INNOVATIVE TECHNOLOGY
Summary Report

DOE/EM-0612

Laser Cutting and Size Reduction

Deactivation and Decommissioning Focus Area

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INNOVATIVE TECHNOLOGY

Summary Report

Laser Cutting and Size Reduction

OST/TMS ID 1477

Deactivation and Decommissioning Focus Area

Demonstrated at
Hanford – 324 Building
Richland, WA
Energy Technology Engineering Center (ETEC)
Radioactive Materials Handling Facility (RMHF)
Santa Susana, CA

Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine whether a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

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TABLE OF CONTENTS

SECTION 1
SUMMARY

Introduction

The U.S. Department of Energy (DOE) continually seeks safer and more cost effective technologies for use in decontamination and decommissioning (D&D) of nuclear facilities. To this end, the Deactivation and Decommissioning Focus Area (DDFA) of the DOE's Office of Science and Technology (OST) sponsors demonstrations of innovative technologies that are potentially beneficial to DOE projects and to others in the D&D community. Benefits sought include decreased health and safety risks to personnel and the environment, increased productivity, and decreased cost of operation.

This report documents the demonstrations, at two DOE sites, that investigated the costs, and other operational parameters, of cutting various metallic objects using laser cutting and size reduction technology, and compares these results to the baseline technology of plasma-arc cutting.

Technology Summary

The Pacific Northwest National Laboratory (PNNL) and Energy Technology Engineering Center (ETEC) separately demonstrated the laser cutting size reduction technology, which was developed to cut metal and equipment of almost any size and shape in a remote-handling, high-radiation environment. Both demonstrations used an off-the-shelf Lumonics 2-kW Nd:YAG (neodymium-doped yttrium aluminum garnet) laser operating in a continuous-wave mode. Innovations to laser cutting technology involve the use of fiber optic technology to deliver the laser beam to remote, hazardous cutting sites (Figure 1). The technology is an adaptation of the commercial laser-cutting method commonly used in automotive manufacturing and other industrial applications. Application of laser cutting to decontamination and decommissioning projects at nuclear reactor and processing facilities across the DOE complex and the commercial nuclear industry was thought to offer potentially large benefits.

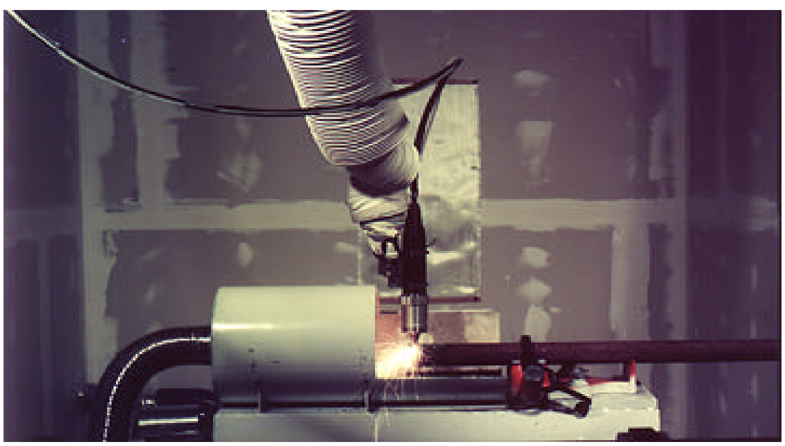

Figure 1: Laser Cutting and Size Reduction for D&D

Laser cutting is performed by generating a laser beam in a water-cooled laser power unit, transmitting this beam through a fiber optic cable, and cutting with the beam using an end effector that incorporates a focusing optics package and an assist gas injection port. While most industrial applications manipulate the laser end effector with a robotic device as in the ETEC demonstration, the PNNL laser-cutting system ultimately manipulated the end effector with a standard hot-cell master/slave manipulator.

Baseline Technologies

Three common size reduction technologies are available to cut large, thick and irregular metal shapes to reduce size: oxyacetylene cutting, plasma-arc cutting and laser cutting. The hazard of a possible explosion exists in using oxyacetylene cutting in hot cells and other radioactive/hazardous environments.

Plasma-arc cutting has been the standard method for remote hot-cell cutting. In plasma-arc cutting, a plasma torch operates by melting the metal to be cut. A jet of ionized gas, blasting holes in the metal, follows the melting. Laser cutting generally involves using a laser beam, focused on a spot to heat and melt metal. An assist gas is used to blow the metal out of the region melted by the laser, called the kerf. If a reactive gas, such as oxygen, is used for assist, it can add up to 70 percent of additional heating.

Major Advantages of Laser Cutting and Size Reduction

Laser cutting and size reduction has a number of advantages over other baseline technologies:

- The laser is markedly superior in cutting deformed metal and dirty material.
- The laser's cutting action is not significantly different from a plasma torch; however, the laser does not require the operator to strike an arc, as with the plasma torch.
- Laser cutting is somewhat faster and a much cleaner technology, generating less smoke and metal vapor.

Demonstration Summary

PNNL Demonstration

The demonstration of the laser cutting and size reduction technology was performed in the 324 Building on the Hanford Reservation. A portion of the demonstration was performed in the hot cell area, on non-radioactively contaminated materials, in a laser cutting enclosure. The laser cutting and size reduction technology was later deployed in the size-reduction of a contaminated crane. The non-radioactive test (i.e., 'cold test') identified several issues that required resolution before the laser cutting technology was deployed. The technology was subsequently deployed in the 324 Building 'B' Hot Cell airlock to size-reduce a contaminated crane and size reduction of racks within the hot cell.

The PNNL staff determined the performance of the laser in cutting common materials found in contaminated areas, observed the generation rate of effluent from the cutting operation, and assessed ease of use. The PNNL staff also performed a limited irradiation test to determine the degree of radiation darkening exhibited by the fiber optic cable. This test involved irradiating fiber optic cables with a gamma source and then performing power measurements and photobleaching with a laser.

<u>Key Test Results</u>

- The laser cutting and size reduction system is easy to use, easy to handle with the hot-cell manipulator, allowing for precise placement.
- The system can cut complex geometries, such as a pipe within a pipe, in a single pass.
- The system can cut material at the desired location, cut difficult geometries in a straightforward manner, and cut material in its current condition.
- The cutting rate of the laser is highly dependent on the geometry of the item being cut.
- Dirt, corrosion, material expansion and surface contamination do not materially affect cutting rate.
- For carbon and stainless steel, oxygen is the preferred assist gas; for more reactive metals, such as titanium, compressed air is the better choice.
- Variations in assist gas pressure can affect the laser's ability to cut material. The specific threshold depends on material composition and geometry.
- Dangerous levels of metal vapor and/or oxide contamination were not present in the effluent air.
- At the end of the testing series, the high-OH fiber optic cable had the greatest transmission capability leading to the conclusion that a high-OH fiber optic cable has a greater resistance to radiation damage.

