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June 1981

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute

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PNL-3660

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
Under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

Price: Printed Copy $_______*; Microfiche $3.00

*Pages	NTIS Selling Price
001-025	$4.00
026-050	$4.50
051-075	$5.25
076-100	$6.00
101-125	$6.50
126-150	$7.25
151-175	$8.00
176-200	$9.00
201-225	$9.25
226-250	$9.50
251-275	$10.75
276-300	$11.00

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Richland, Washington 99352

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SUMMARY

Explosive cutting techniques using linear-shaped charges are being evaluated at Pacific Northwest Laboratory (PNL) for use in decontamination, repair, or decommissioning operations involving nuclear facilities. This work is part of the United States Department of Energy project, "Decontamination and Decommissioning of Hanford Facilities-Technology." The study discussed in this report was a cost/benefit analysis to determine: 1) whether explosive cutting is cost effective in comparison with alternative metal sectioning methods and 2) whether explosive cutting would reduce radiation exposure or provide other benefits.

As a literature search and a telephone survey produced little actual cost data on cutting during decontamination or decommissioning of nuclear facilities, cost and radiation exposure comparisons of various sectioning methods could not be based on existing information. Instead, two separate approaches were pursued. The first was to qualitatively assess cutting methods and factors involved in typical sectioning cases and then compare the results for the cutting methods. The second was to prepare estimates of work schedules and potential radiation exposures for candidate sectioning methods for two hypothetical, but typical, sectioning tasks.

An analysis of the information acquired by using the two approaches shows that explosive cutting would be cost effective and would also reduce radiation exposure when used for typical nuclear facility sectioning tasks. These results indicate that explosive cutting should be one of the principal cutting methods considered whenever steel or similar metal structures or equipment in a nuclear facility are to be sectioned for repair or decommissioning. Because of the potential utility of explosive cutting, its continued development for this purpose is recommended.

The lack of comparative cost or radiation exposure data for nuclear facility sectioning operations shows the need for a program to gather, evaluate, and disseminate actual sectioning operations data. More complete information could provide a base to aid in minimizing future industry costs and reducing radiation exposure in concert with ALARA principles.

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ACKNOWLEDGMENTS

The study discussed in this report was sponsored by the U.S. Department of Energy as part of the project, "Decontamination and Decommissioning of Hanford Facilities-Technology." The authors thank J. M. Usher of the Department of Energy Surplus Facilities Management Program Office for his encouragement in this study.

The authors also gratefully acknowledge the information and assistance provided by the following individuals: S. H. Woodcock and M. Maes of Detonics Corporation, Seattle, Washington; J. L. Scott and G. K. Goethal of Olympic Associates Co., Richland, Washington; A. W. Graves and D. C. Shoemaker of Rockwell Hanford Operations; J. F. Nemec of United Nuclear Corporation, Richland, Washington; and L. K. Fetrow, V. F. Fitzpatrick, G. A. Halseth, and M. W. McCoy of Pacific Northwest Laboratory (PNL).

INTRODUCTION

Shaped explosive charges have been used for many years by both the military and industry to perforate or cut metal. Examples of uses are: separating burned out rocket motors from space craft; severing and ejecting a pilot's compartment from a failed-in-flight military aircraft; and dismantling offshore drilling rigs. Shaped charges are also used for controlled demolition of large, obsolete buildings. Explosive cutting using linear-shaped charges is one of the methods being investigated at Pacific Northwest Laboratory (PNL) as a sectioning tool for decontamination, repair, or decommissioning operations involving nuclear facilities.

As part of the Department of Energy's "Decontamination and Decommissioning of Hanford Facilities-Technology" project, PNL has evaluated explosive cutting in comparison with other alternatives. The purpose of the study was to evaluate:

- whether explosive cutting is cost effective in comparison with other available metal sectioning methods
- whether explosive cutting would also reduce radiation exposure and provide other benefits.

Explosive cutting and other cutting methods can be compared best by using actual cost and operation data insofar as possible. Therefore, to form a basis for comparison, we sought both published and unpublished information on overall sectioning operations cost data, cutting rates of the various methods, and operational elements. While cutting rates were available, no usable overall sectioning operations cost data were found. Consequently, two alternative approaches were taken for the evaluations. The first approach was a qualitative comparison and assessment of several factors involved for thirteen sectioning methods for five generic tasks; the second was the comparison of estimated work schedules and potential radiation for two typical, but hypothetical, sectioning cases using the various cutting methods.

The objective of this study was not to precisely prescribe all equipment, steps, and costs of a sectioning method for a cutting job; rather, it was to give an overview of apparent advantages or disadvantages of explosive cutting relative to other sectioning methods. The purpose of this overview was to determine whether explosive cutting offers potential benefits to warrant its further development for use in nuclear facilities.

This report describes the development of the study and the results of the evaluation, including: 1) how information was acquired, 2) sectioning cases and operation elements, 3) comparison and assessment of sectioning methods, 4) estimated schedules and radiation exposure for cutting operations, and 5) a field demonstration (which was also videotaped) showing the merits of explosive cutting of stainless steel pipe and plate, the two cutting cases evaluated in this study. In addition, the appendixes contain brief descriptions of the sectioning methods compared, a tabulation of the advantages and disadvantages of the methods, and detailed estimated schedule data for the two hypothetical sectioning cases.

Cutting of stainless steel equipment is generally evaluated throughout this report. However, the study results are not limited to stainless steel; the evaluations are also applicable for carbon steels and other metals having similar physical and metallurgical properties.

CONCLUSIONS AND RECOMMENDATIONS

This study to determine the benefits of explosive cutting for nuclear facility applications produced several conclusions and recommendations:

1. Explosive cutting is a practical method for sectioning stainless steel, carbon steel, or other similar metal piping and other apparatus, especially in limited access areas and for sectioning equipment or materials having complex geometries. The successful use of linear-shaped charges for nuclear decommissioning has been demonstrated at the DOE Hanford Site by PNL engineers. A five-minute videotape, "Linear-Shaped Charges for Nuclear Decommissioning Applications," PNL-SA-9024, is available for viewing.

2. Explosive cutting is cost competitive and should be considered among the alternatives when nuclear facility cutting tasks are to be undertaken. Principal results of a qualitative comparison assessment of cutting methods show that explosive cutting has broad applicability, cuts rapidly, has relatively low cost, produces few maintenance or repair problems, minimizes radiation exposure, generates little contaminated waste, and requires easily portable equipment when used in a nuclear facility.

3. Use of explosive cutting will give reduced radiation exposure for applications such as those of cutting closely spaced, nuclear facility process piping or a portion of flat floor plate in a fuel basin. Time schedule estimates for these two hypothetical cases indicate that explosive cutting would reduce radiation exposure and cut operations time and manpower by about one-third, when compared with other methods that could be used for the sectioning cases.

4. The study results show that continued development of explosive cutting for optimization is clearly warranted for its eventual use in nuclear facilities. This continued development is recommended.

5. Little actual overall cost and radiation exposure data for cutting in a nuclear facility have been collected or published in sufficient

detail to allow precise cost and radiation exposure comparisons. A program to collect, evaluate, and disseminate this information to the nuclear industry is recommended. Availability of the information may aid the industry in minimizing its sectioning costs and meeting occupational exposure requirements consistent with ALARA principles.

INFORMATION FOR COMPARING SECTIONING METHODS

To determine if explosive cutting is beneficial in terms of cost, efficiency, and safety, it must be compared with other cutting methods in common sectioning operations. Preferably, the comparisons should incorporate data obtained for actual events, such as decommissioning of a nuclear facility. Accordingly, for this study, we sought both published and unpublished information for costs, sectioning methods, cutting rates, process steps, and supporting operation elements.

COSTS AND CUTTING RATES

The first step was a computerized literature search in which combinations of key words were used to ascertain the availability of published cost data for cutting carbon and stainless steels in a nuclear facility. The key words were: decommissioning, decontamination, steels, cutting, cost, and nuclear facilities. No comparative overall cost information was found in any of the abstracts printed by the computer or other computer referenced literature. However, a decommissioning handbook prepared for DOE (Manion and LaGuardia 1980) provided many applicable equipment costs, typical cutting rates, and other information used throughout this report.

To find unpublished information, we surveyed industries involved in decommissioning. Several individuals from Rockwell International (Canoga Park, California and Hanford Site operations) and UNC Nuclear Industries (Richland, Washington) were queried on sectioning costs for decommissioning of the Sodium Reactor Experiment (SRE) at Canoga Park and the nuclear reactor at Elk River, Minnesota. Unfortunately, the costs for sectioning were not segregated from other costs.

Sectioning methods selected for comparison with explosive cutting were:

- Arc saw
- Plasma arc torch
- Air arc gouger
- Oxygen burner (oxy-fuel)
- Thermite reaction lance
- High-power carbon dioxide laser
- Hydraulic (guillotine) shear
- Miller cutter
- Nibbler
- Abrasive saw
- Reciprocating saw
- Portable band saw

These sectioning methods are described briefly in Appendix A. Reported rates typical for cutting stainless steel pipe or plate for most of these methods are shown in Table 1.

Because little overall cost data were available, the estimations and evaluations of costs and other factors are qualitative rather than quantitative. The qualitative estimates, the cutting rates, the two hypothetical cases, and the process steps form the basis for the comparisons.

TABLE 1. Reported Cutting Rates[a] of Stainless Steel Plate and Pipe by Several Sectioning Methods

Sectioning Method	Pipe, 2-in. Diameter, Sch. 40, per cut	Plate, 1/8 to 1/4-in. Thick
Explosive cutting	Almost instantaneous	Almost instantaneous, ea. cut
Arc saw	--	90 ft/min for 1/4-in. plate (270 in.^{2}/min)
Plasma arc torch	--	48-75 in./min
Air arc gouger	--	12 in./min
Oxygen burner	2 min	20-26 in./min
Carbon dioxide laser	--	200 in./min for 1/4-in. plate
Hydraulic shear	20 sec	--
Nibbler	--	24 in./min
Abrasive saw	10 min	3 to 6 in./min
Reciprocating saw	2 min	6 in./min
Portable band saw	10 min	--

(a) Cutting rates are based upon data developed by D. C. Shoemaker of Rockwell Hanford Operations or L. K. Fetrow of PNL or from the handbook by Manion and LaGuardia 1980.

HYPOTHETICAL SECTIONING CASES

The two hypothetical cases represented typical problems that can occur in a nuclear facility; one in which a moderately complex arrangement of equipment is involved, the other in which a comparatively simple flat surface is to be cut. The two cases are illustrated in Figure 1, a process pipe trench containing a large number of pipes, and in Figure 2, a nuclear fuel basin having a stainless steel floor fastened onto concrete.

The pipe trench was assumed to contain forty-eight 2-in. diameter, Schedule 40 pipes, about equally distributed on a three-tier pipe rack. The pipe trench was about 12 ft deep and 8 ft wide. A 30-ft length was to be removed from each pipe.

The nuclear fuel basin was assumed to be 15 ft wide, 40 ft long, and 20 ft deep. The fuel basin floor was 1/4-in. thick, 304 stainless steel plate with the plate welded to metal anchors imbedded in the concrete. The section of plate to be removed from the center of the basin floor was 16 in. wide and 40 ft long. Four-foot lengths would be cut for ease of removal of the metal from the basin floor. The work would be planned so that cutting at an anchor position and anchor removal would be avoided.

The radiation field for both cases was assumed to be a maximum of 0.6 rem/h at deck level. The nuclear facility radiation dose limits for a worker were assumed to be 0.6 rem/day, 2.4 rem/quarter. These limits were based upon average administrative limits for contractor or inspection personnel for nuclear reactor facilities (Pelletier and Voilleque 1979, Sec. A.4). The process steps for a sectioning operation, the number of setup and cutting crews involved, and the extent of crew training are influenced by the radiation dose limits, the sectioning method selected, and the remote handling equipment requirements.

SECTIONING OPERATION ELEMENTS

The major job process steps and other operational elements, listed below, are nearly identical for the two hypothetical sectioning cases and for other sectioning cases involving limited access, thick metals, or complex material geometries. The list covers individual tasks or requirements from the initial

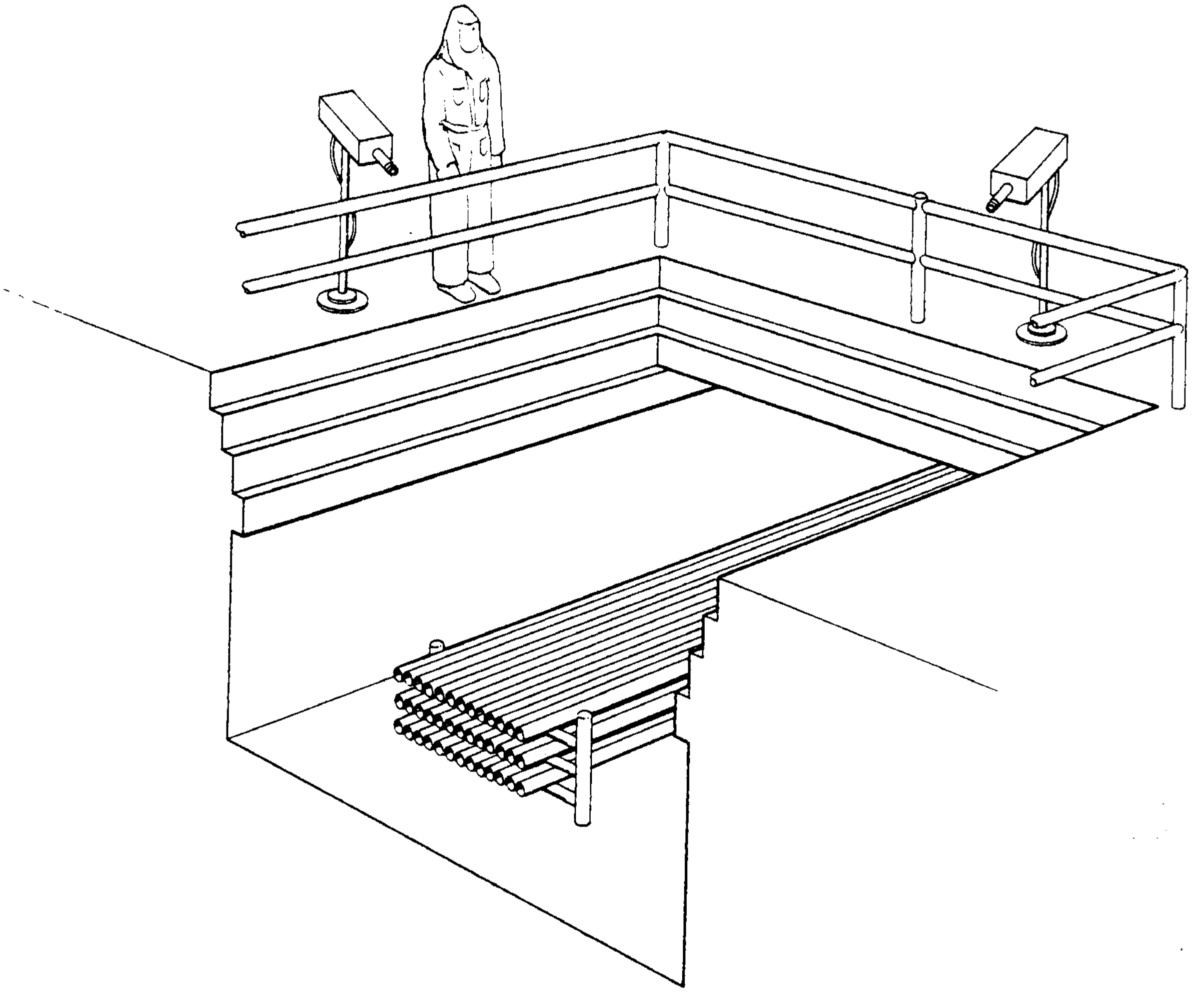

FIGURE 1. Process Pipe Trench with Piping to be Sectioned

planning of a job through disposal of cut materials and other job debris. These factors were used as aids in making the qualitative comparison and assessment of the sectioning methods and in developing the estimates of time schedules and personnel radiation exposures for the two hypothetical cutting cases. The process steps are an extension of activities of assumed schedules for typical, critical path, radiation zone tasks in a nuclear facility during repairs to a nuclear power plant (Pelletier and Voilleque 1979). Except for equipment dismantling and removal of equipment steps, which are similar to equipment setup steps, the process steps are generally concurrent or sequential.

