15 Remote Viewing Systems

Radiation-resistant, remote-viewing systems are available with a variety of accessories to enable both real-time and recorded viewing of the cutting. Most remote camera systems are modular in design. This allows the system to be offered in various formats to suit individual needs.

Several options are available for viewing. The first is a small-diameter, high-resolution camera with low-light-level capability. This camera allows wide-angle viewing and, in conjunction with a pan and tilt mechanism, can provide about a 180° viewing angle. This is sufficient for closeup viewing of processes. If viewing at a greater distance is necessary (e.g., the length of the pressure vessel) a zoom lens must be added to the camera to provide detailed visibility (Rees, 1989).

The R93 camera is shown in Figure 3.15.1. Fitted with a nonbrowning lens and tube, the unit offers resistance to radiation in excess of 10^8 rads absorbed gamma dose. The camera produces an exceptionally high-quality picture even under adverse conditions. Housed within the body are the motor drives that provide remote focus and iris control capabilities. A third motor provides power for ancillary features. such as a radial viewing head or zoom lens (RI, 1981).

A zoom lens viewhead (Figure 3.15.2) is available for the R93 camera. It provides a 12.5 mm to 75 mm zoom capability mounted within a stainless steel housing. The camera can be changed from a standard unit to a zoom unit in 20 seconds. The power drives within the camera provide remote control zoom capability. An optical focus motor within the zoom lens body provides focusing capability from infinity to about 50 mm. The zoom lens is available with a standard lens or a nonbrowning lens. The nonbrowning lens is significantly more expensive than the standard lens.

The pan and tilt mechanism for this system (Figure 3.15.3) is an L-shaped camera tilt platform supplied with a variety of holes and slots to suit a variety of housings. This, together with the vertical platform adjustments, enables the camera to be correctly balanced for optimum performance. The pan and tilt bracket can be mounted upright or inverted. When inverted, the tilt platform can be revolved to maintain the camera in its normal attitude.

The camera-control unit houses a power supply and motor-function control module. Three video monitors are available for use with the control unit. The largest of the three is a 12-in. monitor. This monitor has better resolution than the 3-in. or 9-in. monitors. The control unit provides power to the camera and control for the iris, focus, and rotation motors. The power supply features an automatic protection circuit to prevent generation of high voltage in the control unit until the camera is safely secured to its connector.

Both the camera and zoom lens are made of stainless steel for ease of decontamination. Each camera is used in conjunction with a control unit. A standard quality VCR can be used with the control unit to videotape the process. The time and date capability of the camera facilitates identification.

Table 3.15.1 lists the average cost of a closed-circuit television camera and its associated equipment.

Table 3.15.1 Average Costs of Remote Control CCTV System[a]

R93 Miniature CCTV Camera	$ 7,900
R93/04 Nonbrowning Zoom Lens	$12,600
Radiation Resistant 488R Pan and Tilt Head	$ 1,700
Camera Control Unit	$ 5,200
VCR for Recording	$ 400
Total Cost	$27,800

[a] Costs do not include cable and connections.

