INNOVATIVE TECHNOLOGY
Summary Report

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Diamond Wire Cutting of the Tokamak Fusion Test Reactor Vacuum Vessel

Deactivation and Decommissioning
Focus Area

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Diamond Wire Cutting of the Tokamak Fusion Test Reactor Vacuum Vessel

OST/TMS ID 2389

Deactivation and Decommissioning
Focus Area

Demonstrated at
DOE Princeton Plasma Physics Laboratory
Princeton, New Jersey

Innovative Technology Summary Report

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.

All published Innovative Technology Summary Reports are available on the OST Web site at http://ost.em.doe.gov under "Publications."

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SECTION 1
SUMMARY

Introduction

The United States Department of Energy (DOE) continually seeks safer and more cost-effective remediation technologies for use in the 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 sponsors technology demonstration and deployment projects. Within these projects, developers and vendors of improved or innovative technologies showcase products that are potentially beneficial to the DOE's 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.

The DOE Princeton Plasma Physics Laboratory (PPPL) is a single-purpose fusion energy research laboratory that is operated by Princeton University and funded by the U.S. Department of Energy (DOE). PPPL operated the Tokamak Fusion Test Reactor (TFTR) from 1983 to 1997 to study magnetic confinement fusion energy. TFTR is now shut down and is being prepared for dismantling. Alternatives that allow for the cutting of the TFTR Vacuum Vessel (VV) in-situ and without the removal of vessel internals are greatly desired due to the potential risk for personnel exposure, spread of tritium contamination, and savings in dismantling time and costs.

- Diamond Wire Cutting (DWC) was selected as the innovative technology to demonstrate segmentation of the vacuum vessel. The primary objective of this demonstration was to determine if an effective method for dismantling TFTR was available that would not require workers to be in close proximity to highly contaminated and radioactive materials, thus decreasing the risk of personnel exposure. Such a technology could dramatically reduce health and safety risks for a D&D project.

Technology Summary

Problem

The record-breaking deuterium-tritium experiments conducted on TFTR resulted in vacuum vessel (VV) tritium contamination and activation of materials with 14 Mev neutrons. The total tritium content within the vessel is in excess of 7,000 Curies while dose rates approach 50 mRem/hr. These radiological hazards, along with the size of the Tokamak (110 cubic meters), present a unique and challenging task for dismantling.

Plasma arc cutting, the current baseline technology for dismantling fission reactors, provides for fast cutting times. However, to use a plasma cutting torch for TFTR dismantling, vessel internals would need to be removed at each cut location. This would require personnel entry into the VV with supplied breathing air in conjunction with "bubble suits". In addition, the plasma torch would require additional equipment, which could be difficult to set-up for remote/semi-remote operation, thus increasing risk and personnel exposure. The use of the plasma arc torch would also result in release of radioactive airborne contamination and harmful gases requiring extensive containment, filtering, and respiratory protection.