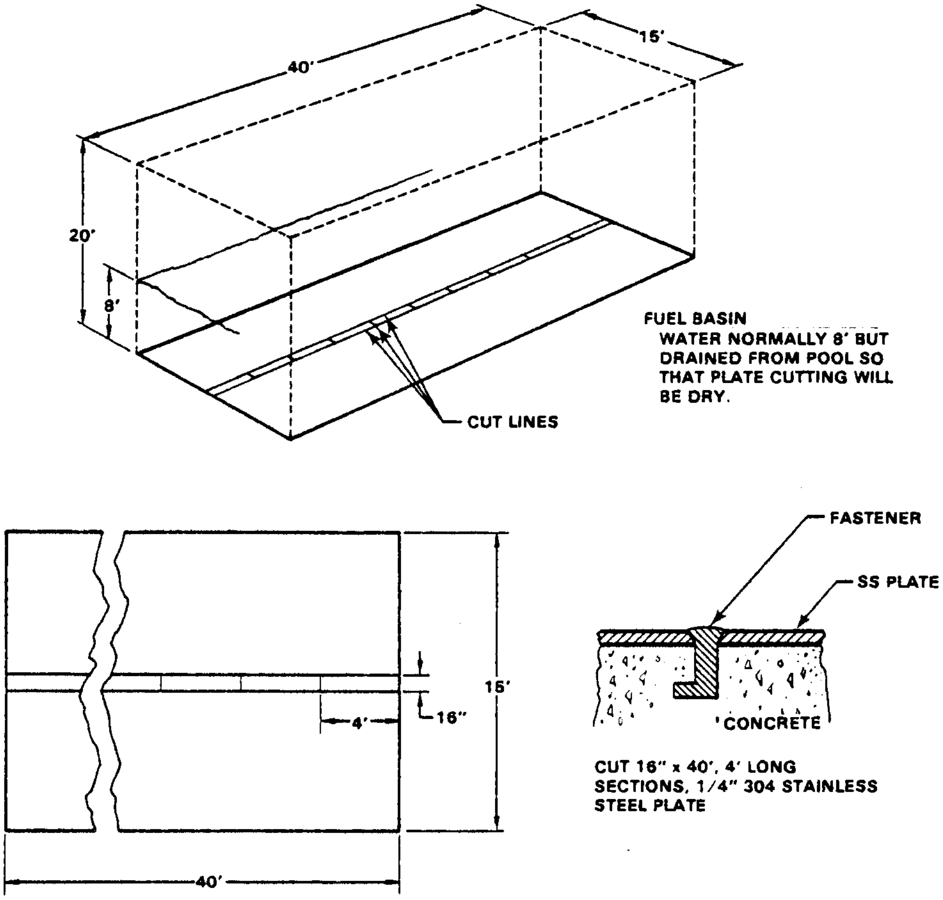

FIGURE 2. Nuclear Fuel Basin with Floor Plate to be Sectioned

Major Process Steps

- planning and engineering
- certification of personnel: medical, security, skill
- initial orientation and training of personnel (possible mockup training)
- equipment setup or dismantling outside of radiation zone
- briefings (including entry permits)
- dressing in radiation zone work clothing and proceeding to access areas
- entry into radiation zone

- job orientation within radiation zone
- equipment setup, repositioning, or dismantling and removal within radiation zone
- work on job (sectioning)
- exit from radiation zone
- leaving access area, removing radiation zone work clothing, cleaning up
- work inspection
- removing or shifting interferring cut material
- disposal of cut material and other debris.

Other Operational Elements

- project management
- sectioning equipment
- HEPA filtration, liquid removal and disposal
- safety, health physics including bioassays
- maintenance, miscellaneous tools and supplies
- clothing and laundry
- utilities (electricity, water, etc)
- communications
- materials (gases, explosives, saw blades, etc.)
- decontamination or disposal of radiation-exposed cutting equipment.

COMPARISON AND ASSESSMENT OF SECTIONING METHODS

For the qualitative comparison and assessment of the sectioning methods, the process steps and cost elements were joined with other factors involved in sectioning in a nuclear facility in Table 2. Table 2 gives an assessment of the advantages and disadvantages based on a ranking scheme that was devised from the qualitative information gathered in this study and the literature (Manion and LaGuardia 1980). Appendix B gives more explicit details on the advantages and disadvantages of various sectioning methods.

The legend of Table 2 gives symbols ranging in the amount of black area used; the more black area contained by a ranking symbol, the more favorable a cutting method is for a sectioning factor. Comparisons are meaningful only within rows, not columns, of the table since factors involved in sectioning were not compared with each other. Some of the sectioning methods are practical for certain sectioning cases whereas others are not or are of limited use. Also, a method that is suitable for one case may be inapplicable for another.

Comparative terms, such as high, moderate, and low, are used for costs, maintenance and repair, radiation dose potential, and other factors. Specific equipment size, for example, that of remote handling equipment, and cost are not quantifiable without a detailed job description, definitive plans, and engineering designs, which were not included in this study. These details for actual, completed jobs should be obtained in a much more extensive study. Because of the lack of data, the qualitative technique was used.

Applicability of a sectioning method for a cutting task was judged on whether the normal function or the principle of the method could be used or had the potential to perform the cutting task. For instance, a hydraulic shear can be used to cut the closely spaced pipe as a pipe could be gripped adequately for the shearing action. On the other hand, the shear could not be used for cutting flat steel plate fastened on concrete because the bottom of the shear could not be placed underneath the plate.

The complexity of a sectioning method would directly affect the costs of a cutting operation. More work planning and engineering may be required to

TABLE 2. Qualitative Assessment of Factors Involved in Sectioning Stainless Steel Materials

	SECTIONING METHOD												
FACTORS INVOLVED IN SECTIONING	EXPLOSIVE CUTTING	ARC SAW	PLASMA ARC TORCH	AIR ARC GOUGER	OXYGEN BURNER (FLAME + FLUX)	THERMITE REACTION LANCE	CARBON DIOXIDE LASER	HYDRAULIC SHEAR	MILLING CUTTER	NIBBLER	ABRASIVE SAW	RECIPROCATING SAW	PORTABLE BAND SAW
METHOD APPLICABILITY													
CLOSELY SPACE PIPE	●	●	○	○	◒	●	●	●	◒	○	◒	●	●
FLAT PLATE ON CONCRETE	●	●	◒	●	◒	●	●	○	●	○	●	◒	○
LIMITED ACCESS AREAS	●	○	◒	◒	◒	○	◒	◒	◒	◒	◒	◒	◒
THICK METALS	◒	●	◒	○	◒	●	○	○	◒	○	◒	◒	◒
COMPLEX GEOMETRY	●	●	●	◒	●	●	●	◒	◒	○	◒	◒	◒
CUTTING SPEEDS	■	⬓	⬓	⊟	⊟	⊟	⬓	⬓	□	□	□	□	□
COST-LABOR, EQUIPMENT & MATERIALS													
PLANNING-ENGINEERING	⬓	⊟	■	■	■	■	□	⬓	⊟	⊟	⊟	⊟	⊟
CERTIFICATION-MEDICAL, SECURITY, SKILL	■	⊟	⬓	⬓	⬓	⬓	⊟	⬓	⬓	⬓	⬓	⬓	⬓
MOCKUP TRAINING	■	⬓	⬓	⬓	⬓	⬓	⊟	⬓	⊟	⬓	⬓	⬓	⬓
PRE-PREPARATION AT SITE	⊟	⊟	⬓	■	■	⬓	⊟	⬓	⬓	⬓	⬓	⬓	⬓
REMOTE HANDLING EQUIPMENT	■	⊟	⬓	⬓	⬓	⬓	⊟	⬓	⬓	⬓	⬓	⬓	⬓
SETUP OPERATION	■	□	⬓	⬓	⬓	⬓	⊟	⊟	⊟	⬓	⊟	⬓	⬓
CUTTING OPERATION	■	⬓	■	■	■	⬓	⬓	■	⊟	⊟	⊟	⊟	⊟
CUTTING MATERIALS	⊟	⬓	⬓	■	■	⬓	⬓	⬓	⬓	⬓	⬓	⬓	⬓
CUTTING EQUIPMENT	■	□	⬓	■	■	■	□	⊟	■	■	■	■	■
ENERGY	■	□	⊟	⬓	⬓	■	□	⊟	⬓	⬓	⬓	⬓	⬓
MAINTENANCE & REPAIR													
PROBLEM POTENTIAL	■	⊟	⬓	■	■	■	⊟	■	⊟	⊟	⊟	⊟	⊟
COST	■	⊟	⬓	■	■	■	□	■	⊟	⊟	⊟	⬓	⬓
RADIATION DOSE POTENTIAL													
SETUP	●	○	●	●	●	●	○	◒	◒	◒	◒	◒	◒
SECTIONING	●	●	●	●	●	●	●	●	◒	◒	◒	◒	◒
MAINTENANCE	●	●	●	●	●	●	●	●	◒	◒	○	○	○
CONTAMINATED MATERIALS GENERATION													
GASES	◒	◒	○	○	○	○	◒	●	⊖	●	◒	◒	◒
SOLIDS	◒	◒	⊖	⊖	⊖	○	◒	◒	◒	◒	⊖	◒	◒
LIQUIDS	●	◒	●	●	●	●	●	●	○	●	○	○	○
PORTABILITY	●	○	◒	◒	◒	●	○	◒	●	●	●	●	●

LEGEND

APPLICABILITY
- ● APPLICABLE
- ◒ LIMITED APPLICABILITY
- ○ NOT APPLICABLE

CUTTING SPEED
- ■ INSTANTANEOUS
- ⬓ HIGH
- ⊟ MODERATE
- □ SLOW

COST; LABOR, MAINTENANCE, ETC.
- ■ LOW
- ⬓ MODERATE
- ⊟ HIGH
- □ VERY HIGH

RADIATION DOSE POTENTIAL
- ● LOW
- ◒ MODERATE
- ○ HIGH

CONTAMINATED MATERIALS GENERATION
- ● NOT APPLICABLE
- ◒ LOW
- ⊖ MODERATE
- ○ HIGH

PORTABILITY
- ● GOOD
- ◒ FAIR
- ○ POOR

select, and perhaps design, support equipment and prepare operating procedures. More workers may be needed to set up cutting equipment and remote handlers if equipment is heavy and setup time is long. It is assumed for this assessment that all this equipment would be brought to the job site by the contractor. If more workers are used, certification costs could increase for health physics, including whole body counts before and after a job, security indoctrination, and verification of skills.

Mockup training costs would also increase with more workers; mockup training to familiarize workers with the specific tasks could be worthwhile to increase the efficiency of the workers while they are in the radiation area. The costs of prepreparation at the site and the setup operation are also dependent upon equipment complexity and size. If heavy remote handling equipment is used, as would be required for an arc saw, setup time and costs could be relatively long. If remote handlers are small and relatively simple, such as those that would be used for placement of shaped explosive charges, setup time and costs would be comparatively low. The purchase cost or use fee of cutting and remote handling equipment allocated to the job would also tend to be greater for larger, more complex equipment and for equipment especially fabricated for the job. Ideally, frequently used equipment would be provided to keep equipment costs low.

Rotating or oscillating cutting equipment, such as conventional saws, will be more prone to have problems requiring maintenance and repair than nonrotating equipment. Saws will wear and could bind in the metal being cut and have to be extracted.

Radiation dose potential is dependent upon the time workers are in a radiation area. If equipment is heavy and complex, more worker time in the area would be required. If workers must continuously be close to the cutting position rather than being able to periodically move away, their exposure would be greater. If time-consuming maintenance is needed, additional nonproductive radiation dose would be received.

Contaminated materials generation is a function of the sectioning method. Gases and liquids are used for burning, cooling, lubrication, and molten material removal. Solids are generated as smoke with torch processes or as cutting debris, the amount dependent upon the precision of a cut.

The rankings in Table 2 are based upon a qualitative assessment of the above factors. More detail for the individual sectioning methods and cases are given in the following discussion on the two cutting cases.

SECTIONING OF PIPE IN PIPE TRENCH

Some, but not all, of the thirteen sectioning methods in their present or development form are applicable for cutting process pipe in a pipe trench.

Sawing Methods

The pipe can be sectioned with a circular abrasive saw, a reciprocating saw, or a portable band saw, but cutting would be relatively slow. Each pipe cut would have to be supported near the cut point to prevent binding of the saw in the cut. If a cutter binds, the tool may break or have to be retrieved from the pipe trench either by brute force using the remote handler, or by having an individual dressed in radiation zone work clothing go into the trench to release the cutting blade. Radiation dose would occur with no productivity during a maintenance or repair period, but radiation dose would be especially high if a trench entrance was required. The trench entrance may well be unsafe and infeasible.

The reaction forces of mechanical sawing tools cause the use of rigid or heavy duty remote handlers. The rental costs of these handlers would be greater than those required for comparable weight, high-temperature operating apparatus, such as the plasma arc or oxygen torch. The setup time for the remote handling and cutting system would probably be longer, also.

Maintenance and repair would have to be performed often to replace worn or broken blades. Coolants or lubricating liquids would extend the life of a cutting blade, but pose another problem: handling and disposing of contaminated liquid waste.

The slow cutting speeds, longer equipment setup times, and possible maintenance problems can increase the number or size of crews required to complete the job. More personnel would have to be certified and trained for the job, raising the costs of labor and mockup facilities.

Thermite Reaction Lance

A thermite reaction lance is essentially a 1/4-in. to 1-in. straight piece of pipe, about 10 ft in length, equipped with a hand valve and filled with steel, magnesium, and aluminum wires through which oxygen can be supplied for combustion. Thermite lances can be used to cut holes in or sever heavy steel and cast-iron sections or a variety of metals and materials otherwise not easily cut. Lance cutting is a rough cutting method used more for construction work and demolition than for production. Since thermite lances can cut any metal, they can be used to cut the closely spaced pipe.

Most of the costs will be at a low or moderate level. The moderate cutting speed may cause a larger number of personnel to be used and require more certification and mockup training than for faster cutting methods. If lances could be adapted to remote handlers, which may not be feasible, relatively light handlers would be used since little weight and reaction forces are involved. Operators using lances must be dressed in fireproof clothing. Auxiliary equipment rental (depending on the complexity of a remote handler) and expendable material cost would be moderate to low; for instance, lances and a lance holder cost $7.00 and $50.00, respectively (Manion and La Guardia 1980).

Radiation dose potential should be low when compared with milling and sawing methods which would require a long setup period, would have slow cutting speeds, and could require repairs. Lance cutting does generate much gas and smoke which would probably obscure the view of the cutting and severely affect efficiency.

Carbon Dioxide Laser

Laser beam cutting uses a single frequency, highly collimated, high energy light beam which is focused onto a metal workpiece. Energy is transferred and raises the temperature of the metal to its melting point. Molten metal is blown from the cut zone with an inert gas. Lasers can cut metals 1/4 to

1/2 in. thick at relatively fast cutting speeds (200 in./min for 1/4-in. stainless steel) and possibly could be used to cut the closely spaced pipe.

Present-day, high-power, carbon dioxide lasers are large and used in a fixed position. If a high-power laser could be made portable, large remote handling equipment would have to be used. A setup operation for the laser and its support equipment would necessarily take a substantial amount of time, which would result in comparatively high radiation exposure of workers in the radiation field.