Rees Instruments

Fig. 3.15.1 R93 Miniature CCTV Camera

Rees Instruments

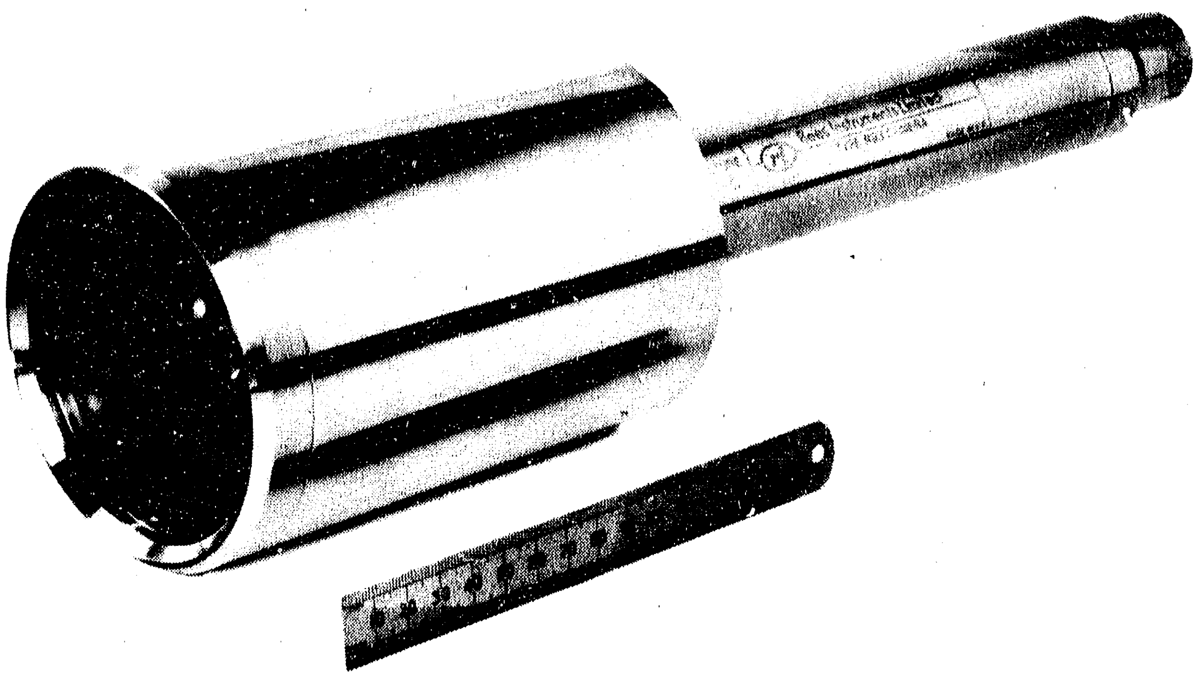


Fig. 3.15.2 R93/04 Nonbrowning Zoom Lens

Rees Instruments

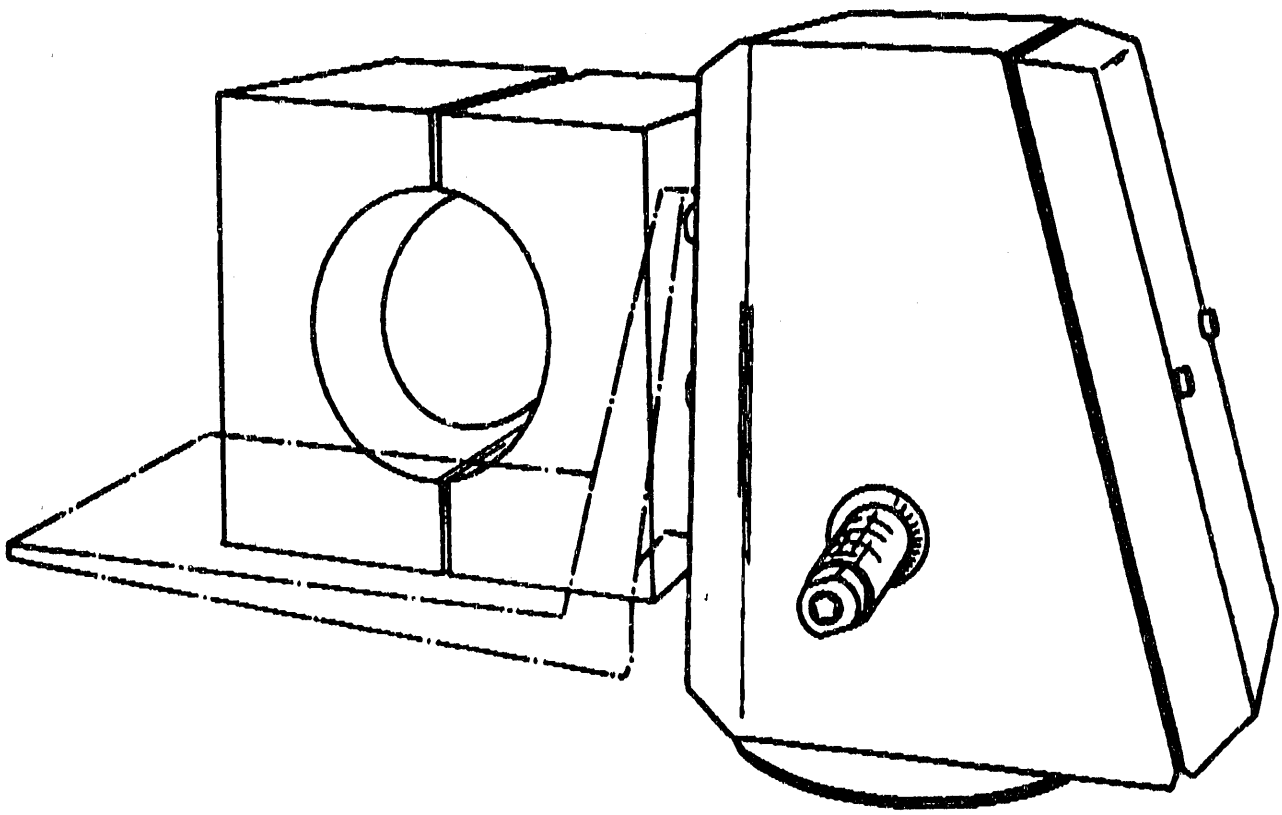


Fig. 3.15.3 Type 488R Pan and Tilt Head

3.16 Contamination-Control Measures

3.16.1 Containment Systems

For most of the cutting methods described in this report, use of a containment system to shroud the reactor vessel opening would be prudent, if not absolutely necessary. The type of containment would vary depending on the cutting technology used.

Herculite and metal frame containment construction is inexpensive and quite effective for cutting methods in which heat or hot particulate matter (e.g., metal shavings) is not generated. This type of containment is easy to install and dismantle, which facilitates decontamination and/or disposal. The waste volume is minimal. The herculite containment can be constructed with clear PVC windows, openings for a HEPA ventilation trunks, prefilters, and an air lock to ensure contaminants do not escape from the containment.

To facilitate maneuverability of the cut reactor pressure vessel sections, a 12 ft x 12 ft x 25 ft (approximate dimensions), containment is needed over the vessel opening. If space permits, the containment can be extended on one side to enclose a waste storage area. This design would ensure that sections of the vessel that have been cut and removed can be hoisted by crane and placed into waste receptacles without leaving the enclosure.

The standard material cost of building a herculite containment is $2.50-$5/ft^2. Assuming about 2,000 ft^2 of herculite will be required, the cost of herculite alone would be $5000 to $10,000. The aluminum frame material would be an additional $3000 (Gatter, 1989). Construction of a containment of this size would require approximately 100 person-hours.

Modular contamination-control enclosures are also available. These units are more expensive than herculite containments but are reusable. More importantly, these units are fire retardant or fireproof. Since the units are modular and lightweight, they are easy to construct. Structure design can be modified for future purposes using the many interchangeable parts. The units are