ETEC Demonstration

The ETEC demonstration was set up in Building 022 of the Radioactive Materials Handling Facility (RMHF), a radiologically controlled building with seven below-grade radioactive materials storage vaults. The laser cutting demonstration was conducted in Vault 1. Vault 1 contained approximately 280 nuclear fuel storage tubes from which fuel was removed several years ago, but which retained some low-level contamination. Each of these carbon steel tubes was 3-m-long by 13-cm in diameter with 16-gauge (1.6 mm thick) walls. Disposal required that each tube be split open to inspect its interior, and sectioning the tubes longitudinally would allow the resulting half-cylinder sections to be nested to reduce the disposal volume. The demonstration cut all 280 tubes in the Vault 1.

Key Results

- Laser cutting and size reduction is effective in cutting thin and thick components.
- The laser achieved an optimum cutting speed of 400 cm/minute.
- Laser cutting is more cost effective for large-scale applications and significantly reduces personnel exposure.

Technology Status

Laser cutting and size reduction technology is commercially available for immediate deployment. The most appropriate application for laser cutting is at D&D sites where a plasma torch can be used but minimization of smoke and secondary waste generation is necessary. It is also beneficial over the plasma-arc cutting torch because the cutting rate is not materially affected when cutting dirty or grout-covered material.

Contacts

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Licensing and Permitting

No Contacts for these areas.

Other

All published Innovative Technology Summary Reports are available on the OST Web site at http://www.em.doe.gov/ost under “Publications.” The Technology Management System (TMS), also available through the OST Web site, provides information about OST programs, technologies, and problems. The OST/TMS ID for Laser Cutting and Size Reduction is 1477.

SECTION 2
TECHNOLOGY DESCRIPTION

Overall System Definition

Historically, plasma-arc cutting has been the standard, or baseline, method for cutting in remote-handling, high-radiation environments. Plasma-arc cutting generates more smoke and metal vapor than laser cutting and it cuts at a slightly slower speed than the laser. These limitations influence the effectiveness of plasma-arc cutting at particular D&D sites. Laser cutting provides an alternative method to reduce the size of metal equipment by heating the metal with a laser spot and blowing/burning the melted metal from that spot. Figure 2-1 illustrates a typical set-up of a remote laser cutting system in a hot cell environment.

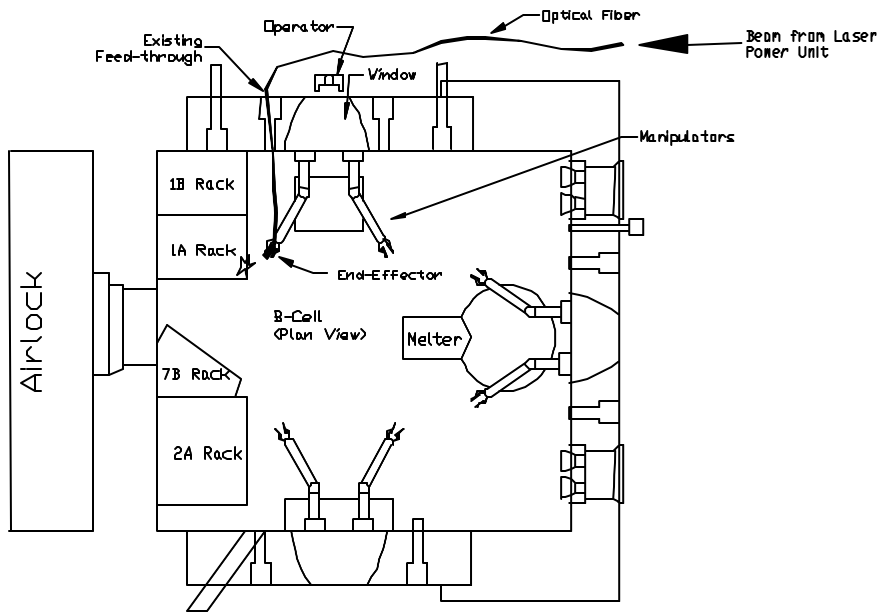

Figure 2-1. Schematic of major components used for a typical Remote Laser Cutting Set-Up, for the 324 Building 'B' Hot Cell, Hanford Reservation

PNNL System Operation

In a typical set-up, at least two operators are required for laser cutting and size reduction: one to operate the master/slave manipulator and one to operate the laser power unit. The manipulator operator manipulates the laser end effector with a standard master/slave manipulator, requiring roughly the same level of operator skill as the plasma torch operator. The laser operator controls the laser using a personal computer (PC). The laser operator determines the waveform (continuous wave, sine wave, or square wave), power output of the laser (continuously variable up to 2000 W), and opens the shutter to initiate the cut when requested by the manipulator operator. If these two operators are physically separated, they can communicate effectively by plant radio or similar devices. Depending on the application, another operator may be required for operational oversight.

For normal operation of the PNNL laser cutting and size reduction system, the following steps were performed:

- The laser operator started the cooling water flow to the laser cabinet and the flashlamp operation with the PC.

- The manipulator operator positioned the end effector near the target, and indicated to the laser operator the readiness to cut.

- The laser operator selected the power level and waveform on the computer and brought the laser into power operation.

- The manipulator operator depressed a permissive pedal, turned on the assist gas, and directed the laser operator to open the laser shutter. Opening the shutter allowed the laser beam to travel through the fiber optic cable, initiating the cut. The shutter could be closed three ways: the laser operator could close it with the computer, the manipulator operator could close it by lifting off the permissive pedal, or a personnel safety interlock switch could close it. The interlock switch would shut down the system if anyone inadvertently entered the laser-cutting enclosure.

For carbon and stainless steel, oxygen is the most efficient assist gas. For more reactive metals, such as titanium, air is sufficiently reactive and more economical. A minimal flow of assist gas, such as that obtained by 30-psi air is necessary to cool the end effector cone and prevent backsplash of metal. One attempt to cut aluminum was unsuccessful. Two possible reasons for this failure is reflectivity in the 1 µm wavelength and the formation of a stable oxide on the cutting surface.

ETEC System Operation

The general configuration used for the ETEC demonstration is shown in Figure 2-2. The laser resonator, power supply, water chiller, gas assist supply, and operational controls were located in non-hazardous environment for protection and maintenance accessibility. The laser focusing head and a tube holding fixture were located within the containment tent. The tent was fitted with a HEPA-filtered ventilation system, a viewing window constructed of laser-wavelength (1064 nm) absorbing material, and an interlocked door that shut off the laser if opened. Since the effective cutting distance was only a few millimeters, the primary laser hazard within the tent was potential eye exposure to a reflected laser beam. The beam was delivered to the cutting site within the containment tent using a 15-m-long, 1-mm-diameter-core fiber optic cable. The cable was terminated at the laser focusing head, which was mounted on the tube holding fixture. Oxygen assist gas was transported from a gas source/regulator outside the tent to the cutting site through a long tube that was attached to the laser focusing head. The laser was an off-the-shelf Lumonics 2-kW Nd:YAG laser, operating in a continuous wave mode.