High-power carbon dioxide lasers are expensive; Manion and La Guardia report that a 12 kW stationary device costs about $600,000. The use or rental fee for an equivalent portable laser, consequently, would be high compared to these costs for other cutting equipment. Much more development is needed before the laser is a practical tool for cutting metal in the field.

Oxygen Burner (Oxy-Fuel)

The oxygen burner (oxy-fuel) method could be used for closely-spaced pipe cutting. The burner has a comparatively moderate cutting speed. Cutting stainless steel with an oxygen burner is difficult, and a chemical or iron powder flux must be used to prevent formation of refractory chromium oxides. (Flux is not needed for carbon steel.) Equipment is portable and can be easily handled remotely. Having minimal reaction forces, the burner would require relatively light remote handling equipment. Setup time could be rapid, as no rugged supports would have to be erected. Because the cutting process is not complex, only a small crew would be needed. A minimum of skill or mockup training would be necessary. Maintenance would be low, if flow of flux is preserved, and would be primarily for replenishment of flux and burning gases. The potential radiation dose would be low because of the moderate cutting speed, minimum setup time, and little maintenance needs, especially at or near the job position. Much smoke and airborne solids are generated, which must be collected primarily by HEPA filtration.

Arc Saw

The arc saw is a high amperage (about 3000 A dc), low voltage (40 V) device with a toothless, circular saw blade that cuts by means of an arc melting the metal workpiece. Molten metal is removed from the kerf by the rotating blade. The arc saw can cut closely spaced pipe very rapidly; in fact, it has been used in a stationary position to cut up tubed heat exchangers. Portable equipment is reportedly being developed; however, even a portable system would be large and require complex and expensive remote handling equipment. The arc saw itself is expensive, over $100,000 (Manion and LaGuardia 1980), giving high rental costs. A complex handling system would require several setup crews if much of the work is performed in a high radiation environment. Labor costs for mockup training and setup could be comparatively high because of the workers' relative inexperience with use of the arc saw and the arc saw's size. Once a cutting operation is under way, maintenance cost should be low since only the blade should wear. The arc saw would produce some gases and solids as the blade is water cooled and cuts through the pipe. Unlike the plasma arc or air arc gouger, no supplemental gas is supplied. The major drawbacks for using an arc saw are its present lack of portability, the need for a complex remote handling system, and the high radiation dose that would probably be received during a relatively long setup period. Furthermore, all piping to be cut must be accessible, which most likely would not be the case.

Hydraulic Shearing

Hydraulic shearing may be one of the more practical cutting methods for cutting the closely spaced pipe of the hypothetical case. Access to a group of pipes on a pipe rack should pose no problem. With heavy duty shear equipment, a 2-in. Schedule 40 pipe can be cut in less than 30 sec. A relatively robust remote handler, compared to those of torches, would have to be provided. If a robust handler were not available at a nuclear facility, one could be expensive to design and purchase. With new equipment, setup time could be long, and the setup would require a number of crews to work sequentially in the radiation environment. Certification and mockup training of the crews would have a moderate cost because the equipment would not be as sophisticated as in the arc saw method. Energy cost would probably be high compared with that of most of the other methods due to the force required to cut pipe quickly. However, the cost of energy would be only a minor portion of the total operational cost. Hydraulic shearing would produce essentially no contaminated material waste in excess of that already present in or on the pipes, unless a hydraulic line were to break and discharge its fluid into the pipe trench.

Explosive Cutting

Explosive cutting is applicable for closely spaced pipe. The linear-shaped explosive charges usually consist of a tubular housing having one side formed into an inverted "V" or cavity, which is placed toward the item to be cut. The tube is filled with explosive.

Lightweight remote handlers can be devised and used for charge placement. Explosive charges, designed especially for the pipe, could be snapped quickly into place by operators. The operators would withdraw behind protective barriers away from the radiation zone before each, almost instantaneous, controlled explosive cut. The protective barriers would minimize the radiation dose, which would probably be considerably less than that for hydraulic shearing, where operators constantly must be in the radiation area with the equipment. The remote handlers and explosive charges would be prepared outside the job area, thus no radiation dose would be involved. Due to the small amount of time required at the job position and the resultant low radiation dose, the number of crews and persons involved would be small, although they would be highly skilled in explosives handling.

Use of explosives would require essentially no maintenance, and the number of individuals involved may be comparatively less. Design, materials, and the use of particularly skilled personnel would have a high daily individual cost rate. Alternatively, technicians skilled in areas other than handling explosives can put charges in place following preliminary training. Depending upon the amount of explosive and the casing material, the cost of explosives can be from $4 to $20/ft of linear charge (Manion and LaGuardia 1980). Detonics Corporation (Seattle, Washington) personnel, who provided explosive cutting background for this study, stated that a linear-shaped charge having a lead casing and containing 100 grains of explosive per ft would cost $12 to $15/ft (1979 dollars). Although the materials and labor costs may be high for explosive cutting, the time to complete a job could be considerably less than that of any other method examined, resulting in a lower overall cost. In addition, the facility from which the pipe would be cut could be returned to use at a much earlier date. This is perhaps the greatest advantage of explosive cutting.

Some gases and solid debris would be generated by controlled explosive cutting, but these materials are less or on par with those generated by most of the other methods considered. About 4 liters of gas are produced by each 2-in. pipe shaped charge. Firing of controlled explosive charges does not scatter contaminated material, although preventive measures are taken to avoid this possibility. Shaped charges are designed to contain all metal fragments and can be designed to contain their own explosion products and release gases at a controlled rate. If only selected pipes dispersed through the array of pipes on the pipe rack are to be cut, explosive cutting would be especially advantageous and perhaps the only usable method.

Inapplicable Sectioning Methods

Inapplicable methods include cutting by the plasma arc, air arc gouger, milling cutter, and nibbler. The cutter heads of these tools need to encircle a piece of pipe to cut it. Encirclement is prevented when pipes are closely spaced. Although other means may be devised to use each of these tools for this pipe cutting job, these cutting methods appear impracticable.

SECTIONING OF FLAT FLOOR PLATE IN DRAINED FUEL BASIN

A different set of sectioning methods are applicable for sectioning the flat floor plate than for sectioning process piping.

Abrasive Saw

The circular abrasive saw would be much more effective for this cutting case than for the closely spaced pipe case. The saw would be restricted from cutting close to basin walls, but this is true for any device having a large cutting head. Cutting rates would be comparatively slow. The remote handler would have to be capable of positioning the saw to provide correct rotation for both the lengthwise and crosscuts of the flat stainless steel plate. The handler must be sufficiently robust to resist forces reactive to the cutting. Due to the time required for setup and cutting, and the limited individual radiation dose, extra crews or personnel would be needed and the resultant total radiation dose would be high compared to that acquired when using faster cutting methods, such as explosive cutting, or relatively lighter remote handling equipment, such as that for the oxygen burner. Cutting fluids or liquid coolants may be required and after use have to be disposed of as radioactively contaminated liquids. Maintenance or replacement of dull saw blades may be frequent, even with use of cutting fluids.

Milling Cutter

Although a usable method, milling presents problems similar to that of circular abrasive sawing. Cutting speed is slow; a moderately, sturdy, remote handler is needed; maintenance to replace dulled tools would be frequent; liquid lubricants would have to be used and discarded as being radioactively contaminated; total personnel radiation dose would be high compared to faster cutting methods.

Carbon Dioxide Laser

A proven, portable laser cutting system could be applicable as cutting speeds are fast, but to date this method appears too expensive and portability is questionable (Manion and LaGuardia 1980).

Torch Cutting Methods

Torch cutting methods such as plasma arc, oxy fuel, air arc gouging, or thermite reaction lance could be used, but each method has its limitations in cutting stainless steel on concrete. A plasma arc cuts stainless steel rapidly; rates of 48 to 75 in./min for cutting up to 1/4-in. thick plate are obtained when the metal is separate from other materials. High rates are also reported for cutting of thick metal; for example, a rate of about 8 in./min for 3-in. thick material has been achieved. The equipment is portable and the torch can be operated readily with relatively light remote handling equipment. Consequently, costs for operating and setup crews and equipment should be moderate.

There are potential problems of cutting stainless steel on concrete with use of the plasma torch. Bounce back of molten metal which adheres to the plasma arc nozzle could short the nozzle. Time-consuming repairs of the radioactively contaminated tool may be required. The double arcing may limit the application of the plasma torch. If this problem were nonexistent, potential radiation dose would be relatively low. When cutting with the plasma arc, smoke and showers of sparks occur. The contaminated gases would have to be HEPA filtered and the solids cleaned up. The high temperatures and heat produced with the plasma arc, or with any other high-temperature burning method, may overheat the concrete underflooring along the cut line causing pressure buildup within the concrete and eventually shattering it.

An oxygen burner (oxy-fuel) system has potential use, as it does with pipe. Essentially the same advantages and disadvantages prevail. Use of an iron powder or chemical flux is needed to inhibit or prevent refractory chromium oxide formation, which would otherwise retard or stop the cutting.

The air arc gouger would be a comparatively slow torch cutting method; its rate for cutting 1/4-in. thick stainless steel is about 12 in./min. The torch is relatively light and compact; thus the remote handling equipment would not be large or expensive. The source of compressed air and a power supply would be placed away from the job position, as would support equipment for the other torch methods. The process requires carbon electrodes which have to be replaced intermittently during a large amount of cutting. Because the process melts rather than oxidizes stainless steel, there is no chromium oxide problem.

The thermite reaction lance, although capable of cutting stainless steel plate, poses the same problems as with pipe cutting. Much smoke would be produced; personnel have to wear both fire and radiation zone work clothing. Because workers' vision would be obscured, cutting control appears questionable, especially for long, straight runs of cutting.

Arc Saw

The cutting principles of the arc saw offer a few advantages for cutting the stainless steel plate in the fuel basin. The method is fast and the cut would be accurate. Molten oxidized metal would be ejected from the cut. The underlying concrete floor would probably be undamaged or be damaged less severely than by using other high temperature methods. There would be no contact between the rotating blade and the metal being cut.

An arc saw that is sufficiently portable has not been developed such that the saw rather than the work pieces would be moved continually. The equipment is large and heavy, requiring a sturdy, remote handling system. The size makes cuts adjacent to walls impossible. Setup of a remote handling system may be more complex than that required for pipe cutting, since the cutter has to be rotated from the position for the lengthwise cuts to a perpendicular position for the cross cuts. Setup of the complex system probably would be lengthy producing comparatively high personnel radiation dose. Water spray cooling is required for the cutting blade. This water must be processed either as a vapor or as a condensate as it may carry contaminants. Smoke produced would be collected by the HEPA filtration system. Energy requirements may be high since high voltages and amperages are required for the arc saw operation. Although the principles of this technique appear to offer future promise, much development is needed before the arc saw can be used for the cutting situations described herein.

Explosive Cutting

From the qualitative comparison (see Table 2), explosive cutting appears to be the most applicable of the cutting methods considered for cutting the fuel basin stainless steel floor. Advantages are shown in the cutting rates, remote handling equipment, setup, personnel radiation dose potential, personnel mockup training due to use of less personnel, maintenance problems, and contaminated material generation and handling.

Each cut of the stainless steel plate would be made instantaneously. However, the complete job would be performed with a series of small, controlled detonations to avoid excessive pressure and gas generation. The slight pressure and gas generated would be contained. Although the cumulative amount of gas and solids produced would be about the same as that with a single cut for the entire job, the HEPA filtration system and other support facilities would not be overtaxed.

The remote handling system would be light and probably be carried by the explosives operating crew. Also, the remote handling system would be much simpler and less expensive than the complex systems required for the other methods. Other than laying charge-offsetting material, the charge itself, fastening material and a blasting mat, and stringing firing leads, little setup would be performed within the nuclear facility at or near the cutting operation position. Much of the preparation work would be in a nonradioactive environment. The operators would withdraw after each placement, fire a charge, and then return to place the next charge. Radiation dose should be comparatively small.

Because explosives can be harmful if improperly handled, only highly skilled, explosives technicians probably would be employed. While the labor cost rate could be high, the minimal mockup training required by using fewer personnel for the specific cutting task, the quickness of job completion, and the comparatively low radiation dose should easily overcome this labor expense. Materials would be expensive ($4.00 to $20.00/ft) because they would have to be designed and manufactured specifically for the cutting job. Maintenance costs should be minimal, even if a misfire were to occur.

Shaped charge devices have a built-in fragment-catch and shock attenuation shield and can be designed to release explosion product gases at a controlled rate. However, a water spray might be used as a supplemental measure to knock down or prevent dust dispersion after a detonation. If water were used, it would have to be condensed, coalesced, collected, and removed before impacting on a HEPA filter to prevent plugging.

Inapplicable Sectioning Methods

Of the methods discussed in this report, those that appear to be inapplicable or having limited applicability for cutting the flat stainless steel plate on concrete are the hydraulic shear, nibbler, reciprocating saw and the portable band saw. Each of these methods requires that a part of the cutting tool be under or below the material to be cut. This accessibility is prevented by the concrete underflooring.

OTHER SECTIONING TASKS

Explosive cutting probably would be the most practical method for sectioning stainless steel, carbon steel, or other metal piping and other apparatus located in limited access areas, such as in corners near large equipment or between narrowly separated walls and vessels. Tools such as saws, milling cutters, hydraulic shears, and the arc saw may be too large. A small hydraulic shear might be used depending on the accessibility and toughness of the item to be cut.

Plasma arc or other torches may be useful but may require manual handling, which could result in high radiation doses compared to that received on placement of an explosive charge. The explosive could be snapped or otherwise quickly fastened in place before firing. Explosive charges can be shaped to conform to most complex geometries of equipment or materials. Only the required cuts need be made for removal or repair of a unit.

Explosive cutting is probably not applicable for sectioning metals over 6 in. thick in a radiation environment, such as reactor walls, because of the amount of explosive needed and the pressures and dispersion of materials that could occur. However, it is not inconceivable that a procedure for use of the method could be devised.

ESTIMATED SCHEDULES AND RADIATION EXPOSURE FOR CUTTING OPERATIONS

Schedule estimates for the two hypothetical cases for cutting pipe and plate, shown in Figures 1 and 2, were prepared by Olympic Associates Co. of Richland, Washington. For comparison with explosive cutting, Olympic chose the methods for evaluation thought most feasible for a job: oxygen burner, thermite lance, reciprocating saw, and shear for cutting pipe; plasma arc torch, oxygen burner, and air arc gouger for cutting plate.

The Olympic work provides an evaluation of these cutting methods independent from the preceding qualitative evaluation. The approaches used in the two evaluations differ somewhat; thus, the results were not expected to be identical in all details. For practicality, Olympic restricted the number of possible variables; Olympic, for example, assumed a fixed crew size of five. No crew size was set in the qualitative assessment since it is thought that crew size would vary with the cutting method used. The schedule estimates were made to determine whether this approach would lead to conclusions different from those of the qualitative assessment.

As a basis for the schedules, Olympic used explosive cutting data provided by Detonics Corporation. A number of assumptions were used in developing the schedules. These are listed below:

- Preliminary work and cutting operations would be performed by a contractor having personnel specially trained for decommissioning type activities. This contractor would furnish all equipment including remote handling systems and other support equipment.
- All personnel, including three cutting crews, would be supplied by the contractor.
- No overhead crane or other internal equipment would be provided in the radiation work area. All needed equipment must be brought in.
- Cut pipe sections would be removed from the pipe trench by contractor crews. Removal of pipe of each tier permits access to the tier below.