constructed of various materials; stainless steel and Lexan are the most common. These structures are also easily decontaminated. Since the Lexan structure is smooth and transparent, there are no irregular surfaces to collect contamination, and there is 100% visibility of the containment internals. Therefore, no interior lighting is required (NPO, 1984). Panels are available with penetrations to accommodate use of internal electricity, supplied air (if necessary), and ventilation. The modular panels can be made with special flexible seals to fit snugly against existing components, walls, pipe penetrations, or other irregular surfaces. Figure 3.16.1 shows a simple Lexan structure (NPO, 1984).

The average cost of such a containment is about $600 for each 4 ft x 8 ft panel (NPO, 1989) and slightly more for special panels, doors, and other such components. DA Services provides the same basic containment at approximately $400 per panel, including the steel frame (Gatter, 1989). Thus, a fire-retardant containment would cost $30,000 to $40,000.

Unlike herculite which is readily available, Lexan modular units (especially the special panels) require 8-10 weeks for delivery.

General Dynamics (Kennedy, 1989), in conjunction with Kelly Structures, sells "PERMA-CON" modular panels. These panels are Lexan or stainless steel. The firm also sells a lightweight and inexpensive material called "VERSA-CON." This is a thin, corrugated plastic costing $220 per 4 ft x 8 ft panel. Additional savings can be realized by using 4 ft x 12 ft panels. Costs are slightly higher for doors ($1600 each), penetrations, and other special units.

Mobility of the crane is a concern for transporting cut sections from within the vessel cavity to a waste processing or storage area. The containment could be built to permit translation of the hook within the enclosure. For some cutting techniques, it is important that fire-retardant material be used. To control costs, it would be feasible to construct a containment partially of VERSACON material (the lower portion) and the remainder (upper portion) of Herculite. Using both VERSACON and Herculite in the construction of a containment would reduce the cost of the containment while providing spark and flame protection where needed.