The cutting process was automated by robotically controlling the tube and laser focusing head movements. This laser cutting and size reduction system was designed by ETEC and fabricated from off-the-shelf items. When installed, the control console was located outside the tent for remote operation of the laser cutting system. Cutting was performed by translating the focusing head, with its assist gas delivery system, along the length of the tube for longitudinal cuts, and rotating the tube for circumferential cuts. These motions were controlled remotely via the fixture console, with the operator monitoring the process through the tent-viewing window.

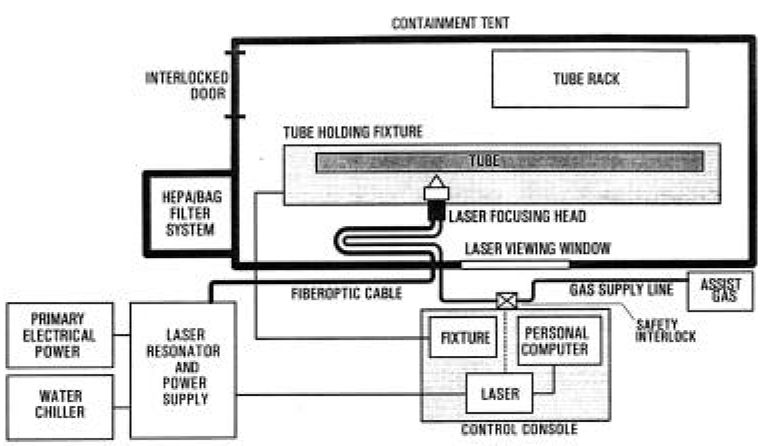

Figure 2-2. Schematic of the Laser Cutting Configuration for the ETEC Demonstration

SECTION 3
PERFORMANCE

Demonstration Plan

The PNNL and ETEC separately demonstrated the laser cutting and size reduction technology, which was developed to cut metal and equipment of almost any size and shape in a remote-handling, high-radiation environment. Both demonstrations used an off-the-shelf Lumonics 2-kW Nd:YAG (neodymium-doped yttrium aluminum garnet) laser operating in a continuous-wave mode. Innovations to laser cutting technology involve the use of fiber optic technology to deliver the laser beam to remote, hazardous cutting sites (Figure 1). The technology is an adaptation of the commercial laser-cutting method commonly used in automotive manufacturing and other industrial applications. Laser cutting's application to D&D projects at nuclear reactor and processing facilities across the DOE complex and the commercial nuclear industry was thought to offer potentially large benefits.

PNNL Demonstration Plan

The demonstration sequence at PNNL was designed to determine laser performance in cutting common materials found in contaminated areas, to observe the generation rate of effluent from the cutting operation, and to assess ease of use. The test sequence included a 'cold test' or non-radioactive test as a high radiation environment was not present during this portion of the demonstration. The effects of radiation on the fiber optic system were explored in the fiber optic cable irradiation testing portion of the demonstration.

During the PNNL demonstration, the target holding fixture captured off-gas generated by the cutting operation, and a blower drew gases and smoke through a high efficiency particulate air (HEPA) filter and discharged it through the building ventilation system. Effluent sampling was performed to determine airborne concentrations of chromium (IV) and other heavy metals in the surrounding air. Sampling results revealed that dangerous levels of contamination did not exist in the air at the jobsite.

A plan was developed to test the performance of the fiber optic cable under radiation conditions. Two competing processes affect the transmission of laser light through fiber optic cable in a radiation environment--radiation darkening and photobleaching. Radiation darkening is a loss of transmission in fiber optic cable due to a change in the cable structure from radiation damage. Photobleaching is an improvement in transmission by passing laser power through a cable resulting in irradiation damage being somewhat repaired. PNNL staff tested irradiated cable transmission both before significant laser power was passed through the cable and under power. Two types of fiber cable were tested--a high-OH concentration cable and a low-OH concentration cable.

ETEC Demonstration Plan

Laser Cutting and Size Reduction

The laser cutting was initiated with a series of cutting tests on clean mock-up tubes to refine laser system operating parameters. Those tests demonstrated that good cutting performance could be achieved using a laser power level of 0.8 kW, an oxygen assist gas pressure of about 70 psi, and a standoff distance between the tip of the focusing head and the cutting surface of about 5 mm. The optimum linear cutting speed established for the tube cutting was about 400 cm/minute. This produced a clean cut with little dross and a kerf width of about 0.9 mm. The cutting speed could be increased significantly by using higher laser power levels, but optimized cutting would have required an auto-focusing cutting head for finer control of the stand-off distance. The use of an auto-focusing head was not justified for this initial demonstration.

These system optimized cutting parameters were then utilized to segment the inventory of contaminated storage tubes. The laser cutting was controlled from outside the containment tent, and a radiation-trained worker was stationed in the tent to perform the material handling operations.

Plasma-Arc Cutting

The laser cutting demonstration was followed by a series of cutting tests using a plasma-arc torch and clean mock-up tubes. Those tests were performed to provide comparative data using current-practice (i.e., baseline) technologies, and the plasma-arc torch was selected because ETEC has used it extensively for a wide range of D&D applications. The plasma-arc tests used the same tube holding fixture, remote operation, and cutting procedures as used in the laser cutting demonstration.

ETEC's extensive experience with plasma-arc torches in D&D applications indicates that such torches require more frequent maintenance when used in extended applications. That factor was not demonstrated in this application because of the limited extent of the plasma-arc tests.

Results

The PNNL and ETEC testing and deployments demonstrated that laser cutting and size reduction technology has a number of advantages over other baseline technologies:

- The laser is markedly superior in cutting deformed metal and dirty material.
- The laser's cutting action is not significantly different from a plasma torch; however, the laser does not require the operator to strike an arc, as with the plasma torch.
- Laser cutting is somewhat faster and a much cleaner technology, generating less smoke and metal vapor.

PNNL Demonstration Results

Cutting Performance

The laser's performance in cutting various materials is summarized in Table 3-1. The results from the cold tests revealed the following:

- The cutting rate of the laser is highly dependent on the geometry of the item being cut.
- For carbon and stainless steel, oxygen is the preferred assist gas; for more reactive metals, such as titanium, compressed air is the better choice.
- Variations in assist gas pressure can affect the laser's ability to cut material. The specific threshold depends on material composition and geometry.