- All cut plate sections would be removed by the facility operator.
- Cutting tools would not become contaminated by operations; thus, no decontamination would be required and is excluded from the schedule.
- No maintenance or repair of dulled, broken, or malfunctioning tools would be needed.
- A crew consists of five persons: two operators at the work position within the 0.6 or 0.12 rem/h radiation field, one operator outside for support, one supervisor, and one radiation monitor. During explosive cutting, one of the crew would always be stationed at the end of the firing line.
- A crew-change involves replacing the entire crew.
- The administrative control daily dose limit for all contractor personnel is set at 0.6 rem per day per individual. This administrative control limit is based upon a paper by Pelletier and Voilleque (1979). With the radiation field at 0.6 rem/h, each crew member would be in the radiation area 1 h per day; the time would be 5 h per day with a 0.12 rem/h field. (Note: If an individual were to work in the 0.6 rem/h radiation field for 5 h, he would have received his quarterly radiation dose limit of 3 rem as set forth by the Code of Federal Regulations, Title 10, Part 20, commonly referred to as 10 CFR-20.)
- All cutting methods would have been developed for nuclear facility operations at time of use so that personnel could do the cutting operations at deck level.
- In explosive cutting of pipe, every other pipe on a tier would be cut sequentially with about a 1/4 sec delay between firings.
- A special support for cut pipe would be provided for each cutting method to allow orderly retrieval.
- Explosive cutting of pipe in the trench would use circular cutters designed to rapidly snap around a pipe and be placed using specially designed but simple robotics or manipulating devices. The charges

have a built-in frag-catch and shock attenuation shield. The plate cutters use a single, prefabricated, field-assembled rectangular charge which is similarly remotely emplaced.

- Specific shear cutting apparatus would be a shear punch or die and cavity type punch which punches out a small section of pipe. The apparatus would be suspended above the pipe by a specially designed system, such as a jib crane, which can advance across the pipe tiers.
- The air arc gouger and plasma arc remote handling systems would be similar, employing a rail or a like guidance system for equipment to track on.
- The oxygen burner remote handling system, which is less complex than that of the air arc gouger or plasma arc, would consist primarily of a manipulator extension arm.
- The reciprocating saw system requires a specially fabricated table having tracking capability to hold the saw for work in the pipe trench. A crane would be required to manipulate the saw.

PIPE CUTTING ANALYSIS

The analysis assumed that forty-eight, 2-in. diameter, Schedule 40 stainless steel pipe would be arranged in a pipe trench in three racks or tiers of sixteen closely spaced pipe. Each rack would be cut in three places or positions. The pipe racks would be mounted on the floor, with available space in the pipe trench to work. In all cases, outside vendors would be contracted for the work and mockup training would be conducted prior to the actual cutting.

For the duration matrix comparison (Table C.1), mockup training and equipment setup would also be accomplished before the crews begin cutting the pipe. Of the applicable methods considered, oxygen burn, thermite reaction lance, reciprocating saw, and shear cutting had cutting times of 2 min per 2-in. pipe with similar crews. Of these four methods, the shear cutting method was considered most feasible.

Shear cutting crimps the pipe end and reduces the potential spread of contamination from the pipe. Other methods, including explosive cutting, generate smoke and dust which could be controlled by a protective filtered tent and possibly water fog spray. The shear cutting method for pipe is the most applicable to a remote handling device using an overhead crane and closed circuit TV, if a permanently installed crane were available. The torch cutting methods were not readily adaptable to remote devices for closely spaced pipe.

The duration matrix assumes five workers per crew, including a radiation monitor. The repositioning of the equipment was held as a constant, which is possible because the mechanical cutting devices may be handled on mounting devices and moved to the different positions with the protective tent attached. The schedules shown are extremely optimistic with no down time for broken blades and other malfunctions. The final qualifier is that the shear mechanism is quite heavy, and, if not held in place by an overhead crane, a support device must be fabricated.

The limitation of the shear cutting method is the pipe diameter. As the size of the pipe increases, the explosive cutting technique becomes more feasible. There is no pipe size limitation with the explosive cutting method. The other methods become limited by blade size and maneuverability which add to the time of the cut per pipe. The pipe cutting results were due to dimension and similarity of the pipe considered. Two other cutting methods were applicable but not considered due to the slow cutting rate: abrasive saw, requiring 10 min/2-in. pipe, and portable band saw, with the same relative time.

Details of the time schedules for cutting the stainless steel pipe in the pipe trench are given in Table C.1 and Figures C.1 and C.3. Some of the details from the duration matrix table are summarized in Table 3 for comparison.

The data in Table 3 show that the total estimated time and manhours and the time and manhours for work in the radiation area are less for explosive cutting than for the other cutting alternatives. The slight variance in manhours for activities between the two radiation fields for a cutting method

TABLE 3. Work Times and Radiation Exposures for Cutting Pipe in a Nuclear Process Pipe Trench

	Explosive Cutting		Oxygen Burner		Thermite Reaction Lance		Reciprocating Saw		Shear Cutting	
	Radiation Field, rem/h									
	0.6	0.12	0.6	0.12	0.6	0.12	0.6	0.12	0.6	0.12
Worktime and Manhours										
Cutting Operations, Total Time, Hours	10	8	12	10	12	10	13	10	13	11
Cutting Operations, Total Manhours	48	38	71	45	72	45	64	50	64	51
Radiation Data										
Work in Radiation Area, Hours	6	6	8	8	8	8	9	8	9	9
Work in Radiation Area, Manhours	13	12	20	18	20	18	21	19	22	20
Radiation Exposure, Manrem	8	1	12	2	12	2	13	2	13	2

is primarily due to crew replacements. The estimated radiation exposures acquired during explosive cutting are also less than that obtained during cutting by any of the other methods. This comparison indicates that explosive cutting is a viable option for a pipe cutting situation similar to that posed herein.

PLATE CUTTING ANALYSIS

The assumptions for the plate cutting included cutting 1/4-in. steel plate on concrete on the bottom of a steel-lined basin that was dry and unobstructed. Ten plates, 4 ft x 16 in., would be cut from the middle of the basin (a 40-ft x 16-in. area). Two cuts adjacent to the vertical wall would be required. The same background radiation was considered as in the pipe cutting analysis. Again, outside vendors would be contracted for the work. There also would be mockup training and equipment setup prior to the crew entry for cutting. The sectioning methods evaluated for this case were plasma arc, oxygen burner, and air arc gouger, along with explosive cutting. The one applicable method not considered was the abrasive saw which had a slow cutting rate of 4 in./min.

The analysis showed that of the three applicable torch cutting methods, each could be handled on a carriage type mechanical handler and re-positioned relatively easily. Each torch method required a filtered contamination containment which could be incorporated on the handler. Therefore, the results of the comparison are related to the cutting time of the method considered. An easily movable, filtered contamination containment or canopy hood would also be used for explosive cutting. The crew size was the same in all cases and the most optimistic conditions were considered.

Details of the time schedules for cutting flat steel plate in the drained fuel basin are given in Table C.2 and Figure C.2 and C.3 of the Appendix. Table 4 summarizes key data from the duration matrix table for comparison. Similar to the data for pipe cutting, the estimated data given in the table show that the time and manhours for work within the radiation area, and thus radiation exposure, are less for explosive cutting than for the other cutting alternatives. The total time and manhours is also less except for that of the

TABLE 4. Work Times and Radiation Exposures for Cutting Floor Plates in a Drained Nuclear Fuel Basin

	Explosive Cutting		Plasma Arc Torch		Oxygen Burner		Air Arc Gouger	
	Radiation Field, Rem/h							
	0.6	0.12	0.6	0.12	0.6	0.12	0.6	0.12
Work Time and Manhours								
Cutting Operations, Total Time, Hours	9	8	11	8	6	5	12	9
Cutting Operations, Total Manhours	45	39	65	37	36(a)	25(a)	72	45
Radiation Data								
Work in Radiation Area, Hours	3	3	8	8	4	4	9	9
Work in Radiation Area, Manhours	8	8	24	24	9	9	26	26
Radiation Exposure, Manrem	5	1	14	3	5	1	16	3

(a) This assumes that the oxygen burner cutting using iron powder or chemical flux is a steady, uninterrupted operation. In actual practice this ideal is not normally encountered, as the use of the flux with the oxygen burner is a difficult procedure.

oxygen burner. The oxygen burner method, when a chemical or iron flux is used, is prone to stainless steel cutting difficulties which would probably increase cutting times and radiation exposure with its use. This comparison also indicates that explosive cutting should be considered whenever a cutting situation, such as that of cutting the flooring plate in a fuel basin, arises.

EXPLOSIVE CUTTING FIELD DEMONSTRATION

The merits of explosive cutting discussed in the preceding sections have been further substantiated by a demonstration of linear-shaped charges held at the DOE Hanford Site by PNL engineers. This demonstration was videotaped by PNL and a five-minute videotape was produced entitled, "Linear-Shaped Charges for Nuclear Decommissioning Applications." This videotape, PNL-SA-9024, is now available for viewing. It points out that linear-shaped charges have been used in the aerospace industry for 25 to 30 years, and have been demonstrated as safe and highly reliable energy storage systems used for emergency egress of aircraft crew.

Several types of explosive cuts were made demonstrating the cutting of 2-in. Schedule 40 stainless steel pipe, and a 10-in. diameter circle cut in 1/4-in. stainless steel plate. There was also an attempt to cut steel plate backed by concrete, a common situation found in reactor fuel pools. In this demonstration, a 10-in. diameter hole cutter was placed on 1/4-in. stainless steel plate backed by 6 in. of concrete. A rubber attenuation mat was placed over the charge to prevent debris from flying. This particular cutting demonstration was not a total success because the shape charged did not have the proper standoff. A second attempt to cut the plate was successful after the shaped charge was put in place with the proper standoff distance. Two other cuts were detonated in plastic (greenhouse) tents to demonstrate that only a small quantity of combustion product (gas) is generated from explosive cutting charge and that shrapnel, if produced, can be controlled by using rubber attenuation mats.

This demonstration was observed by 44 managers and engineers from the U.S. Department of Energy, Surplus Facilities Management Program Office; UNC Nuclear Industries, Office of Surplus Facilities Management; Rockwell-Hanford Operations; Westinghouse Hanford Company; and PNL. There were many positive comments made about the use of explosive cutting as related to nuclear decommissioning; many individuals, for the first time, realized that explosives could be used and controlled very easily.

"Linear-Shaped Charges for Nuclear Decommissioning Applications" has been shown to about 150 technical people at four separate meetings and various informal groups throughout the United States. Comments from attendees are very positive, and many individuals feel that work in the explosive cutting area should continue.

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Manion,. W. J. and T. S. LaGuardia. 1980. Decommissioning Handbook. Prepared for the U.S. Department of Energy by Nuclear Energy Services, Inc., Danbury, Connecticut.

Pelletier, C. A. and P. G. Voilleque. 1979. Potential Benefits of Reducing Occupational Radiation Exposure. AIF/NESP-010R Revised. Prepared for Atomic Industrial Forum, Inc., Washington, D.C. by the National Environmental Studies Division of Science Applications Inc., Danbury, Connecticut.

APPENDIX A

DESCRIPTIONS OF SELECTED SECTIONING METHODS

APPENDIX A

DESCRIPTIONS OF SELECTED SECTIONING METHODS

Of the many ways to cut metal, the methods that may be considered for sectioning materials in a nuclear facility are:

- Explosive cutting
- Arc saw
- Plasma arc torch
- Air arc gouger
- Oxygen burner (oxy-fuel)
- Carbon dioxide laser
- Shear
- Milling cutter

No descriptions are given for conventional sawing methods, which are well known, or for nibbling, which in its simplest terms is a punch and die cutting tool for cutting light gauge metal stock.

EXPLOSIVE CUTTING WITH SHAPED CHARGES

Shaped charges have been used extensively for over two decades to explosively perforate or cut metal. Originally developed as a means for destroying military armored equipment, shaped charges have been developed and adapted for many other uses. Examples of uses are separating burned out rocket motors in space programs, severing a pilot's compartment from a failed aircraft, perforating oil well casings, dismantling offshore oil drilling rigs, and controlled demolition of large obsolete buildings.

The term "shaped charge" is used to describe explosives with unlined or lined cavities formed in them. Shaped charges usually consist of a tubular housing, one side forming an inverted "V" or cavity. A cross section of a typical linear, chevron-shaped charge is shown in Figure A.1. The casing made of aluminum, zinc, or copper, is filled with explosives such as RDX (cyclotrimethylenetrinitramine). The charge size for the two hypothetical cutting situations would be about 100 grains/ft. The charges are equipped with detonators that would be fired electrically from a remote position.

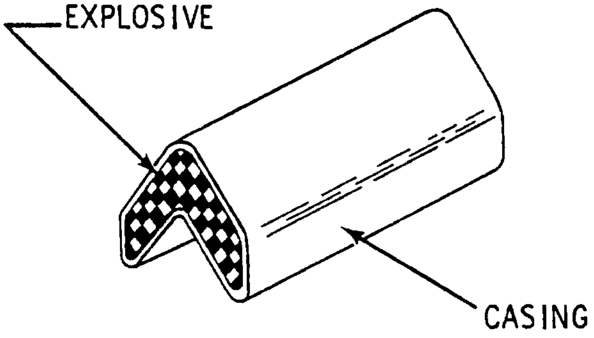

FIGURE A.1. Section of Linear-Shaped Explosive Charge

When the shaped charge having the inverted "V" or cavity is fired in contact with a material that can undergo plastic deformation, such as steel, iron, etc., the approximate mirror image of the cavity is produced. The shaped or cavity charges produce very high pressures on the chevron-shaped metal liners. The metal reacts to the pressure in the range of 4×10^6 psi as would a perfect fluid because the strength of the metal even below its melting point is negligible at this pressure. The velocity of the shaped charge jet varies from about 30,000 fps at the tip to about 3,000 fps at the tail. The tail is followed by a slowly moving slug made up of the remainder of the liner. The jet, not the slug, does the penetrating.

Various factors affect the performance of a shaped charge. The liner material and configuration of the shaped charge must be optimized to the type of target and target material. The explosive must be of a certain type and it must be loaded to a certain density to achieve maximum, controlled penetration. The standoff distance between the target and the shaped charge must be optimized for each type of target to allow the jet to obtain maximum velocity.

The above description is based upon information provided by Detonics Corporation, Penthouse, Seattle Tower, 3rd & University, Seattle, Washington 98101 and upon the following report:

Kaser, J. D. and J. O. Vining. 1972. Size Reduction of Large Contaminated Process Equipment Using Explosive Shaped Charges. BNWL-B-192, Pacific Northwest Laboratory, Richland, Washington.

ARC SAW CUTTING

The arc saw, developed by Retech, Inc. of Ukiah, California, is a device basically comprised of a rotating, circular, toothless metal blade, a direct current power supply, and controls to feed the blade into the workpiece. Rapid cutting action is derived from a direct current arc between the blade and the metal workpiece. The arc melts the portion of the work in the saw kerf and the rotating blade sweeps out the melt. No physical contact occurs between the saw and the work.

Arc saws can have a variety of configurations, but essentially an arc saw is a large piece of equipment having blades 6 to 36 in. in diameter. The power supply is also large. A schematic of a stationary arc saw located at PNL is shown in Figure A.2. This arc saw is equipped with a 3000-A dc power supply having a load voltage of 40 V dc. The blade, which rotates at about 1000 rpm, is nominally 30 in. in diameter. Cutting is performed in a cooled water bath.

Costs for an arc saw system range between \$110,000 and \$254,000 (Manion and LaGuardia 1980), depending on the nominal blade size. Much of the cost is for the power supply.

Reference: Allison, G. S. 1980. Prototype Arc Saw Design and Cutting Trials. PNL-3446, Pacific Northwest Laboratory, Richland, Washington.

PLASMA ARC

A plasma arc torch provides an extremely high temperature (20,000 to 50,000°F), high velocity plasma capable of rapidly melting a narrow kerf in a workpiece and flushing away the molten metal. This cutting method uses a tungsten electrode centered in a gas- or water-cooled nozzle as the source for an electric arc. Argon or another gas is injected into the torch and flows past the electrode through the nozzle directly to the cutting point. The arc between the torch nozzle and the workpiece heats the gas to a sufficiently high temperature so that it is partially ionized, or turned into a plasma.