Care is needed when using a containment wherever heat, sparks, or hot metal fragments may exist. Cooling time for the cut section will be required. Cold water rinsing may be used to rapidly decrease temperature; however, addition of water to the system would increase the volume of wastewater to be processed.

3.16.2 Ventilation Systems

The purpose of contamination control is to minimize radiation exposure to personnel. Safety of personnel and the public is the paramount consideration. In controlled areas where airborne contamination may exist, personnel must be protected. Wherever feasible, engineering controls should be applied. High-efficiency particulate air (HEPA) filtration is an effective method for controlling airborne contamination. Temporary ventilation minimizes the spread of radioactive contamination and, in turn, reduces the amount of radioactive waste generated. Other methods are available but would not be cost effective for this purpose.

Three ventilation sources should be utilized during cutting operations:

-- Normal building ventilation to draw on the containment building.

-- HEPA ventilation to draw on the temporary containment.

-- HEPA vacuum suction at the area being cut.

Normal building ventilation will ensure that a negative pressure is maintained on the containment building throughout the cutting campaign. This ventilation should be maintained as backup in the event other system or mechanical failures occur, releasing contaminated air into the containment bldg.

Dust, fumes, and particulate matter may be generated by cutting. A containment enclosure will keep airborne contamination from spreading, but the air within the containment must be processed to remove the contaminants. Portable, filtered ventilation units are used to draw a suction on the containment. Containment structure ventilation has two purposes:

-- A negative pressure is drawn on the containment thus directing the flow of air and minimizing the potential for leakage into the uncontrolled area.

-- By directing the flow of air through the ventilation unit, airborne contamination, dust, and fumes can be removed from the containment atmosphere.

A suitable ventilation system will contain prefilters and HEPA filters for removing particulates. Depending upon the cutting technique used, it may also be prudent to install a special prefilter to remove moisture.

Prefilters or roughing filters are placed upstream to collect large particulate matter. This will extend the life of the more expensive HEPA filters. Not all portable ventilation units are capable of incorporating a moisture separator. Therefore, should it be necessary to use this feature, a suitable system must be selected. Such units generally contain a filter pan and drain assembly designed to allow water to drain under a negative pressure.

The HEPA filters are used to remove small particulate material on the order of 0.3 μm. The filters are a paper-like medium, folded and attached within a rigid casing by special adhesives. For the particle size mentioned, HEPA filters are rated at 99.97% efficient.

To ensure that a portable ventilation unit is sufficient to exhaust the containment atmosphere, a minimum 1000-ft^3/min fan with a 3 hp motor and blower should be used. An "elephant trunk" (air duct) is connected from the containment to the fan inlet. This system has a large static pressure range to compensate for dirty filters and the flexible hose. This capacity ventilation unit should provide approximately 12 air changes per hour within the containment.

The "bag-out" design of most portable ventilation units is ideally suited to this purpose. The filters can be removed from the housing into a plastic bag without ever exposing the filter. Therefore, any contaminants trapped in the filter media cannot escape.

The cost of HEPA filtered ventilation units varies somewhat, but a standard, Nuclear Power Outfitters 1000-ft^3/min, 3-hp unit averages $6000. Table 3.16.1 shows the cost breakdown of a typical unit with the necessary attachments.

Metal shavings generated in the cutting process must be collected for disposal as radioactive waste. A HEPA-filtered, wet-dry vacuum system can be adapted to take suction at the cutting location and deposit the material directly into a 55-gal drum. However, HEPA vacuum systems are available with a stainless steel drum that can be easily decontaminated should radiological conditions preclude direct deposit into 55-gal drums. Placement of vacuumed material directly into a 55-gal disposal drum is the optimal method since it reduces material-handling time.

Various models can be purchased commercially. The length of suction hose and the hose diameter needed, as well as the suction capacity of the unit, limits the selection.