Table 3-1. Cutting Performance Results

Description of Item	Average Time of Complete Cut (min)	Assist Gas	Gas Pressure (psi)
1 in. stainless steel tubing	0.517	Compressed Air	85
3/8 in. diamond plate	0.587	Oxygen	70
2 in./1 in. carbon steel schedule 40	0.587	Oxygen	70
1 in. stainless steel ASME A53F	0.732	Compressed Air	85
1 in. stainless steel-304L schedule 40	0.758	Oxygen	---
¾ in. stainless steel conduit	0.767	Compressed Air	85-60
1 in. stainless steel ASME A53F	1.067	Oxygen	45
1 in. square tube 316 stainless steel	1.202	Oxygen	85
2 in. angle/1 in. carbon steel schedule 40	1.302	Oxygen	72
2 in. carbon steel schedule 40	1.437	Oxygen	85-70
3/2 in. carbon steel schedule 40	1.500	Oxygen	50-45
1 in. square stainless steel tube	1.517	Compressed Air	85-45
¼ in. carbon steel plate	1.772	Oxygen	30
4 in. angle/ ¼ in. iron	1.872	Oxygen	70
1 ¾ in. carbon steel round bar	2.867	Oxygen	90
2in./1in. carbon steel schedule 40	3.015	---	---
2 in. carbon steel square plate	3.033	Oxygen	75-70
3 in./4 in. carbon steel I beam	3.217	Oxygen	70
4 in. titanium plate	3.300	Compressed Air	70

Effluent Production and Monitoring

The generation rate of effluent produced by the cutting process was measured by monitoring the differential pressure change across the HEPA filter connected to the target holding fixture. Table 3-2 shows the change in the pressure differential over the course of the testing series.

Table 3-2. HEPA Filter Pressure Differential

Date	Pressure Differential in Inches of Water	
1/23/97	Beginning -	0.60
1/23/97	Ending -	0.60
1/28/97	Beginning -	0.58
1/28/97	Ending -	0.70
1/29/97	Ending -	1.25
1/30/97	Beginning -	1.25
1/30/97	Ending -	1.43
2/3/97	Beginning -	1.95
2/3/97	Ending -	2.20

Ease of Use

In general, the operators found the laser cutting and size reduction system easy to use. Based on operator experience, the laser cutting and size reduction system has the following features:

- The system can, in general, cut material at the desired location, cut difficult geometries in a straightforward manner, and cut material in its current condition.
- The system is easily handled with the hot-cell manipulator, allowing for precise placement.
- The system can cut complex geometries, such as a pipe within a pipe, in a single pass, simplifying complex tasks.
- Dirt, corrosion, material expansion, and surface contamination are less of a problem for the laser than for the plasma torch during laser cutting.

Fiber Optic Cable Irradiation Test

A test was performed to determine the characteristics of the fiber optic cable under radiation conditions. Two types of fiber cable were tested--a high-OH concentration cable designated as Cable A and a low-OH concentration cable designated as Cable B. Table 3-3 shows the results of the irradiation tests.

Table 3-3. Transmission Capability of Cables After Irradiation

Test Number	Total Radiation Exposure (Rads)	Starting Transmission (± 1.4%)		Ending Transmission (± 1.4%)	
		A	B	A	B
1	0	94.5	95.8	NA	NA
2	50,000	94.4	94.5	93.8	93.2
3	250,000	91.6	93.0	91.6	93.0
4	750,000	89.0	94.0	93.0	94.0
5	1,750,000	91.7	88.9	91.7	88.9

Test results show that radiation effects are observed when exposure is significant. The high-OH cable (A) started to show signs of radiation damage at a lower exposure level than the low-OH cable (B), but photobleaching quickly restored the transmission capabilities of the cable. When the exposure level was significant (Test Number 5), the degradation of the transmission cable could not be restored through photobleaching. At the end of the testing series, the high-OH cable had the greatest transmission capability offering a possible conclusion that a high-OH cable has a greater resistance to radiation damage.

Laser Cutting and Size Reduction

The laser cutting was initiated with a series of cutting tests on clean mock-up tubes to refine laser system operating parameters. Those tests demonstrated that good cutting performance could be achieved using a laser power level of 0.8 kW, an oxygen assist gas pressure of about 70 psi, and a stand-off distance between the tip of the focusing head and the cutting surface of about 5 mm. The optimum linear cutting speed established for the tube cutting was about 400 cm/minute. This produced a clean cut with little dross and a kerf width of about 0.9 mm. Figure 3-1 is a close-up photograph of a laser-cut mock-up tube section, showing the clean cut and absence of dross. Figure 3-2 shows a short test cut performed for the measurement of the kerf width. The cutting speed could be increased significantly by using higher laser power levels, but optimized cutting would have required an auto-focusing cutting head for finer control of the stand-off distance. The use of an auto-focusing head was not justified for this initial demonstration.

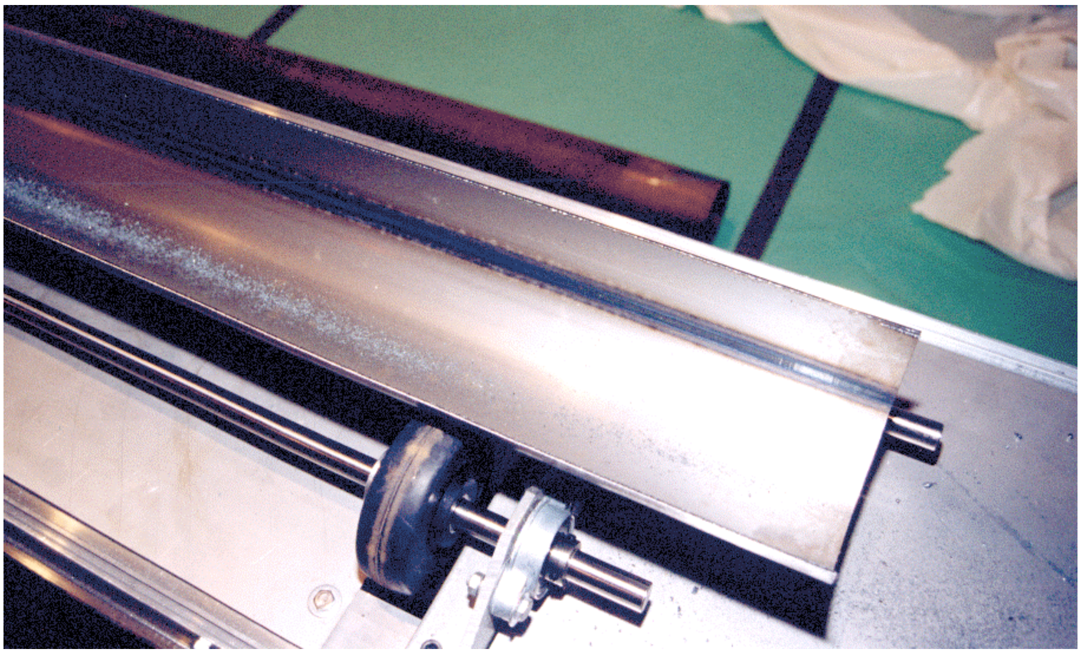

Figure 3-1. Close-Up of a Laser-Cut Fuel Storage Tube Section

Figure 3-2. Short Laser Test Cut to Measure the Kerf (Cut) Width

These system optimized cutting parameters were then utilized to segment the inventory of contaminated storage tubes. The laser cutting operation is shown in Figure 3-3, and a close-up of the laser cutting process is shown in Figure 3-4. (The photographs in Figures 3-3 and 3-4 were taken at the end of the mock-up test period rather than during contaminated-tube size reduction for safety reasons.) Each of the contaminated tubes was sectioned in about 2½ minutes, including the time required to load the tube on the fixture and unload the cut sections. The laser cutting was controlled from outside the containment tent (Figure 3-5), and a radiation-trained worker was stationed in the tent to perform the material handling operations. The laser system worked well, and the entire inventory of fuel storage tubes from the ETEC storage vault was successfully size-reduced for packaging (Figure 3-6) and disposal within a two-week period.