Figure A.3 is a schematic of a typical plasma cutting torch. Required equipment includes the torch, cylinders of argon or other cutting gas, a direct current power supply capable of about 1000 A with a voltage of 250V, and controls. A mechanical travel system can also be provided.

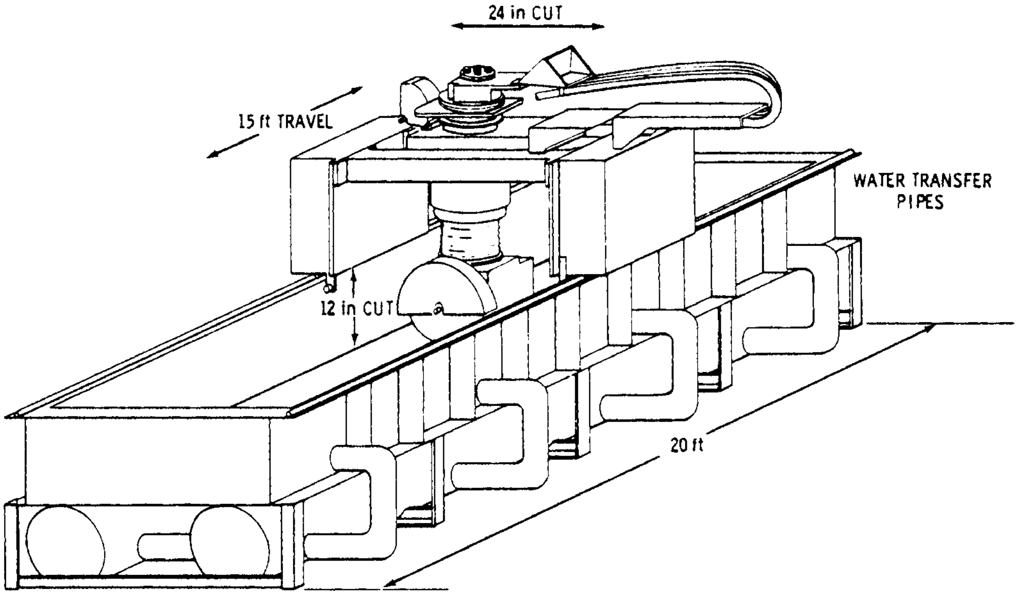

FIGURE A.2. PNL Arc Saw

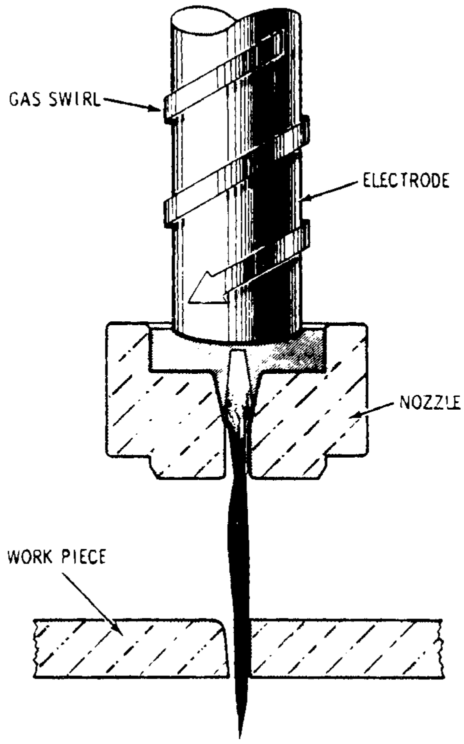

FIGURE A.3. Dry Plasma Arc Torch

Although systems can have a number of configurations and capabilities, one capable of cutting 3-in. stainless steel would cost about $15,000 (Manion and LaGuardia 1980).

Reference: Lyman, T., ed. 1967. Machining. Vol. 3 of Metal Handbook. 8th ed. American Society of Metals, Metals Park, Ohio.

AIR ARC GOUGING

Air arc gouging is a metal cutting process that uses an electric arc from an electrode to intensely heat and melt a kerf through a grounded metal workpiece. Basically, the equipment includes carbon-graphite electrodes, a torch with an air passage and jets, an air compressor, electric cables, air hoses, and a power supply. Electric current flows from the power supply through leads, the torch, and arcs from the electrodes to the workpiece. Air provided by the air compressor blows away molten metal as it is formed by the arc. Because air arc gouging melts rather than oxidizes metal, it is equally effective on ferrous, nonferrous, and alloy metals. An air arc gouging system including a cutting machine and a track for controlled straight line cutting is shown in Figure A.4.

Reference: Linde Air Arc Gouging Equipment. 1978. Linde Gases & Welding Products Bulletin NWSA 360, Linde Division, Union Carbide Corporation, New York.

OXYGEN BURNER

A typical oxygen burner system using an iron or other chemical powder flux for cutting refractory oxide-forming metals is shown in Figure A.5. Initially, a metal such as stainless steel is heated with a torch supplied with an industrial fuel gas (propylene, for example) and oxygen. Rapid cutting begins upon injection of the flux by compressed air through the torch into the cut zone along with a stream of oxygen. The ignition of the flux raises the flame temperature above that of the combustion of fuel gas. Chromium or other oxides, which would form a heat insulating layer upon the metal to be cut, are melted and blown out of the kerf along with the molten base metal.

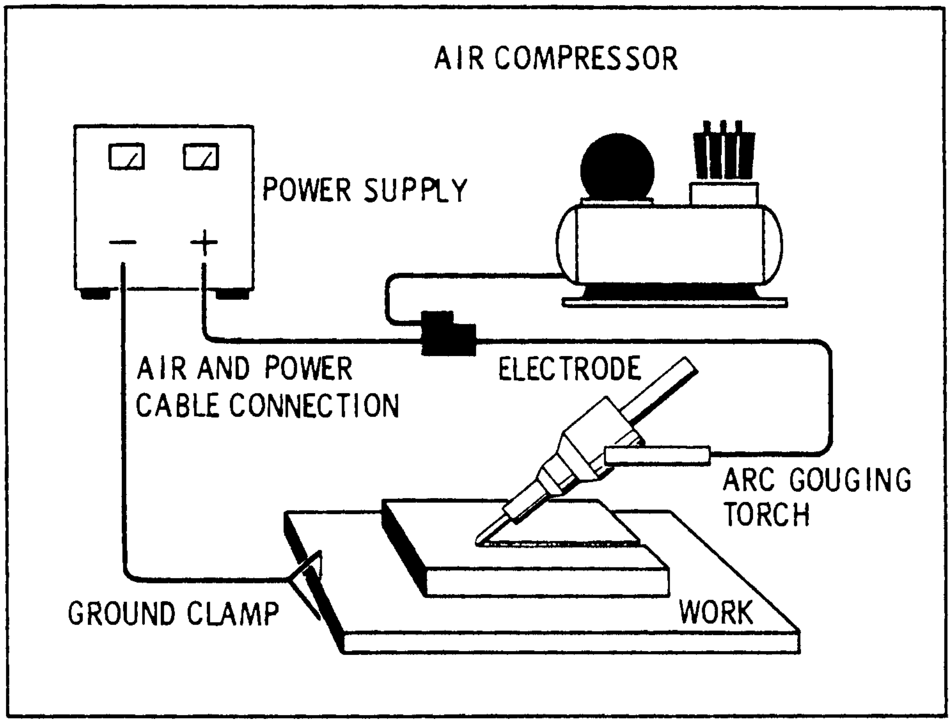

FIGURE A.4. Air Arc Gouging System

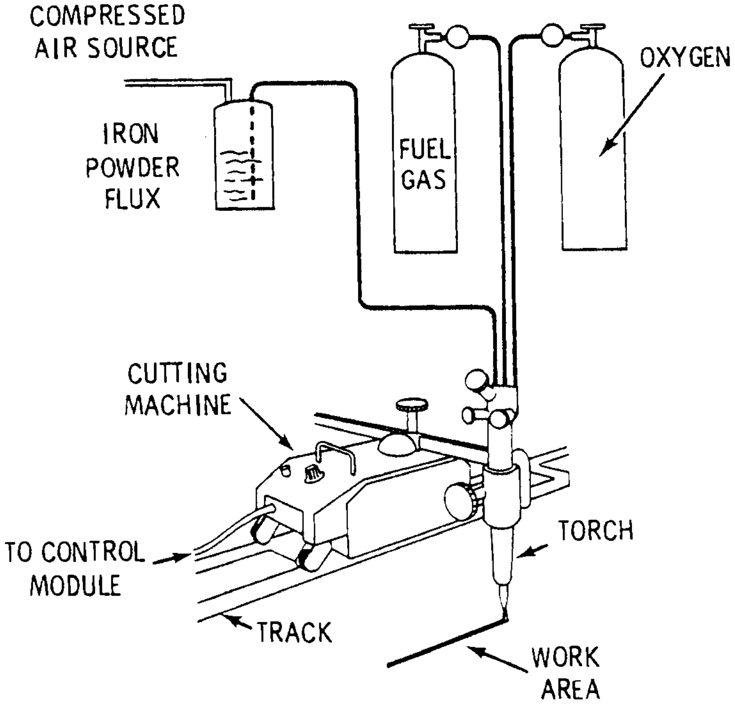

FIGURE A.5. Oxygen Burner System Using Iron Powder Flux

The system requires cylinders of fuel gas and oxygen, a vessel containing powdered flux, a source of compressed air, and a torch capable of supplying the various gases and flux. A torch can be manipulated either manually or automatically with a cutting machine on a track adjacent to the workpiece. The cutting equipment is inexpensive.

Reference: Althouse, A. D., C. H. Turnquist, and W. A. Bowditch. 1976. Modern Welding. The Goodheart-Wilcox Co., So. Holland, Illinois.

THERMITE REACTION LANCE

A thermite lance is essentially a straight piece of pipe filled with a mixture of steel, aluminum, and magnesium wires. Oxygen, controlled by a valve on the pipe, is delivered to the lance through a hose connected to oxygen cylinders. The lance is used primarily for gross cutting of thick metal sections. A cut is started using a conventional oxygen-fuel cutting torch which heats the workpiece. The cutting end of the lance held adjacent to the oxy-fuel torch is ignited when oxygen is supplied through the pipe. Cutting is then continued using the lance.

The lance operator must not only be protected from radiation in the nuclear facility but fully protected from fire as well. Lance cutting is comparatively inexpensive. A more complete description of the thermite lance may be found in the manual by Manion and LaGuardia (1980).

CARBON DIOXIDE LASER BEAM CUTTING

Lasers are devices, which, by using the natural oscillations of atoms or molecules between high and low energy levels, produce unique kinds of radiation and intense beams of light of a very pure color. The laser principle has been adapted for precise machining of metals.

Laser beam cutting involves converting electrical energy into light energy which in turn is converted into thermal energy. A simplified diagram of laser beam cutting is shown in Figure A.6. An electrically powered flash lamp discharged at high frequency excites carbon dioxide molecules in the laser tube to a higher energy level for the laser action to take place. The laser beam, having been intensified within the rod by repeated internal reflections between

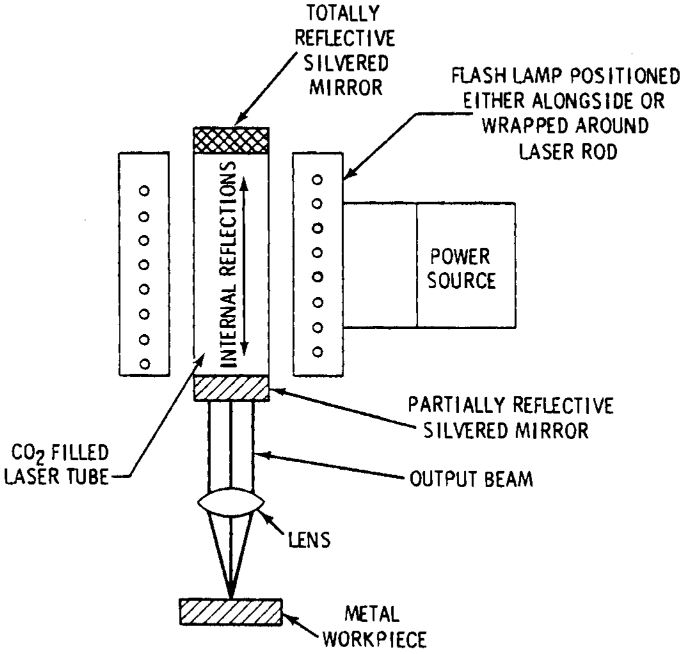

FIGURE A.6. Simplified Diagram of Laser Beam Cutting

two mirrors, finally breaks through the partially reflective or weaker mirror and is focused by a lens into a very small intense spot of light on the work surface. The light changed to heat produces a temperature sufficient to rapidly melt a kerf through a workpiece.

Reference: Dallas, E. B. ed. 1976. Tool and Manufacturing Engineers Handbook. 3rd ed. McGraw-Hill Company, New York.

SHEARING

Industrial shears employ the principle of common scissors; in other words, two cutting edges slide past each other. Usually, one blade of an industrial shear will be movable and the other stationary. The movable blade is mechanically actuated, often by hydraulic force. Shears are designed so that only a small portion of the moving blade is touching and cutting a small amount of metal at a time. A blade will gradually move through the metal workpiece until the item is completely cut.

Industrial shears have a wide variety of configurations with descriptive classification names. Two of interest are the alligator shear and the guillotine shear. The alligator or C-type shear has an open mouth with blades running from throat to nose. A C-type shear may be built like a punch press, as shown schematically in Figure A.7, and incorporate actions of both the alligator and guillotine shears. Blades can be arranged so that there are three instead of two. The upper blade cuts down through an item such as a pipe until a metal slug is pushed clear through the two lower blades until the item is severed.

Reference: Wilson, F. W. and P. D. Harvey, eds. 1959. Tool Engineers Handbook. 2nd ed. McGraw-Hill Book Co., New York.

MILLING

Milling is a machining process which uses a rotating, multiple-tooth, circular cutter to remove metal from a workpiece. Each tooth removes a small amount of metal from the workpiece with each revolution of the cutter. There is a wide variety of milling cutters; three general types are peripheral mills, face mills, and end mills. Peripheral mills have the cutting teeth on the periphery or edge of the tool; face mills have cutting edges on the face; and end mills have cutting edges on both the face end and the periphery. For many milling operations, a cutting fluid, either an oil or an aqueous solution containing emulsified oils and additivies, is supplied at the cutting site to provide lubrication and cooling. A schematic of a typical peripheral milling cutter is shown in Figure A.8.

Reference: Lyman, T., ed. 1967. Machining. Vol. 3 of Metals Handbook. 8th ed. American Society for Metals, Metals Park, Ohio.