One specially adapted portable HEPA-filtered vacuum system capable of providing the necessary service is the "Vaculoader" by VACTAGON. This system is capable of adapting several 3-in. ID suction hoses. The system can be purchased with its own bag-lined drum or a drum loader attachment that will fill 55-gal drums. The system is 220 volts single phase with 320 ft^3/min capacity. Its maximum loading distance is 75 ft using 3-in. hose and the unit can accommodate three hoses with negligible suction reduction. The unit utilizes a special prefilter that is washable for reuse. Only the HEPA filter requires changing. The system is capable of handling wet or dry material. The cost of the system is higher than other wet-dry HEPA systems available commercially, but the capacity and power greatly surpasses most other available systems. The cost of the typical Vaculoader system ranges from $10,625 to $13,625 (Willcott, 1989).

Air-driven HEPA-vacuums are nonelectric units powered by compressed air. They utilize Venturi powerheads and thus have no moving parts. These units can also be adapted to fit 55-gal drums. Air compressors of 15-20 hp are needed to supply power to the vacuum. These systems are capable of using 1- to 2-in. suction hoses. Each system can only accommodate one hose. Static lift (in inches of water) for typical systems range from 18 to 250 in. The capability of these systems is much less than the VACTAGON system. The average cost is also considerably less, about $3,000 (PRO, 1989). These smaller units would be useful if placed at some location below the cutting area where gravity will aid in the transport of heavy material. Tornado "TOX VACS", Pro Controls Products, and Hako Minuteman are among the more reasonably priced comparable models.