The cutting process generated more vapors than expected. This required that the in-tent radiation worker wear a filter mask, and that some modifications be made to the ventilation system to reduce maintenance requirements. The ventilation system modifications included the addition of a bag filter and two pre-filters upstream from the HEPA filter. The pre-filters were changed after every five tubes processed, and the bag filter was changed once a day (approximately every 30 tubes). The HEPA filter did not require replacement during the demonstration period using this configuration. Later laser cutting tests indicated that the vapor generation could be reduced by finer control of the laser focusing head stand-off distance using auto-focusing, and subsequent bench-scale tests also demonstrated it to be correlated with the thickness of the material being cut.

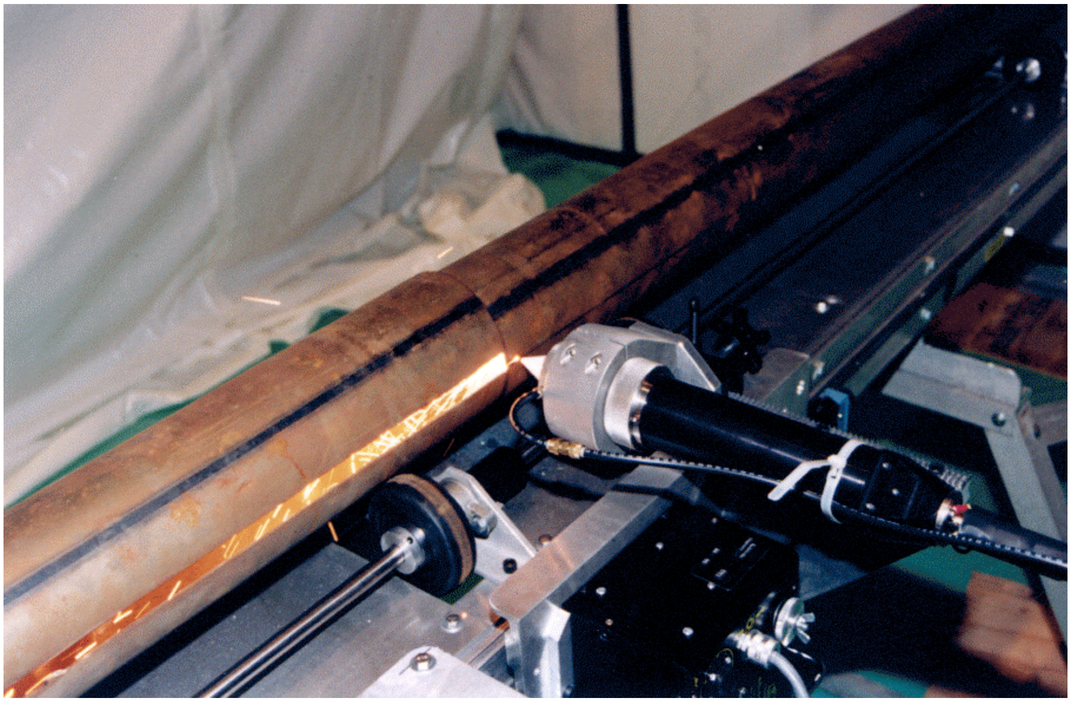

Figure 3-3. Laser Cutting of a Fuel Storage Tube

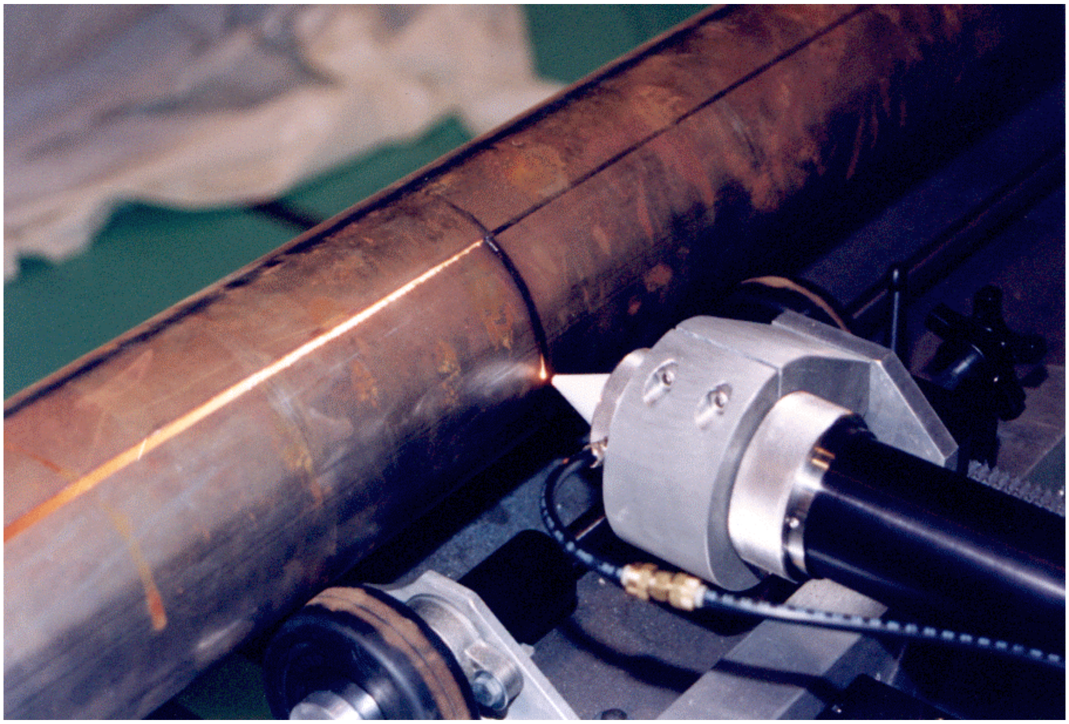

Figure 3-4. Close-Up of the Laser Cutting Process, Showing the Cutting Operation and the Laser Focusing Head

Figure 3-5. Remote Control of the Laser Cutting Operations from Outside the Containment Tent

Figure 3-6. Laser-Cut Tube Segments Packaged for Disposal

Plasma-Arc Cutting

The laser cutting demonstration was followed by a series of cutting tests using a plasma-arc torch and clean mock-up tubes. Those tests were performed to provide comparative data using current-practice technologies, and the plasma-arc torch was selected because ETEC has used it extensively for a wide range of D&D applications. The plasma-arc tests used the same tube holding fixture, remote operation, and cutting procedures as used in the laser cutting demonstration. Figure 3-7 shows the system in operation.