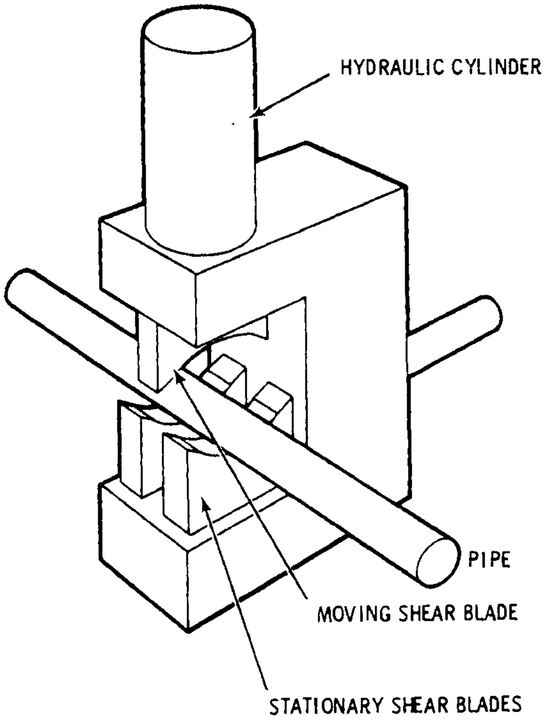

FIGURE A.7. C-Type Hydraulic Shear

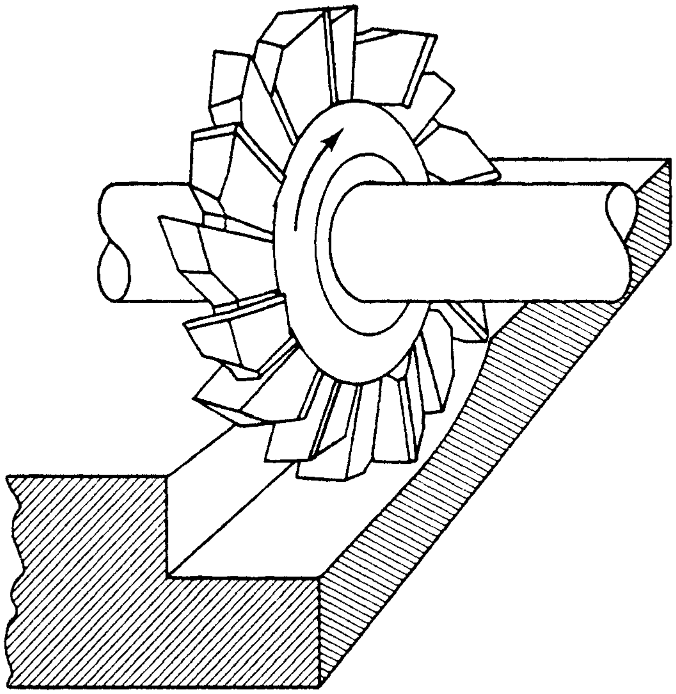

FIGURE A.8. Milling Cutter

APPENDIX B

TABULATED COMPARISON OF METHODS FOR SECTIONING STAINLESS STEEL ITEMS IN A RADIATION ENVIRONMENT

APPENDIX B

TABULATED COMPARISON OF METHODS FOR SECTIONING STAINLESS STEEL ITEMS IN A RADIATION ENVIRONMENT

The following table gives the advantages and disadvantages of each of the sectioning methods considered in the main body of the report. The information is based in part on the literature (for example, Manion and LaGuardia 1980, and others cited in Appendix A) or data obtained from technical people at Hanford. The actual appraisals are by the authors.

Stainless steel is used as an example for cutting in this comparison table. However, much of the information is directly applicable for carbon steel and other metals.

TABLE B.1. Comparison of Methods for Selecting Stainless Steel Items in a Radiation Environment.

Sectioning Method	Advantages	Disadvantages	Comments
Explosive Cutting	- Cutting speed is essentially instantaneous; although, for control of pressure and gases, a series of cuts will have to be made. - With light weight, easily maneuverable, remote handling apparatus, charges can be quickly placed. - Remote handling apparatus should be relatively inexpensive. - Charges can be formed to fit most configurations, even those in restricted locations where cutting by other methods is impracticable. - After cutting process is completed, no large size equipment will have to be removed from cutting area, be held for dosimeter checking, or be decontaminated or disposed of. - Most equipment setup will be done outside of radioactive environment resulting in minimal radiation exposure. - In controlled explosive cutting, gas evolution is low and pressures contained. - Minimum mock-up work is required before cutting task is performed. - Cutting support equipment is inexpensive.	- Shaped, explosive charges would be expensive. - Special care is required for handling from point of supply to point of use - Although minimal, some gases will be generated and contaminants must be removed by HEPA filtration. - Explosive cutting crew may have to make several entries and exits from job location to place and fire charges by standard explosive safety routines. - Pipe ends are not sealed and radioactive material on walls may be jarred loose. Therefore, when pipe is picked up, loose contamination may be spread. Preventive measures need to be taken. - Although equipment used to install explosives is inexpensive, cost of expendable material is relatively high.	- To allow inspection to assure completeness of cut, metal plate sections may have to be buckled in center to draw cut material apart. - Pressures caused by explosive charges will not scatter debris; preventive measures are taken to avoid the possibility.

TABLE B.1. (contd)

Sectioning Method	Advantages	Disadvantages	Comments
Arc saw	- Blade loss through operation is less than 5% of material removed from kerf. - Saw can cut metal sections up to 11-in. thick.	- Water spray is desirable to aid blade cooling. In-air cutting generates significant smoke and noise. - Portable equipment is only in development stage. - Present equipment is bulky and expensive: $111,000 to $254,000 (1979 dollars). - A complex, heavy remote handling system in a portable mode is needed.	- Cutting speed is about 1750 cm^2/min, or 270 in.^{2}/min.
Plasma arc torch	- Automated system would require only one person at controls. Field application may require 3-man team. - Further developments may expand capabilities.	- "Double arcing" or flare back can occur and cause nozzle damage. - Torch is not useful for cutting closely spaced pipes since head must encircle a pipe to cut it. - More smoke and solids are generated than with explosive cutting. - Arc cannot be maintained with complex geometries. - System excluding remote control can cost up to $25,000 (1979 base). Automation would result in much higher costs.	- Cutting speed for 1/2 in. stainless steel is 48-75 in./min.
Air arc gouger	- Automation systems would be similar to that for plasma arc. - Equipment is inexpensive: about $10,000 (exclusive of remote control).	- Much smoke and solids are generated. - Cutting system and remote handler is of moderate size, but complex.	- Cutting speed is about 12 in./min for 1/4-in. thick stainless steel.

TABLE B.1. (contd)

Sectioning Method	Advantages	Disadvantages	Comments
Oxygen burner (Oxy-Fuel)	- Equipment is inexpensive. - Fuel and oxygen cost is relatively low. - Equipment would be comparatively light and compact.	- Ordinarily burner is unable to cut stainless steel because refractory oxides (chromium oxide) form with high melting temperatures. Flux is required to inhibit refractory oxide formation. - Much smoke and solids are generated.	- Cutting speed by machine operation is 20-26 in./min for 1/4-in. stainless steel. - Time to cut 2-in., Schedule 40 pipe is about 2 min.
Thermite reaction lance	- Lance is well suited for cutting irregular surfaces with minimum access. - Material is inexpensive.	- Operator must be provided with complete fireproof protective clothing and faceshield. - Gross manual cutting technique is required. - Lance has limited use in sectioning highly activated and contaminated components. - Much smoke is generated.	
Carbon dioxide laser		- Systems are not portable enough for field use. - A 12 kW high-power laser and auxiliaries cost on the order of $600,000.	- Cutting speed is about 200 in./min for 1/4-in. stainless steel.

TABLE B.1. (contd)

Sectioning Method	Advantages	Disadvantages	Comments
Hydraulic shear (guillotine cutter)	- Shear is capable of cutting 2-in., Schedule 40, stainless steel pipe.	- It cannot be applied to making initial cut on closely spaced pipe. - It is not applicable for flat metal plate on concrete. - Size of cutter head would prevent use in relatively inaccessible areas. - Heavy remote handling equipment is required to force cut. - Maintenance will have to be performed frequently to keep cutter blade sharp. - Initial cost of equipment can be moderate to relatively high.	- Cut time for 2-in. pipe is less than 30 sec. - It can take up to 10 min to reposition from one pipe to another and to 15 min to reposition from one cutting location to another.

TABLE B.1. (contd)

Sectioning Method	Advantages	Disadvantages	Comments
Milling cutter	- Cutter has been used to cut reactor thermal shield metal. - Equipment cost is low to moderate.	- It requires liquid cutting lubricants which will become contaminated. - Vibration and chatter of equiment will occur if supports lack sturdiness and cutting speed is too great. - Cutter will have to be replaced frequently due to wear. Radiation exposure may be excessive during replacement.	
Nibbler	- It has been successful in sectioning thin vessel intervals about 1/8-in. thick. - Equipment cost is low.	- Nibbler is limited to 1/8-in. thick material. - It is not usable with either pipe or flat plate fastened on concrete. Access needed to both sides of flat plate.	- Cutting speed is 2 ft/min with 1/8-in. stainless steel.
Abrasive saw (abrasive wheel)	- Equipment cost is low.	- Remote machining can require heavy remote handling equipment and supports to withstand reactive forces. - Blade can bind in partially cut pipe if preventive steps not taken in equipment design. - Blades will have to be replaced when dull. - Cutting rates are comparatively slow. - Cutting fluids may be required.	- Time to cut 2-in., Schedule 40 pipe is 10 min.

TABLE B.1. (contd)

Sectioning Method	Advantages	Disadvantages	Comments
Abrasive saw - contd.	- Saw is designed to cut structural forms, concrete, reinforcing rods, etc.	- Saw creates considerable sparking. - It should be used in a portable filtered ventilation enclosure. - It would be difficult or impossible to use in relatively restricted or inaccessible areas. - Diamond saw blades are expensive and can loose cutting teeth.	- Typical unit weights about 28 lb. - Time per cut for 2-in., Schedule 40 pipe is about 10 min. - Flat plate not backed up by concrete can be cut at rate of 6 in./min.
Reciprocating saw	- Saw can be used to cut pipe. - Equipment cost is low.	- Saw is not applicable for flat metal plate on concrete. - It can bind during pipe cutting and require retrieval from high radiation area. - Provisions are required to supply cutting fluid and to recover contaminated spent fluid.	- Time per cut for 2-in., Schedule 40 pipe is about 2 min. - Flat stainless steel plate can be cut at a rate of 6 in./min.
Portable band saw	- Saw can be used to cut pipe. - Equipment cost is low.	- It is not applicable for flat metal plate on concrete. - Disadvantages are similar to those for reciprocating saw. - It would be difficult to use in relatively restricted or inaccessible areas.	- Time per cut for 2-in., Schedule 40 pipe is about 10 min.

APPENDIX C

SCHEDULE DATA AND FIGURES FOR PIPE AND PLATE CUTTING

APPENDIX C

SCHEDULE DATA AND FIGURES FOR PIPE AND PLATE CUTTING

Detailed schedule estimates for sectioning stainless steel piping in a nuclear facility pipe trench and flat floor plate in a drained fuel basin are given in Tables C.1 and C.2, respectively. These estimates were prepared by Olympic Associates Co. of Richland, Washington. The schedules are discussed in the report section, "Estimated Schedules and Radiation Exposure for Cutting Operations." Figures C.1, C.2, and C.3 show the various activities involved in the schedules for the two sectioning cases using several cutting methods.

TABLE C.1. Duration Matrix for Pipe Cutting[a]

	OXYGEN BURN Rate = 2M/2" Pipe								THERMITE REACTION LANCE Rate = 2M/2" Pipe								RECIPROCATING SAW Rate = 2M/2" Pipe								SHEAR CUTTING Rate = 2M/2" Pipe								EXPLOSIVE CUTTING Rate = 15M/2" Pipe							
	(.6 Rem)				(.12 Rem)				(.6 Rem)				(.12 Rem)				(.6 Rem)				(.12 Rem)				(.6 Rem)				(.12 Rem)				(.6 Rem)				(.12 Rem)			
Activities	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP
Planning & Eng.	0	0	20D		0	0	20D		0	0	20D		0	0	20D		0	0	20D		0	0	20D		0	0	20D		0	0	20D		0	0	20D		0	0	20D	
Contractor Certification	0	0	10D		0	0	100		0	0	10D		0	0	10D		0	0	100		0	0	100		0	0	100		0	0	100		0	0	100		0	0	100	
Prep. Operating Procedures	0	0	10D		0	0	10D		0	0	10D		0	0	10D		0	0	100		0	0	100		0	0	100		0	0	100		0	0	100		0	0	100	
Orientation & Mockup Training			5D				5D				5D				5D				50				50				50				50				50				5D	
Fab & Install Pipe Support			50				5D				5D				5D				5D				5D				5D				5D				50				50	
Fab & Test HEPA Filtered Tent			50				50				50				5D				5D				5D				50				50				5D				50	
Remove Charges from Magazine																																			30M	5			30M	5
Fab Shear Support																											100				10D									
Inspect & Set Arming Devices																																			48M	3			48M	3
Attach Shear Mech to Support																											2D				20									
Equipment Set up																																								
- Install Lifting Equipment																	15M	2	15M	5	15M	2	15M	5	15M	2	15M	5	15M	2	15M	5								
- Install Remote Handling Equip.																	10M	2	10M	5	10M	2	10M	5	10M	2	10M	5	10M	2	10M	5								
- Install Pipe Support	15M	2	15M	2	15M	2	15M	2	15M	2	15M	2	15M	2	15M	2	15M	2	15M	5	15M	2	15M	5	15M	2	15M	5	15M	2	15M	5	15M	2	15M	5	15M	2	15M	5
- Install Cutting/Shear Table																	20M	2	20M	5	20M	2	20M	5	20M	2	20M	5	20M	2	20M	5								
- Crew Change																			16M	5							16M	5												
Initial Briefing			20M	5			20M	5			20M	5			20M	5			20M	5			20M	5			20M	5			20M	5			20M	5			20M	5
Pre Ingress Equipment Set-up			25M	5			25M	5			25M	5			25M	5			25M	5			25M	5			25M	5			25M	5			25M	5			25M	5
Gather Tools			5M	5			5M	5			5M	5			5M	5			5M	5			5M	5			5M	5			5M	5			5M	5			5M	5

(a) Duration matrix developed by Olympic Associates Co. of Richland, Washington.