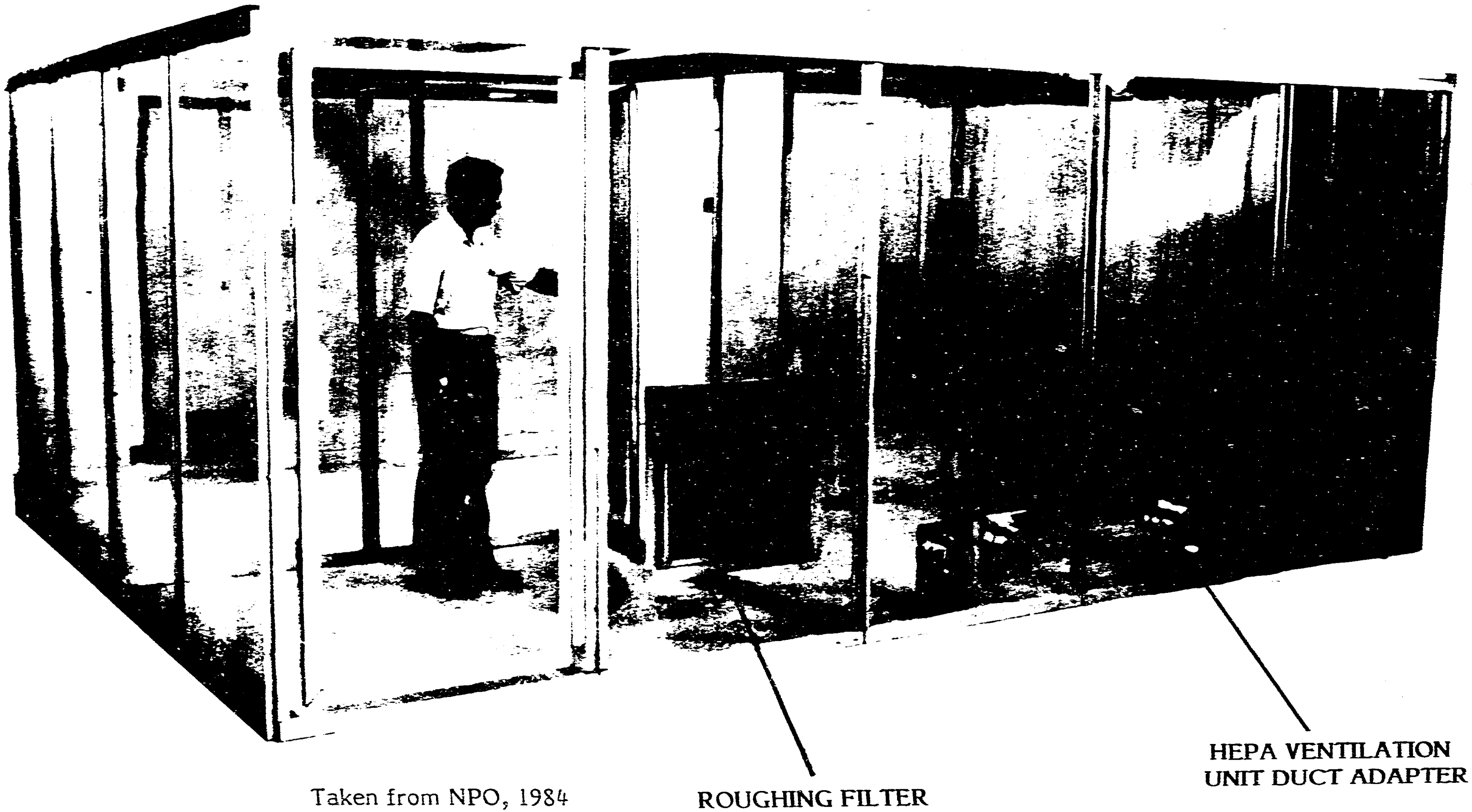
3.16.3 Liquid Waste Filtration

Cutting methods that utilize water or oils require a mechanism for filtering the liquid to remove contaminants. In wet cutting, a slurry consisting of liquid metal shavings can be generated. The slurry is channeled to a separator in which the heavy particulate matter sinks and drops to another container for dewatering. The liquid can be pumped to a sump or designated holding tank after proper filtration. The dewatered material can be stabilized and disposed as radioactive waste.

A unit capable of processing up to 20 gal/min of slurry costs $25,000-$35,000 (McCauley, 1989). This does not reflect the cost of holding tanks or recovery systems for contaminated materials. The cost of a unit capable of processing greater flow rates increases substantially as flow rate increases. Most waste-filtration services, such as Hydro-Nuclear (McCauley, 1989) or Chem-Nuclear, will perform the service on the site, either on a time and material basis or a cost per cubic foot basis. This cost would be predicated on a number of factors, such as volume, curie content, cask-handling fees, and other special handling fees.

Table 3.16.1 Portable HEPA Ventilation Unit Cost

Standard 3-hp, 1000 ft^3/min HEPA unit	\$ 6,300
Moisture separator	\$ 500
1.5-hp, 15-amp, Single-phase motor	\$ 300
Total	\$ 7,100



Taken from NPO, 1984

Fig. 3.16.1 NPO (Lexan) Rigid Modular Contamination Control Enclosure
(Taken from NPO, 1984)

4.0 COST COMPARISONS AND RECOMMENDATIONS

In addition to reviewing various metal cutting techniques, as discussed in Section 3.0 of this report, ANL sent out a request for quotes for two different tasks: (1) furnish ANL with a machine or system capable of cutting up the EBWR pressure vessel, or (2) perform the task of cutting up the EBWR pressure vessel.

In either case the cost of the equipment was to be provided as a fixed-price quote. For option B, the labor cost could be quoted on a cost-plus-fixed-fee basis.

Six responses were obtained for each option. Because of the way in which the requests for quotes was worded, the vendors had the option of quoting on the entire system or just certain components. For example, a vendor providing a quote on an arc-saw system might also include a closed-circuit television system and a contamination-control system, or he could simply state in his proposal that these other systems were required.

Proposals were received for four different types of systems: (1) plasma-arc systems, (2) arc-saw systems, (3) oxyacetylene systems, and (4) abrasive water jet systems.

To compare these quotes on an equal basis, a table was developed for use in calculating the total cost to ANL for each proposal. The table included costs for the following items:

1. Cutting system and manipulator,
2. Cost of jacking the vessel if required,
3. Containment and HEPA system,
4. Closed circuit television system,
5. Material handling equipment,
6. Expendables,
7. Contamination control,
8. Grit and/or water cleanup (if required),
9. ANL crew, and
10. Surplus value of equipment.

The first thing that became apparent when the table was complete was that the total cost to the Laboratory would be 25%-40% higher if an outside firm was hired to do the cutting. This is probably due to the fact that some management and health physics functions would be duplicated if an outside vendor was used. The table also showed that the most costly approach was plasma-arc cutting. The next lowest method was the arc-saw technique, at about 90% of the cost of the plasma system. The least expensive approaches were abrasive water-jet cutting and oxyacetylene at 50% and 40% of the cost of a plasma approach, respectively. Both the oxyacetylene approach and the abrasive water-jet approach proposed required that the vessel be jacked up and the cutting be done from the main floor proceeding from the outside inward.