Results of the plasma-arc cutting tests showed that the optimum linear cutting speed was about the same as for the laser cutting, but the kerf width was about 2½ times larger (2.2 mm). A test cut used to measure the kerf width is shown in Figure 3-8. Plasma-arc cutting generated a proportionately larger quantity of secondary waste that included more airborne particulate and required more frequent air filter changes. ETEC's extensive experience with plasma-arc torches in D&D applications indicates that such torches also require more frequent maintenance when used in extended applications. That factor was not demonstrated in this application because of the limited extent of the plasma-arc tests.

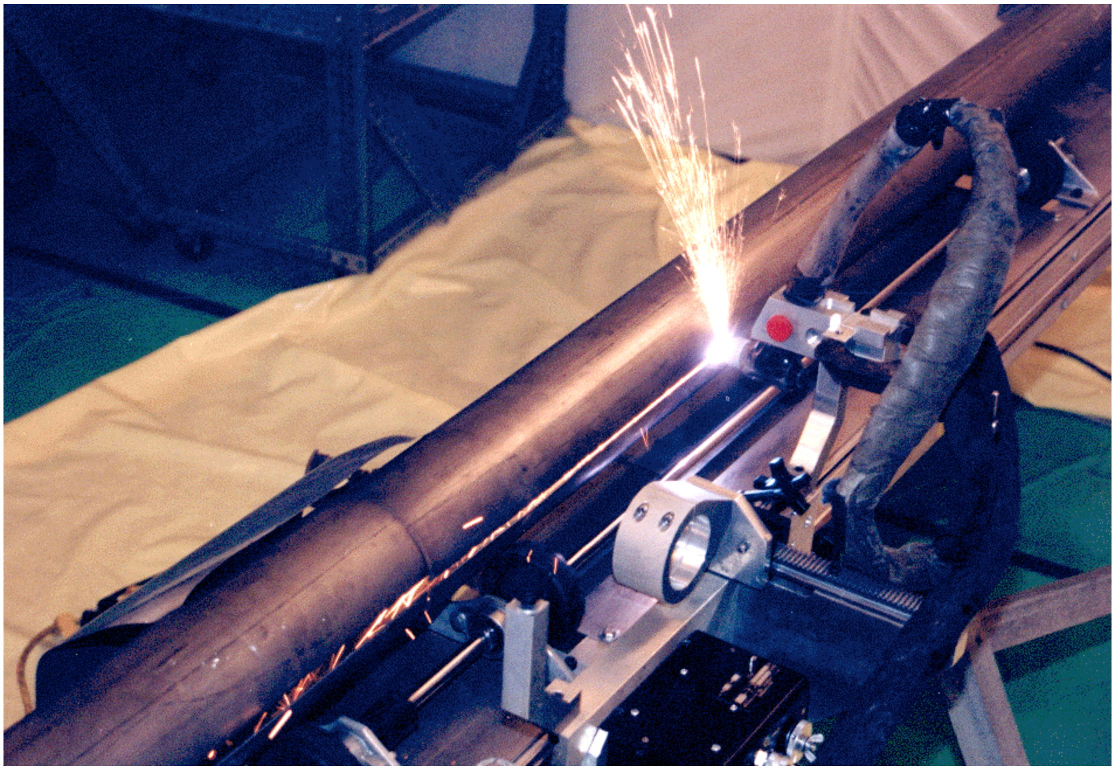

Figure 3-7. Plasma-Arc Cutting of a Mock-Up Fuel Storage Tube, Using the Same Fixture and Identical Cutting Procedures as Used in the Laser Cutting Demonstration

Figure 3-8. Short Plasma-Arc Test Cut to Measure the Kerf (Cut) Width

Cutting Performance

The ETEC laser cutting tests successfully demonstrated the use of an off-the-shelf laser system to segment a large inventory of contaminated storage tubes for inspection and disposal. The laser system was located outside of the hazardous materials handling and cutting environment, simplifying maintenance and precluding contamination of the more costly system components. The latter greatly improves transportability of the system from site to site and thus offsets the relatively high initial capital cost of the system. Preliminary laboratory tests demonstrated that this same laser system could be used to cut much thicker materials. Further, the laser cutting speed for the ETEC storage tubes could have been increased significantly by using a higher laser power and an auto-focusing cutting head, coupled with some modifications to the tube holding device or system.

Comparisons between the laser cutting and plasma-arc cutting results showed that the two technologies could cut at comparable rates, but the plasma-arc system generated a much larger quantity of secondary waste. That difference, plus the higher maintenance requirements for plasma-arc hardware, results in higher cutting costs for the plasma-arc system. For example, filter change-out is required 2½ times as often for plasma-arc cutting, and plasma head change-out is required about 40 times as often as replacement of the laser focusing head's front disposable cone. This translates to higher personnel exposures (more frequent and longer hazardous environment entries) and greater waste generation (filters, personal protective equipment) for plasma-arc cutting.

SECTION 4
TECHNOLOGY APPLICABILITY AND ALTERNATIVE TECHNOLOGIES

Competing Technologies

Oxyacetylene torch cutting—There is a possible explosion hazard when using oxyacetylene torches in hot-cell cutting.

Plasma-arc cutting--The main competing technology is plasma-arc cutting. Plasma-arc cutting is more commercially developed than laser cutting. It has a lower capital cost for units of similar cutting power and proven radiation hardness. The plasma torch does not present any unusual eye hazard and has a much more limited range. The limited range of the plasma torch precludes damage to structures at a distance from the intended cutting target. The main disadvantages of the plasma-arc cutting technology are that it generates a greater amount of smoke, metal vapor and secondary waste and has a slightly lower cutting rate.

Technology Applicability

Laser cutting and size reduction and associated system components described herein are commercially available. Prospective users must establish a set of procedures and safety protocols, similar to the procedures used in the demonstration to manage eye and skin burn hazards, and to protect any equipment that is not to be cut. Remote laser cutting is appropriate for use at any hot-cell D&D site where a plasma torch would be applicable and the following conditions exist:

- Smoke generation is a particular problem; i.e., HEPA filter plugging and there are visibility problems.
- Generation of secondary waste must be held to a minimum.
- Dirty or grout-covered materials are to be cut.
- Difficult geometries, such as expanded metal or pipe within pipe structures, are to be cut.

Patents/Commercialization/Sponsor

The laser used in both demonstrations was an off-the-shelf Lumonics 2-kW Nd:YAG (neodymium-doped yttrium aluminum garnet) laser, operating in a continuous wave mode. The technology is an adaptation of the commercial laser-cutting method commonly used in automotive manufacturing and other industrial applications.