LEGEND:
ED - Exposure duration
MP - Manpower in radiation zone
TD - Total duration of activity
TMP - Total manpower of activity
D - Days
M - Minutes

TABLE C.1. (contd)

	OXYGEN BURN								THERMITE REACTION LANCE								RECIPROCATING SAW								SHEAR CUTTING								EXPLOSIVE CUTTING							
	Rate = 2M/2" Pipe								Rate = 2M/2" Pipe								Rate = 2M/2" Pipe								Rate = 2M/2" Pipe								Rate = 15M/2" Pipe							
	(.6 Rem)				(.12 Rem)				(.6 Rem)				(.12 Rem)				(.6 Rem)				(.12 Rem)				(.6 Rem)				(.12 Rem)				(.6 Rem)				(.12 Rem)			
Activities	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP
Crew #1 Don Protective Clothing			15M	5			15M	5			15M	5			15M	5			15M	5			15M	5			15M	5			15M	5			15M	5			15M	5
Ingress to Work Site			3M	5			3M	5			3M	5			3M	5			3M	5			3M	5			3M	5			3M	5			3M	5			3M	5
Job Orientation	4M	4	4M	5	4M	4	4M	5	4M	4	4M	5	4M	4	4M	5	4M	4	4M	5	4M	4	4M	5	4M	4	4M	5	4M	4	4M	5	4M	4	4M	5	4M	4	4M	5
Set Up Tent & Equipment	10M	4	10M	5	4M	4	10M	5	10M	4	10M	5	4M	4	10M	5	10M	4	10M	5	4M	4	10M	5	10M	4	10M	5	4M	4	10M	5								
Set Up Shear Equipment Apparatus																											10M				10M									
String Firing Cable/Set Firing Box																																	2M	2	5M	5	2M	2	5M	5
Cut 1st Pipe Top Tier 3 Position																															15M	2								
Place and Prepare Charges for First Firing;Set Up Tent																																	40M	2	48M	5	40M	2	48M	5
Retire to Firing Area																																			1M	2			1M	2
Fire Charges																																			1M	5			1M	5
Vent Area																																			3M	5			3M	5
Compl. Sect. Pipe Top Tier Pos. #1	38M	2	38M	5	38M	2	38M	5	38M	2	38M	5	38M	2	38M	5	38M	2	38M	5	38M	2	38M	5	38M	2	38M	5	38M	2	38M	5								
Start Relocate Tent Pos. #2	2M	4	2M	5	2M	4	2M	5	2M	4	2M	5	2M	4	2M	5	2M	4	2M	5	2M	4	2M	5																
Crew Change																																			16M	5				
Egress Area			3M	5							3M	5							3M	5							3M	5												
Status Briefing			6M								6M								6M								6M													
Crew Ingress			3M	5							3M	5							3M	5							3M	5												
Job Orientation	4M	4	4M	5					4M	4	4M	5					4M	4	4M	5					4M	4	4M	5					4M	2	4M	5				
Place Charges on 8 Remaining Top Tier Pipe. Prepare Charges																																	40M	2	48M	5	40M	2	48M	5
Retire to Firing Area																																			2M	5			2M	5
Vent Area																																			3M	5			3M	5
Retrieve Cut Metal From Top Tier																																	15M	2	15M	5	15M	2	15M	5
Compl. Reloc Tent & Equip. Pos. #2	8M	4	8M	5	10M	4	10M	5	8M	3	10M		8M		10M		10M		10M		10M		10M		10M		10M		10M		10M									
Compl. Sect. Top Tier Pos. #2	38M	2	38M	5	38M	2	38M	5	38M	2	38M	5	38M	2	38M	5	38M	2	38M	5	38M	2	38M	5	38M	2	38M	5	38M	2	38M	5								

TABLE C.1. (contd)

	OXYGEN BURN								THERMITE REACTION LANCE								RECIPROCATING SAW							
	Rate = 2M/2" Pipe								Rate = 2M/2" Pipe								Rate = 2M/2" Pipe							
	(.6 Rem)				(.12 Rem)				(.6 Rem)				(.12 Rem)				(.6 Rem)				(.12 Rem)			
Activities	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP
Start Relocating Equip. Pos. #3	2M	4	4M	5					2M	4	4M	5					2M	4	4M	5				
Egress Area			3M	5							3M	5							3M	5				
Status Briefing			6M	10							6M	10							6M	10				
Crew Ingress			3M	5							3M	5							3M	5				
Crew Change																								
Job Orientation	4M	4	4M	5					4M	4	4M	5					4M	4	4M	5				
Compl. Reloc. Tent & Equip. Pos. #3	8M	4	8M	5	10M	4	10M	5	8M	4	8M	5	10M	4	10M	5	8M	4	8M	5	10M	4	10M	5
Compl. Sect. Pipe Top Tier Pos. #3	38M	2	38M	5	38M	2	38M	5	38M	2	38M	5	38M	2	38M	5	38M	2	38M	5	38M	2	38M	5
Start Reloc. Tent & Equipment	4M	4	4M	5					4M	4	4M	5					4M	4	4M	5				
Egress Area			3M	5							3M	5							3M	5				
Status Briefing			6M	10							6M	10							6M	10				
Crew Ingress			3M	5							3M	5							3M	5				
Job Orientation	4M	2	4M	5					4M	2	4M	5					4M	2	4M	5				
Remove Cut Pipe Top Tier	15M	2	15M	5	15M	2	15M	5	15M	2	15M	5	15M	2	15M	5	15M	2	15M	5	15M	2	15M	5
Relocate Tent & Equip. Pos. #1	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5
Compl. Sect Pipe Mid Tier Pos. #1	38M	2	38M	5	38M	2	38M	5	38M	2	38M	5	38M	2	38M	5	38M	2	38M	5	38M	2	38M	5
Egress			3M	5							3M	5							3M	5				
Repeat Operation for 2nd Tier																								
Repeat Operation for 3rd Tier																								
Repetitive Sect. Activities	157M	2	194M	5	124M	2	124M	5	157M	2	194M	5	124M	2	124M	5	157M	2	194M	5	124M	2	124M	5

	SHEAR CUTTING								EXPLOSIVE CUTTING							
	Rate = 2M/2" Pipe								Rate = 15M/2" Pipe							
	(.6 Rem)				(.12 Rem)				(.6 Rem)				(.12 Rem)			
Activities	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP
Start Relocating Equip. Pos. #3																
Egress Area			3M	5												
Status Briefing			6M	10												
Crew Ingress			3M	5												
Crew Change											16M	5				
Job Orientation	4M	4	4M	5					4M	2	4M	5				
Compl. Reloc. Tent & Equip. Pos. #3	8M	4	8M	5	10M	4	10M	5								
Compl. Sect. Pipe Top Tier Pos. #3	38M	2	38M	5	38M	2	38M	5								
Start Reloc. Tent & Equipment																
Egress Area			3M	5												
Status Briefing			6M	10												
Crew Ingress			3M	5												
Job Orientation	4M	2	4M	5												
Remove Cut Pipe Top Tier	15M	2	15M	5	15M	2	15M	5								
Relocate Tent & Equip. Pos. #1	5M	4	5M	5	5M	4	5M	5								
Compl. Sect Pipe Mid Tier Pos. #1	38M	2	38M	5	38M	2	38M	5								
Egress			3M	5												
Repeat Operation for 2nd Tier									103M	2	161M	5	95M	2	121M	5
Repeat Operation for 3rd Tier									103M	2	161M	5	95M	2	121M	5
Repetitive Sect. Activities	157M	2	194M	5	124M	2	124M	5								

TABLE C.1. (contd)

	OXYGEN BURN Rate = 2M/2" Pipe							
	(.6 Rem)				(.12 Rem)			
Activities	ED	MP	TD	TMP	ED	MP	TD	TMP
Compl. Sect Lower Tier Pos. #3	38M	2	38M	5	38M	2	38M	5
Crew #9 Egress			3M	5				
Status Briefing			6M	10				
Crew #10 Ingress			3M	5				
Clean Up Charge Debris								
Start Pickup Tools & Cleanup	39M	4	39M	4	45M	4	45M	4
Inspector Ingress	3M	1	3M	5	3M	1	3M	5
Inspect & Release	12M	1	12M	1	15M	1	15M	1
Inspector & Crew Egress			3M	5			3M	5
Status Briefing			10M	5			10M	5
Remove Protective Clothing			15M	5			15M	5
Clean Up Outside Area			30M	5			30M	5
Issue Report								
TOTAL MINUTES	501M		717M		461M		587M	
Time, hours	8		12		8		10	
Crews required		3				1		
Shifts		8				2		
Crew Size		5				5		
Total Manhours		71				45		
Radiation Exposure								
Manhours		20				18		
Manrem		12				2		

	THERMITE REACTION LANCE Rate = 2M/2" Pipe							
	(.6 Rem)				(.12 Rem)			
Activities	ED	MP	TO	TMP	ED	MP	TD	TMP
Compl. Sect Lower Tier Pos. #3	38M	2	38M	5	38M	2	38M	5
Crew #9 Egress			3M	5				
Status Briefing			6M	10				
Crew #10 Ingress			3M	5				
Clean Up Charge Debris								
Start Pickup Tools & Cleanup	39M	4	39M	4	45M	4	45M	4
Inspector Ingress	3M	1	3M	5	3M	1	3M	5
Inspect & Release	12M	1	12M	1	15M	1	15M	1
Inspector & Crew Egress			3M	5			3M	5
Status Briefing			10M	5			10M	5
Remove Protective Clothing			15M	5			15M	5
Clean Up Outside Area			30M	5			30M	5
Issue Report								
TOTAL MINUTES	501M		717M		461M		587M	
Time, hours	8		12		8		10	
Crews required		3				1		
Shifts		8				2		
Crew Size		5				5		
Total Manhours		72				45		
Radiation Exposure								
Manhours		20				18		
Manrem		12				2		

	RECIPROCATING SAW Rate = 2M/2" Pipe							
	(.6 Rem)				(.12 Rem)			
Activities	EO	MP	TO	TMP	ED	MP	TD	TMP
Compl. Sect Lower Tier Pos. #3	38M	2	38M	5	38M	2	38M	5
Crew #9 Egress			3M	5				
Status Briefing			6M	10				
Crew #10 Ingress			3M	5				
Clean Up Charge Debris								
Start Pickup Tools & Cleanup	39M	4	39M	4	45M	4	45M	4
Inspector Ingress	3M	1	3M	5	3M	1	3M	5
Inspect & Release	12M	1	12M	1	15M	1	15M	1
Inspector & Crew Egress			3M	5			3M	5
Status Briefing			10M	5			10M	5
Remove Protective Clothing			15M	5			15M	5
Clean Up Outside Area			30M	5			30M	5
Issue Report								
TOTAL MINUTES	546M		778M		506M		632M	
Time, hours	9		13		8		10	
Crews required		3				1		
Shifts		8				2		
Crew Size		5				5		
Total Manhours		64				50		
Radiation Exposure								
Manhours		21				19		
Manrem		13				2		

	SHEAR CUTTING Rate = 2M/2" Pipe							
	(.6 Rem)				(.12 Rem)			
Activities	ED	MP	TD	TMP	ED	MP	TD	TMP
Compl. Sect Lower Tier Pos. #3	38M	2	38M	5	38M	2	38M	5
Crew #9 Egress			3M	5				
Status Briefing			6M	10				
Crew #10 Ingress			3M	5				
Clean Up Charge Debris								
Start Pickup Tools & Cleanup	39M	4	39M	4	45M	4	45M	4
Inspector Ingress	3M	1	3M	5	3M	1	3M	5
Inspect & Release	12M	1	12M	1	15M	1	15M	1
Inspector & Crew Egress			3M	5			3M	5
Status Briefing			10M	5			10M	5
Remove Protective Clothing			15M	5			15M	5
Clean Up Outside Area			30M	5			30M	5
Issue Report								
TOTAL MINUTES	552M		780M		516M		642M	
Time, hours	9		13		9		11	
Crews required		3				1		
Shifts		9				2		
Crew Size		5				5		
Total Manhours		64				51		
Radiation Exposure								
Manhours		22				20		
Manrem		13				2		

	EXPLOSIVE CUTTING Rate = 15M/2" Pipe							
	(.6 Rem)				(.12 Rem)			
Activities	ED	MP	TD	TMP	ED	MP	TD	TMP
Compl. Sect Lower Tier Pos. #3								
Crew #9 Egress								
Status Briefing								
Crew #10 Ingress								
Clean Up Charge Debris	30M	4	30M	5	30M	4	30M	5
Start Pickup Tools & Cleanup								
Inspector Ingress	3M	1	3M	1	3M	1	3M	1
Inspect & Release	15M	1	15M	1	15M	1	15M	1
Inspector & Crew Egress			3M	5			3M	5
Status Briefing			10M	5			10M	5
Remove Protective Clothing			15M	5			15M	5
Clean Up Outside Area			30M	5			30M	5
Issue Report								
TOTAL MINUTES	359M		594M		335M		474M	
Time, hours	6		10		6		8	
Crews required		3				1		
Shifts		6				1		
Crew Size		5				5		
Total Manhours		48				38		
Radiation Exposure								
Manhours		13				12		
Manrem		8				1		

TABLE C.2. Duration Matrix for Plate Cutting(a)

Activities	PLASMA ARC TORCH Rate = 65"/Min								OXYGEN BURNER Rate = 23"/Min								AIR ARC GOUGER Rate = 12"/Min								EXPLOSIVE CUTTING Rate = 29 Min/Plate 4' x 16"							
	(.6 Rem)				(.12 Rem)				(.6 Rem)				(.12 Rem)				(.6 Rem)				(.12 Rem)				(.6 Rem)				(.12 Rem)			
	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP
Planning & Eng.	0		20D		--	--	20D		0	--	20D		0		20D		0		20D		0		20D		0		20D		0		20D	
Contractor Cert.	0		10D		--	--	10D		0	--	10D		0		100		0		10D		0		10D		0	--	10D		0	--	10D	
Orientation & Mockup Training	0		5D		--	--	5D		0	--	5D		0		50		0		5D		0		5D		0	--	5D		0	--	5D	
Set-up & Test Remote Hand. App.																																
- Unload Equipment	0		1D		0	--	1D		0	--	1D		0		10		0		1D		0		1D				1D				1D	
- Assemble & Test Outside	0		2D		0	--	2D		0	--	2D		0		20		0		2D		0		2D									
- Install Portable Hoist	90M	4	90M	5	90M	4	90M	5									90M	4	90M	5	90M	4	90M	5								
- Install Cutting Equipment	90M	4	90M	5	90M	4	90M	5	15M	2	15M	5	15M	2	15M	5	90M	4	90M	5	90M	4	90M	5								
- Hook up Services	30M	2	30M	5	30M	2	30M	2	1M	2	1M	5	1M	2	1M	5	30M	2	30M	5	30M	2	30M	3								
- Final Test	30M	2	30M	5	30M	2	30M	2	3M	2	3M	5	3M	2	3M	5	30M	2	30M	5	30M	2	30M	5								
- Crew Changes			80M	10															80M	10												
Remove Charges from Magazine																											30M	5			30M	5
Initial Briefing			20M	5			20M	5			20M	5			20M	5			20M	5			20M	5			20M	5			20M	5
Inspect & Assemble Detonator																											11M	5			11M	5
Crew #/Don Protective clothing			15M	5			15M	5			15M	5			15M	5			15M	5			15M	5			15M	5			15M	5
Ingress			3M	5			3M	5			3M	5			3M	5			3M	5			3M	5			3M	5			3M	5
Job Orientation	4M	2	4M	5	4M	2	4M	5	4M	2	4M	5	4M	2	4M	5	4M	2	4M	5	4M	2	4M	5	4M	2	4M	5	4M	2	4M	5
String Firing Cable																									5M	2	5M	5	5M	2	5M	5
1st Cut 96" Length	2M	2	2M	5	2M	2	2M	5	4M	2	4M	5	4M	2	4M	5	8M	2	8M	5	8M	2	8M	5								
Cut 1st Plate 4'x16"																									15M	2	29M	5	15M	2	29M	5
Reposition Remote Handler	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5								
Cut 2 - 7 (Typ)	42M	2	42M	5	42M	2	42M	5																								
Cut 2 - 4 (Typ)									27M	2	27M	5	27M	2	27M	5																
Cut 2 - 4 (Typ)																	39M	2	39M	5	39M	2	39M	5								
Crew Change			16M	10								16M	10						16M	10							16M	10				

(a) Duration matrix developed by Olympic Associates Co. of Richland, Washington.