The oxyacetylene system was the least expensive and would require very little worker training; however, it did present a fire hazard. While the abrasive water-jet system was slightly more expensive, it did not present a fire hazard and could also be used to scabble concrete. Thus, a large amount of savings would result from not having to purchase separate equipment for cleaning concrete.

While abrasive water jet cutting does not generate much airborne contamination, it does produce a contaminated slurry of water and grit. The water and grit would have to be separated for disposal. Argonne has a facility capable of handling the contaminated water that would be produced.

If for some reason the abrasive water-jet approach does not work as predicted on the first cut, it would be relatively easy and inexpensive to switch to oxyacetylene cutting. The only problems with the latter system would be controlling the airborne contamination and the fire hazards. After considering all of the options, it was decided that abrasive water-jet cutting was the most appropriate method for sectioning the EBWR reactor vessel.

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6.0 VENDOR CONTACTS

The following is a list of vendors who were contacted for information used in this report. It is not claimed to be a complete list of companies working in the various areas nor is it intended to imply any recommendation for those vendors.

1. Plasma-Arc

PCI ENERGY SERVICES
1 Energy Drive
P.O. Box 3000
Lake Bluff, IL 60544
(708) 680-8100
Contact: Mike McGough

L-TEC
308 Harper Drive
Morristown, NJ 08057
(609) 722-1802
CONTACT: Michael Bushwack

BABCOCK AND WILCOX
Nuclear Power Division
P.O. Box 10935
Lynchburg, VA 24506-0935
(804) 385-3138

HOBART TORCH
435 Eisenhower Lane So.
Lombard, IL 60448
(708) 495-8530
Contact: Phil Hensley

HYPERTHERM
Etna Rd.
P.O. Box A-10
Hanover, NH 03755
(603) 643-3441
Contact: M. Ginzel

2. Arc-Saw

BABCOCK AND WILCOX
Nuclear Power Division
P.O. Box 10935
Lynchburg, VA 24506-0935

RETECH
100 Henry Station Road
P.O. Box 997
Ukiah, CA 954882
(707) 462-6522
Contact: Leroy Leland

3. Oxyacetylene

L-TEC
308 Harper Drive
Morristown, NJ 08057
(609) 722-1802
Contact: Michael Bushwack

PCI ENERGY SERVICES
1 Energy Drive
P.O. Box 3000
Lake Bluff, IL 60044
(708) 680-8100
Contact: Mike McGough

4. Thermite Reaction Lance

AMERICAN OXYLANCE
1600 3rd Street West
Birmingham, Alabama 35204
(205) 322-9906
Contact: Dale DeRieux

BURNING BAR SALES CO.
6010 Yolanda Avenue
Tarzana, CA 91356
(213) 881-1082

ARCAIR CO.
P.O. Box 406
Route 33 North
Lancaster, OH 43130
(614) 653-5618
Contact: Jeff Henderson

THERMOLANCE CO., Inc.
26 Dino Drive
Ballston Lake, NY 12019
(518) 899-2433

5. Powder Cutting

BABCOCK AND WILCOX
Nuclear Power Division
P.O. Box 10935
Lynchburg, VA 24506-0935
(804) 385-3138

L-TEC
308 Harper Drive
Morristown, NJ 08057
(609) 722-1802
Contact: Michael Bushwack

6. Plasma/Oxyacetylene

BABCOCK AND WILCOX
Nuclear Power Division
P.O. Box 10935
Lynchburg, VA 24506-0935
(804) 385-3138

L-TEC
308 Harper Drive
Morristown, NJ 08057
(609) 722-1802
Contact: Michael Bushwack

7. Laser Cutting

BABCOCK AND WILCOX
Nuclear Power Division
P.O. Box 10935
Lynchburg, VA 24506-0935
(804) 385-3138

CE LASERS, INC.
name changed to:
TRUMPF INDUSTRIAL LASERS
32 Cobble Hill Road
Sumerville, MA 02143
(617) 497-6025
Contact: Cheryl Newton

UNITED TECHNOLOGIES INDUSTRIAL LASERS
400 Main Street 129-53
East Hartford, CT 06108-8450
(203) 727-7092
Contact: Clyde Brown