SECTION 5
COST

Methodology

A cost analysis was performed to evaluate the plasma-arc torch and laser cutting and size reduction system and to determine the potential cost savings of laser cutting and size reduction. The objective of this cost analysis is to assist decision makers that are selecting from among competing technologies. The analysis strives to develop realistic estimates that represent actual D&D work within the DOE weapons complex. However, this is a limited representation of actual cost, because the analysis uses only data observed during the demonstrations. Some of the observed costs were eliminated or adjusted to make the estimates more realistic. These adjustments were allowed only when they would not distort the fundamental elements of the observed data (i.e., does not change the productivity rate, quantities, work element, etc.,) and eliminated only those activities which are atypical of normal D&D activities. Descriptions contained in later portions of this analysis detail the changes to the observed data.

Both technologies were demonstrated at the PNNL site and at the ETEC for size reduction of metallic waste items. The PNNL demonstration involved the size reduction of racks within the ‘B’ hot cell. The ETEC demonstration involved the size reduction of fuel tubes within a low-level radioactive environment. The majority of the demonstration at the PNNL site was actually performed in a “cold” environment. Therefore, certain cost factors, such as the effect of a hot-cell work environment on the life of the fiber optic cables, could not be evaluated.

Test engineers observed the demonstrations at both PNNL and the ETEC. Summary cost and performance data were provided for use in the cost analysis. Separate analyses were performed for each demonstration.

The cost and performance data collected for the PNNL demonstration was based on the number of days required to perform the same amount of D&D work (size reduction of racks within a non-radioactive environment). There was no quantity or unit of measure available for the racks; therefore, a production rate could not be determined. The cost and performance data collected for the ETEC demonstration was based on the cost per fuel tube size reduction. However, the data did not allow an analysis of production rate. Both cost analyses were based on acquisition of new technology equipment.

Personal protection equipment (PPE) costs are included in the ETEC cost analysis because a D&D laborer was stationed within the cutting cell to manually load and unload the cutting jig. PPE costs are not included in the PNNL cost analysis, because personnel would not be placed in a hot-cell during an actual technology deployment.

Cost Analysis

PNNL Demonstration

Data was provided that, for each technology, summarized the costs required to perform the same amount of work (size-reduction of racks). The demonstration assumed that work would be performed continually using three shifts per day. Costs were calculated for (1) size-reduction of racks including maintenance of technology equipment, (2) maintenance of electrostatic precipitators (ESP), and (3) maintenance of HEPA filter systems. The data provided showed that 133 days were required to size-reduce the racks using laser cutting and size reduction, while the plasma-arc torch required 146 days. Due to lack of data on the racks, no analysis was performed on production rate.

A labor rate of $35 per hour was used in the analysis. No information was provided as to labor burdens this rate might include.

Equipment costs were not included in the data provided. For both laser cutting and size reduction and the plasma-arc torch, an hourly equipment rate was calculated using a spreadsheet based on the methodology outlined in EP 1110-1-8, Construction Equipment Ownership and Operating Expense Schedule, Region 8, U.S. Army Corps of Engineers, August 1997. The hourly rates are based on the capital costs of new technology equipment, a discount rate of 5.6 percent, an assumed equipment life of

20,000 operating hours (approximately 5 years), estimated yearly usage of 1,040 hours (50% usage), and estimated operating and maintenance costs.

Costs for waste disposal were included in the data provided.

The following modifications were made to the cost data for laser cutting and size reduction to reflect a more typical technology deployment: The cost of the technology equipment was added to the analysis. Laser cutting and size reduction requires cooling of the laser head during operation. This was performed at the PNNL site by running a “dump-to-waste” water line to the laser. No costs for this cooling were provided with the data, and cooling costs are not included in the analysis.

ETEC Demonstration

Data was provided that, for each technology, summarized the costs required to size-reduce fuel tubes within a cutting cell. Costs were calculated for (1) size-reduction of fuel tubes included maintenance of technology equipment, (2) operation and maintenance of electrostatic precipitators, and (3) operation and maintenance of HEPA filter system. For a large-scale deployment, self-cleaning filters were assumed. This resulted in a large cost saving for both technologies. Production rates for both technologies were calculated from the data provided.

A labor rate of $100 per hour was used in the analysis. No information was provided as to labor burdens this rate might include.

Equipment costs were not included in the data provided. For both laser cutting and size reduction and the plasma-arc torch, an hourly equipment rate was calculated using a spreadsheet based on the methodology outlined in EP 1110-1-8, Construction Equipment Ownership and Operating Expense Schedule, Region 2, U.S. Army Corps of Engineers, August 1997. The hourly rates are based on the capital costs of technology equipment, a discount rate of 5.6 percent, an assumed equipment life of 20,000 operating hours (approximately 5 years), estimated yearly usage of 1,040 hours (50% usage), and estimated operating and repair costs.

Costs for waste disposal were included in the data provided.

The following modifications were made to the cost data for laser cutting and size reduction to reflect a more typical technology deployment: The cost of the technology equipment was added to the analysis. For laser cutting and size reduction, the hourly ownership and operating cost of a 25-ton capacity water chiller was added for cooling of the laser head during operation.

Cost Conclusions

PNNL Demonstration

A comparison of the major cost elements is shown in Table 5-1:

Table 5-1 Summary Cost Comparison

LASER CUTTING AND SIZE REDUCTION (INNOVATIVE)			PLASMA ARC TORCH (BASELINE)		
Cost Element	**Unit Cost**	**Production Rate**	**Cost Element**	**Unit Cost**	**Production Rate**
D&D Work	$5,944/day	N/A	**D&D Work**	$5,403/day	N/A
ESP Maintenance	$1,480/day	N/A	**ESP Maintenance**	$2,732/day	N/A
HEPA Filter Maintenance	$663/day	N/A	**HEPA Filter Maintenance**	$1,208/day	N/A

The comparative unit costs for the two technologies for the demonstrated application are:

$9,343/day – Plasma Arc Torch

$8,087/day – Laser Cutting and Size Reduction

Therefore, for the demonstrated application, the laser cutting and size reduction offers a 13 percent cost savings over the baseline alternative. The laser cutting and size reduction was more costly than the plasma-arc torch for performing the D&D work; however, it was less costly for ESP and HEPA filter maintenance due to the lower levels of airborne material generated during cutting operations.

Because no fixed cost data were supplied for the demonstration, no break-even analysis was performed.

Because of the higher capital cost of laser cutting and size reduction, a calculation was performed to determine the time required for the unit cost savings to recover the difference in capital cost between the two technologies.

Payback is achieved in about 132 days.

ETEC Demonstration

A comparison of the major cost elements is shown in Table 5-2:

Table 5-2 Summary Cost Comparison

LASER CUTTING AND SIZE REDUCTION (INNOVATIVE)			PLASMA ARC TORCH (BASELINE)		
Cost Element	**Unit Cost**	**Production Rate**	**Cost Element**	**Unit Cost**	**Production Rate**
D&D Work	$7.18/tube	N/A	**D&D Work**	$7.57/tube	N/A
Filter Maintenance	$0.04/tube	N/A	**Filter Maintenance**	$0.07/tube	N/A
Waste Disposal	$16.73/tube	N/A	**Waste Disposal**	$16.91/tube	N/A

The comparative unit costs for the two technologies for the demonstrated application are:

$24.55/tube – Plasma Arc Torch

$23.95/tube – Laser Cutting and Size Reduction

Therefore, for the demonstrated application, the laser cutting and size reduction offers a 2.5 percent cost saving over the plasma-arc. This difference is insignificant, and neither technology offers a cost advantage over the other.