LEGEND:
ED - Exposure duration
MP - Manpower and radiation zone
TD - Total duration of activity
TMP - Total manpower of activity
D - Days
M - Minutes

TABLE C.2. (contd)

	PLASMA ARC TORCH Rate = 65"/Min								OXYGEN BURNER Rate = 23"/Min								AIR ARC GOUGER Rate = 12"/Min								EXPLOSIVE CUTTING Rate = 29 Min/Plate 4' x 16"							
	(.6 Rem)				(.12 Rem)				(.6 Rem)				(.12 Rem)				(.6 Rem)				(.12 Rem)				(.6 Rem)				(.12 Rem)			
Activities	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP
Cuts 8 - 10 (Typ)	21M	2	21M	5	21M	2	21M	5																								
Cuts 4 - 10 (Typ)									54M	2	54M	5	54M	2	54M	5																
Cuts 5 - 8 (Typ)																	52M	2	52M	5	52M	2	52M	5								
Crew Change																			16M	10												
Cuts 9 and 10																	26M	2	26M	5	26M	2	26M	5								
Cut End 16"	1M	2	1M	5	1M	2	1M	5	1M	2	1M	5	1M	2	1M	5	2M	2	2M	5	2M	2	2M	5								
Cut Plates 2 & 3																									30M	2	58M	5	30M	2	58M	5
Repos Rem Hand 4'	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5								
Crew Change											16M	10															16M	10				
1st Cut 16"	1M	2	1M	5	1M	2	1M	5	1M	2	1M	5	1M	2	1M	5	2M	2	2M	5	2M	2	2M	5								
Cut Plates 4 & 5																									30M	2	58M	5	30M	2	58M	5
Repos Rem Hand 4'	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5								
Crew Change																																
Cut Plates 6 & 7																									30M	2	58M	5	30M	2	58M	5
Crew Change																											16M	10				
Cut Plates 8 & 9																									30M	2	58M	5	30M	2	58M	5
Cut 2 - 5 (Typ)	24M	2	24M	5	24M	2	24M	5																								
Cut 2 - 7 (Typ)									54M	2	54M	5	54M	4	54M	5																
Cut 2 (Typ)																	7M	2	7M	5	7M	2	7M	5								
Crew Change			16M	10							16M	10							16M	10												
Cut 3 - 9																	49M	2	49M	5	49M	2	49M	5								
Cut 6 - 9 16" Length	24M	2	24M	5	24M	2	24M	5																								
Cut 7 - 9 (Typ)									12M	2	12M	5	12M	2	12M	5																
Crew Change																			16M	10												
Repos Rem Hand	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5								
Cut End 16"	1M	2	1M	5	1M	2	1M	5	1M	2	1M	5	1M	2	1M	5	2M	2	2M	5	2M	2	2M	5								
Cut Plate #10																									15M	2	29M	5	15M	2	29M	5
Start Pickup Tools & Equip.	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5	5M	4	5M	5
Crew Change																											16M	10				
Clean up Charge Debris																									30M	4	30M	5	30M	4	30M	5

TABLE C.2. (contd)

Activities	PLASMA ARC TORCH								OXYGEN BURNER							
	Rate = 65"/Min								Rate = 23"/Min							
	(.6 Rem)				(.12 Rem)				(.6 Rem)				(.12 Rem)			
	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP
Inspect & Release	5M	1	5M	1	5M	1	5M	1	5M	1	5M	1	5M	1	5M	1
Complete Pickup Tools & Equip.	5M	4	5M	4	65M	4	5M	4	5M	4	5M	4	25M	4	5M	4
Crew & Inspector Egress			3M	5			3M	5			3M	5			3M	5
Status Briefing			6M	5			6M	5			6M	5			6M	5
Remove Protective Clothing			15M	5			15M	5			15M	5			15M	5
Clean up			30M	5			30M	5			30M	5			30M	5
Equipment Removal/ Salvage	60M	4	60M	5					20M	4	20M	5				
Crew Changes			16M	5							16M	5				
TOTAL MINUTES	455M		675M		455M		487M		232M		372M		232M		304M	
Time, hours	8		11		8		8		4		6		4		5	
Crews required		3				1				3				1		
Shifts		5				5				5				5		
Crew Size		8				1				4				1		
Total Manhours		65				37				36				25		
Radiation Exposure																
Manhours		24				24				9				9		
Manrem		14				3				5				1		

Activities	AIR ARC GOUGER								EXPLOSIVE CUTTING							
	Rate = 12"/Min								Rate = 29 Min/Plate 4' x 16"							
	(.6 Rem)				(.12 Rem)				(.6 Rem)				(.12 Rem)			
	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP	ED	MP	TD	TMP
Inspect & Release	5M	1	5M	1	5M	1	5M	1	5M	1	5M	1	5M	1	5M	1
Complete Pickup Tools & Equip.	5M	4	5M	5	65M	4	5M	4	5M	4	5M	4	5M	4	5M	4
Crew & Inspector Egress			3M	5			3M	5			3M	5			3M	5
Status Briefing			6M	5			6M	5			6M	5			6M	5
Remove Protective Clothing			15M	5			15M	5			15M	5			15M	5
Clean up			30M	5			30M	5			30M	5			30M	5
Equipment Removal/ Salvage	60M	4	8M	5												
Crew Changes			16M	5												
TOTAL MINUTES	526M		726M		526M		558M		204M		525M		204M		477M	
Time, hours	9		12		9		9		3		9		3		8	
Crews required		3				1				3				1		
Shifts		5				5				5				5		
Crew Size		9				1				4				1		
Total Manhours		72				45				45				39		
Radiation Exposure																
Manhours		26				26				8				8		
Manrem		16				3				5				1		

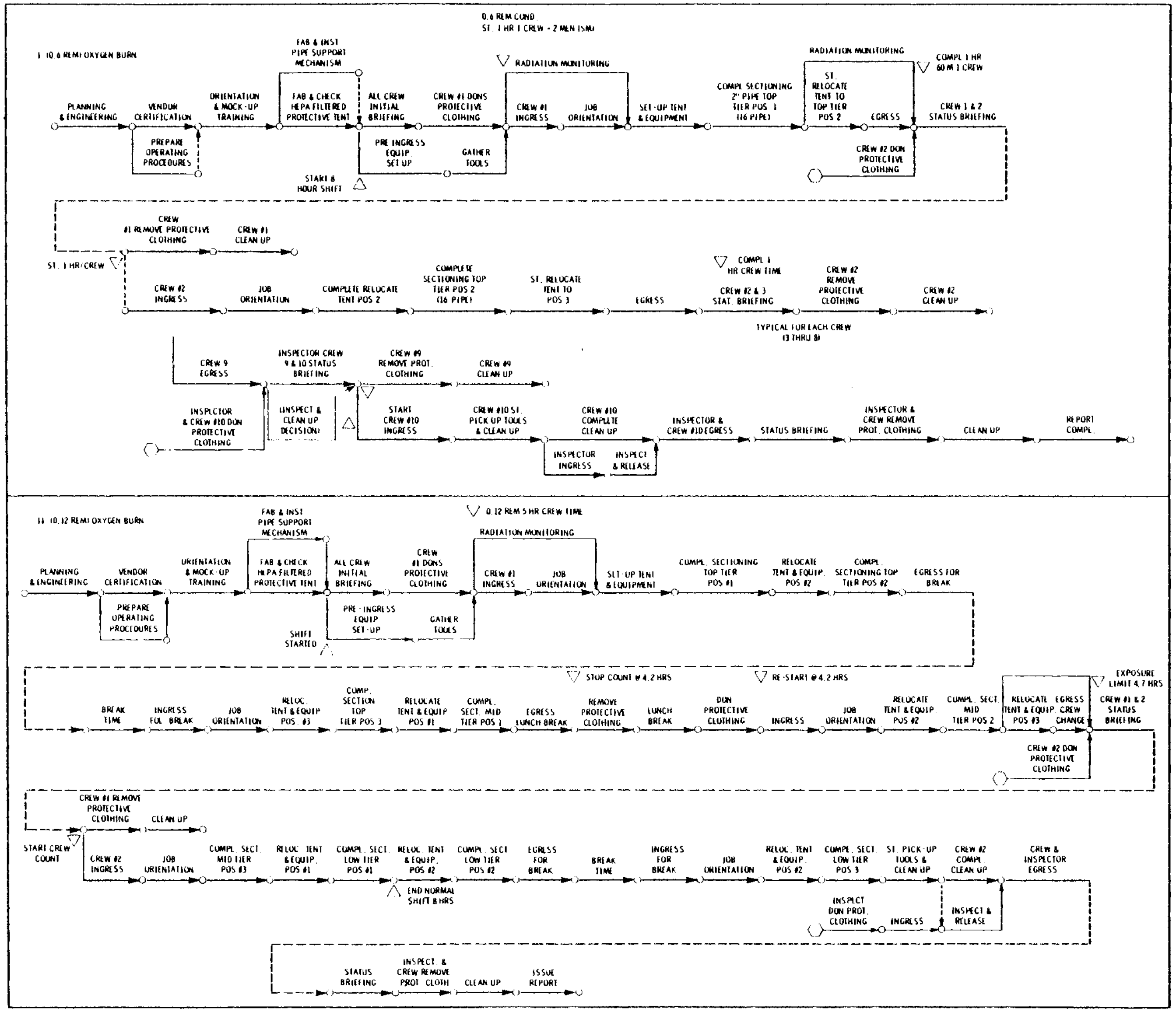

FIGURE C.1. Schedule Elements for Pipe Cutting Case Using an Oxygen Burner

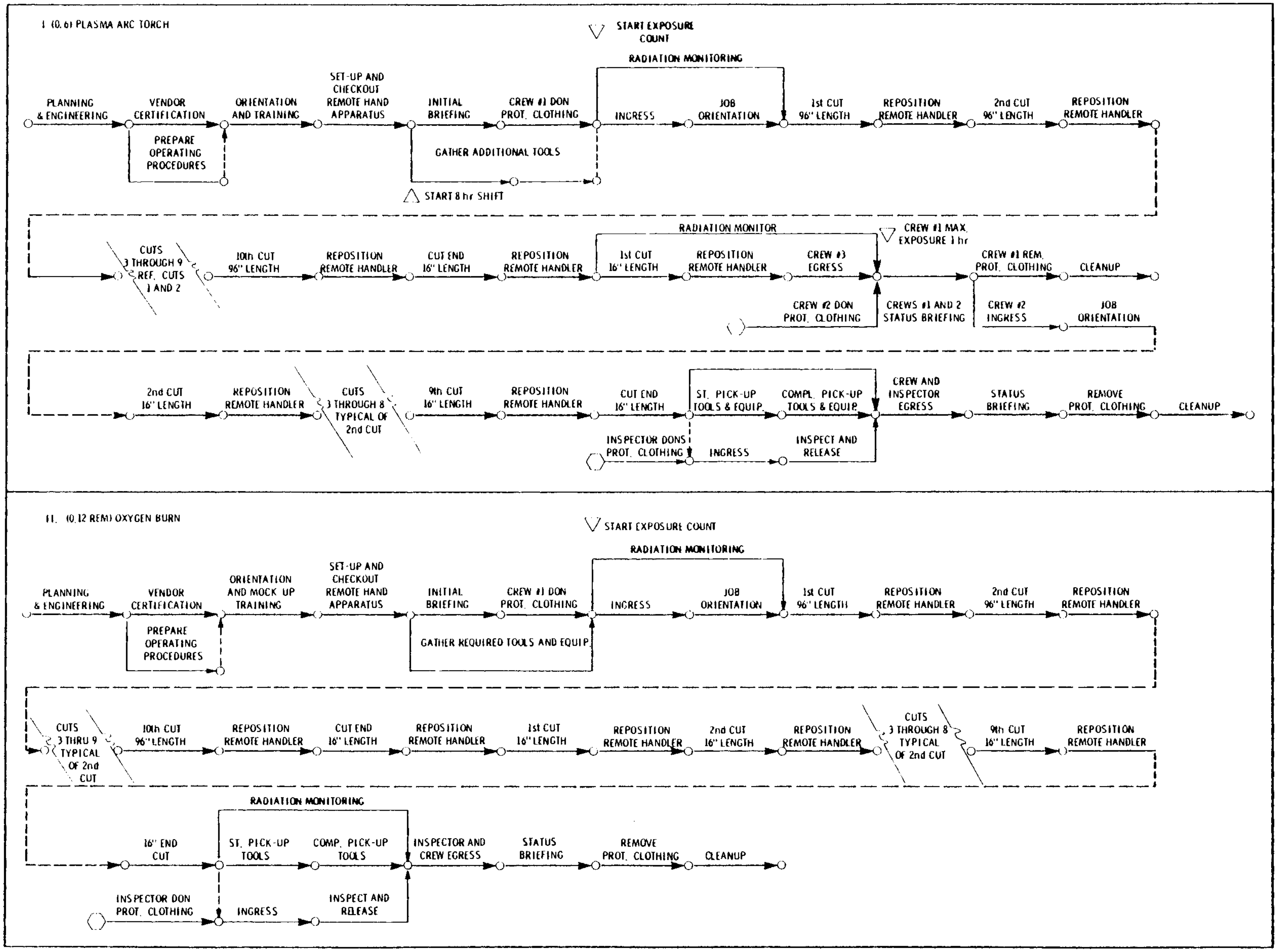

FIGURE C.2. Schedule Elements for Floor Plate Cutting Case Using a Plasma Arc and Oxygen Burner Torches

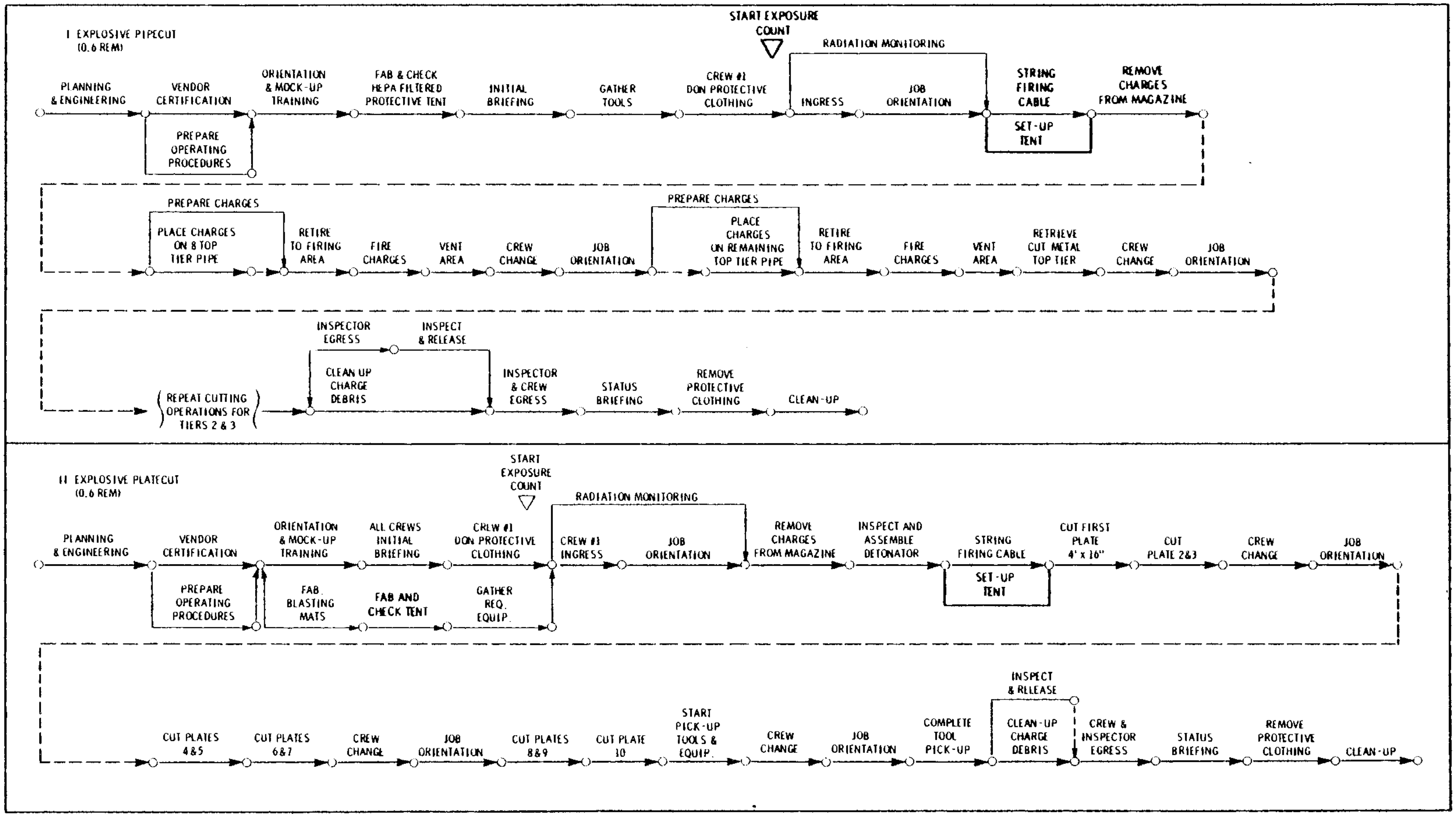

FIGURE C.3. Schedule Elements for Pipe and Floor Plate Cutting Case Using Explosive Charges

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