8. Mechanical Milling

BABCOCK AND WILCOX
Nuclear Power Division
P.O. Box 10935
Lynchburg, VA 24506-0935
(804) 385-3138

E. H. WACHS
100 Shepard Street
P.O. Box A
Wheeling, IL 60090

(708) 537-8800
Contact: Charles Wachs

MACTECH, INC.
1007 Tile Drive
P.O. Box 11
Red Wing, MN 55066
(612) 388-7117
Contact: Jim Keaney

9. Water Jet Cutting

BABCOCK AND WILCOX
Nuclear Power Division
P.O. Box 10935
Lynchburg, VA 24506-0935
(804) 385-3138

INGERSOLL RAND
635 W. 12th Street
Baxter Springs, KS 66713
(316) 856-2151

FLOW INTERNATIONAL
21440 68th Avenue South
Kent, Washington
(206) 872-4900
Contact: Mark Fleck

10. Diamond Wire Cutting

BABCOCK AND WILCOX
Nuclear Power Division
P.O. Box 10935
Lynchburg, VA 24506-0935
(804) 385-3138

DIAMANT BORAT
U.S. HWY 1 North
P.O. Box 1317
Columbia, SC 29202
Contact: Richard Knight

TRENTEC
7851 Palace Drive
Cincinnati, OH 45249
(513) 489-8002
Contact: Robert Carson

LASER TECHNOLOGY INC.
10624 Ventura Boulevard
North Hollywood, CA 91604
(213) 877-8270
Contact: Howard McLaughlin

TRU-CO
P.O. Box 1317
Columbia, SC 29202
(800) 845-1312
Contact: D. Tuttle

DIAMANT BORAT
15955 T. W. Hardy
Houston, TX 77060-3151
(713) 999-4530
Contact: Richard Knight

11. Controlled Explosive Cutting

JET RESEARCH CENTER, INC.
P.O. Box 246
Arlington, TX 76010
(817) 483-0933

BABCOCK AND WILCOX
Nuclear Power Division
P.O. Box 10935
Lynchburg, VA 24506-0935
(804) 385-3138

EXPLOSIVE TECHNOLOGY
P.O. Box KK, Dept. TR
Fairfield, CA 94533-0659
(707) 422-1880
Contact: R. Richards

12. Remote Manipulation and Handling

CINCINNATI MILACRON
Industrial Robot Division
Greenwood, SC 29648
(803) 227-6000

BABCOCK AND WILCOX
Nuclear Power Division
P.O. Box 10935
Lynchburg, VA 24506-0935
(804) 385-3138

CIMCORP, INC.
899 W. Highway 96
Shoreview, MN 55126
(612) 484-7261
Contact: Tom Fuantz

13. <u>Electronic Discharge Machining</u>

BABCOCK AND WILCOX
Nuclear Power Division
P.O. Box 10935
Lynchburg, VA 24506-0935
(804) 385-3138

PCI ENERGY SERVICES
1 Energy Drive
P.O. Box 3000
Lake Bluff, IL 60044
(708) 680-8100
Contact: Mike McGough

EASCO SPARCATRON
P.O. Box 469
Brighton, MI 48116
(312) 227-7102
Contact: Dan Rigan

ELTEE PULSITRON
26 Fairfield Place
West Caldwell, NJ 07006
(201) 575-8816

ELOX DIVISION COLT INDUSTRIES
P.O. Box 2227
Davidson, NC 28036
(704) 892-8011

HYNES MACHINE TOOL INC.
1259 Kings Highway
Fairfield, CT 06430
(203) 336-3277
Contact: B. Hynes

POCO GRAPHITE
1601 S. State St.
Decatur, TX 76234
(817) 627-2121
Contact: L. Waites

14. <u>Electric-Arc Gouging/Flame Cutting</u>

ARCAIR CO.
P.O. Box 406
Route 33 North
Lancaster, OH 43130
(614) 653-5618
Contact: Jeff Henderson

15. Abrasive Cutting

NEW ENGLAND DIAMOND
P.O. Box 585
Worcester, MA 01613
(508) 798-8546
Contact: B. Bollander

HERMES MACHINE TOOL CO., INC.
3 Gardner Road
Fairfield, NJ 07006
(201) 227-9150
Contact: Gary Roberson

END

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