Because no fixed cost data was supplied for the demonstration, no break-even analysis was performed.

The insignificant cost advantage of laser cutting and size reduction would not achieve payback of the capital cost difference between the two technologies.

SECTION 6
REGULATORY/POLICY ISSUES

Regulatory Considerations

The demonstration was granted a categorical exclusion under the National Environmental Policy Act (no environmental impact). Therefore, no specific permits from external agencies were required to use the laser during this demonstration.

Safety Risks, Benefits, and Community Reaction

Safety Risks

The Nd:YAG laser beam used in this project produces near-infrared light at 1064 nm. The lens of the human eye focuses the beam. Therefore, exposure to the light can present a severe eye hazard that must be carefully managed. In a hot cell, placing a sheet of 1064 nm absorbing plastic over the window(s) can provide adequate personnel protection. Using special laser goggles can also mitigate the hazard to personnel working with the laser cutting system.

When using the laser in a hot cell, it is theoretically possible to damage an oil-filled window by inadvertently directing the beam at the window. Calculations were performed to estimate the length of time at minimum distance before the oil in the window would start to vaporize. This risk can be minimized by limiting the ability of the manipulator to point at any windows in question and placing the 1064 nm absorbing plastic over the inside of the window.

Benefits and Environmental and Socioeconomic Impacts

The laser performs size reduction while generating less smoke, resulting in less frequent HEPA and/or electrostatic precipitator cleanings.

The laser has a faster cutting rate and is easier to use when cutting difficult geometries than the plasma torch. Laser cutting and size reduction has minimal economic or labor force impact. Generally, the same personnel who currently operate plasma torches and other cutting devices would operate the laser. The laser would require at least one additional person to operate the laser cabinet.

Community Reaction

The general public has limited familiarity with laser cutting and size reduction.

SECTION 7
LESSONS LEARNED

Implementation Considerations

The cables originally supplied with the PNNL laser were not robust enough when tried in the contaminated crane job (i.e., the fiber continuity wire failed during normal service). Improved cables were designed and obtained for the PNNL deployment.

The end effectors originally supplied with the PNNL laser were not optimized for freehand manipulation. The original end effectors were intended for use by an industrial robot. The focal length of the end effector determines how far the beam converges in front of the end effector. The end effectors used in the PNNL demonstration had a short focal length, providing the smallest spot size and thus maximum power density. The short focal length also causes the standoff distance to be critical. Small deviations in standoff distance from optimal cause the spot size to increase dramatically. This short focal length is not a problem for an industrial robot but presents a challenge to a manipulator operator.

The cutting process during the ETEC demonstration generated more vapors than expected. This required that the in-tent radiation worker wear a filter mask, and that some modifications be made to the ventilation system to reduce maintenance requirements. The ventilation system modifications included the addition of a bag filter and two pre-filters upstream from the HEPA filter. The pre-filters were changed after every five tubes processed, and the bag filter was changed once a day (approximately every 30 tubes). The HEPA filter did not require replacement during the demonstration period using this configuration. Later laser cutting tests indicated that the vapor generation could be reduced by finer control of the laser focusing head stand-off distance using auto-focusing, and subsequent bench-scale tests also demonstrated it to be correlated with the thickness of the material being cut. Plasma-arc cutting generated a proportionately larger quantity of secondary waste that included more airborne particulate and required more frequent air filter changes.

Technology Limitations/Needs for Future Development

The PNNL laser cutting end effector needs to be perfected for freehand use. Several improvements were proposed but were not implemented because of time and budget constraints. The simplest and most promising improvement would be to mount a positioning finger on the end effector so the manipulator operator could touch the finger to the cutting target to establish standoff distance instead of judging distance by eye alone. A focal length longer than 200 mm could also be tried because a longer focal length results in a larger and less critical optimum standoff distance but a larger focused spot size. The larger spot size would, however, reduce the energy density and thus decrease cutting rate and increase kerf width.

Further testing is needed to confirm the PNNL conclusion that high-OH concentration cables suffer less irradiation-induced darkening than low-OH concentration cables. Testing high-OH and low-OH cables was limited to irradiating one sample of each cable type. Higher irradiation levels should also be tried, as well as irradiation during cutting instead of sequential irradiation and photobleaching.

The laser cutting speed for the ETEC storage tubes could have been increased significantly by using a higher laser power and an auto-focusing cutting head, coupled with some modifications to the tube holding device or system.

Technology Selection Considerations

Laser cutting and size reduction is appropriate at sites where reducing smoke and off-gas and/or cutting difficult geometries is more important than the capital cost of equipment. Site conditions and specific job requirements will dictate the appropriate cutting technology used at a particular site. Innovative technologies, such as laser cutting and size reduction, should be considered within the spectrum of all available technologies.

APPENDIX A
REFERENCES

Bach, F.W., et. al., 1993, *Analysis of Results Obtained with Different Cutting Techniques and Associated Filtration Systems for the Dismantling of Radioactive Metallic Components*, EUR-14213.

Gabzdyl, J.T., 1996, *Effects of Gases on Laser Cutting of Stainless Steel*, Laser Institute of America Proceedings, October 14-17, 1996, Volume 81, p. C/39-C/44.

G. Subbaraman, L. B. Spiegel, J. Vetrovec, and R. N. Hindy, "Fiber Delivered Lasers for Dismantlement Applications," in *Decommissioning, Decontamination and Reutilization Worldwide Experience - D&D, What Does It Mean*, M. G. White, Ed., American Nuclear Society, Washington, DC, 10-14 November 1996, pp. 126-131

D. W. Kneff, S. N. Shah, R. B. Hardy, and R. A. Marshall, "Remote Laser Cutting Demonstration Test," Report No. RMHF-AR-0009, October 1998.

APPENDIX B
ACRONYMS AND ABBREVIATIONS

cm	centimeter
D&D	decontamination and decommissioning
DDFA	Deactivation and Decommissioning Focus Area
DOE	U. S. Department of Energy
ESP	electrostatic precipitator
ETEC	Energy Technology Engineering Center
HEPA	high efficency particulate air
ITSR	Innovative Technology Summary Report
kW	kiloWatt
m	meter
mm	millimeter
Nd:YAG	Neodymium-doped yttrium aluminum garnet
nm	nanometer
OH	hydroxide
OST	Office of Science and Technology
PC	personal computer
PNNL	Pacific Northwest National Laboratory
PPE	personal protection equipment
psi	pounds per square inch
RMHF	Radioactive Materials Handling Facility
TMS	Technology Management System
W	Watt
WA	Washington State