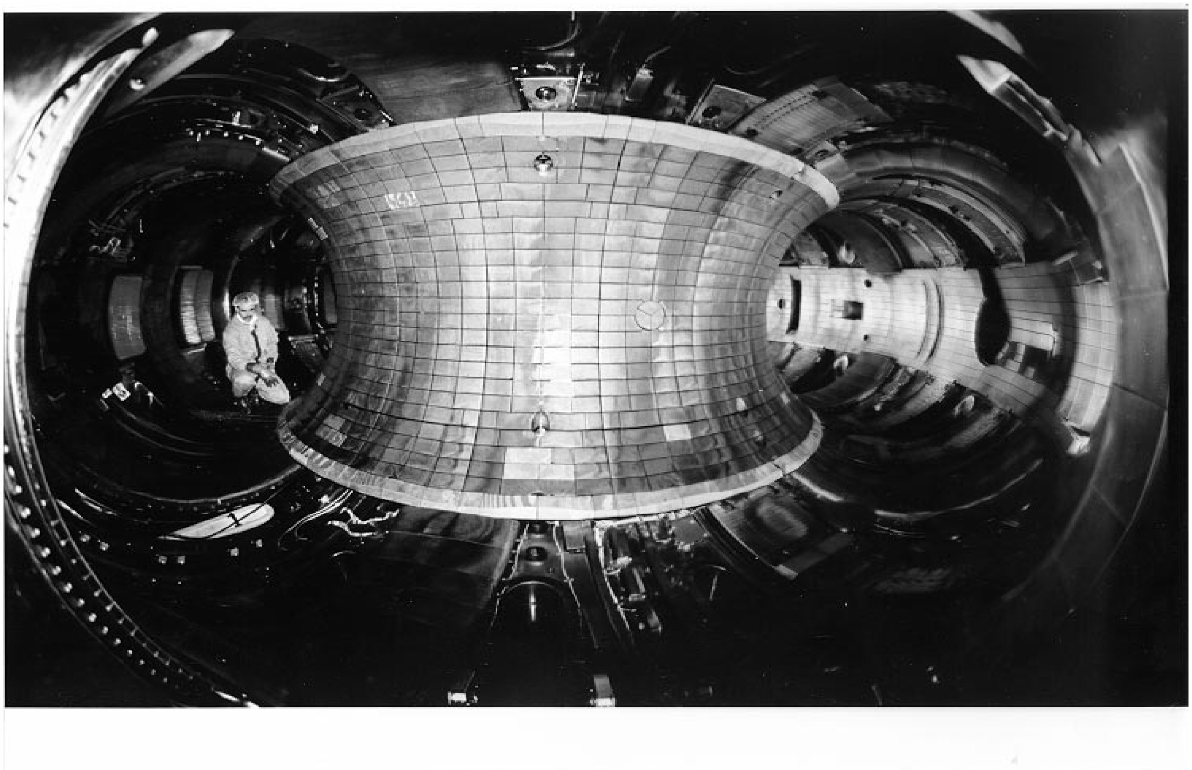

Figure 1
Internal TFTR vessel (prior to tritium operations)

Baseline Technology – Plasma Arc Torch

Plasma arc cutting is the current baseline technology for dismantling fission reactors. This technology is typically used because of its fast cutting times. However, there are significant personnel hazards associated with this technology application for the TFTR segmentation. In particular, the vessel walls are lined with graphite tiles which cannot be cut with this technology. Therefore, the tiles would need to be removed using personnel entry for physical removal. Multiple additional entries would be required to position the semi-remote operated plasma cutting system in order to cut the multiple layers of Inconel and stainless steel prior to the actual cutting of the ½" thick, 304 stainless steel vessel wall.

Figure 2
Plasma arc cutting on stainless steel (minimal PPE due to low/no activity)

Innovative Technology – Diamond Wire Cutting

An innovative approach for dismantling TFTR is the use of diamond-wire cutting technology. This cutting technology, developed in the early 1980's, has been successfully applied to the cutting of reinforced concrete. This technology has been successfully used on a variety of commercial and government facility decontamination and decommissioning (D&D) projects such as Fort St. Vrain and Shoreham for the removal of large thick concrete. Recent improvements in diamond wire technology have allowed the cutting of carbon steel components such as pipe, plate, and tube bundles in heat exchangers.

In the past, this technology was not considered for the following reasons:

- Concerns about the kerf (cutting path) closing and trapping the diamond wire as it cuts.
- Concerns that stainless steel tends to plate (cover the cutting edge) of the diamond bits making them ineffective.
- The use of water as a coolant for the diamond wire rope is not desirable in many radiological situations.

This demonstration addressed these concerns. Three void space fillers were selected for demonstration: Rheocell-15 (foamed, low density concrete), mortar and Perma-Fill foam (aqueous based). Each was expected to maintain the structural integrity of the vessel during cutting, clean the diamond bits as they cut through the vessel, limit the dispersal of contaminants, and provide shielding during cutting operations. Two non-aqueous agents (liquid nitrogen and air) were also tested to provide an alternative to water cooling. The bulk of this report addresses the performance of diamond wire cutting with water cooling using the Rheocell-15 void filler. Appendix C contains information on the other void fillers and cooling agents.

Figure 3
Diamond Wire Rope and Pulleys

Demonstration Summary

The performance of void space fillers and coolants during cutting of a TFTR surrogate section were evaluated to obtain optimum conditions for the size-reduction of TFTR for eventual disposal at Hanford. This demonstration also evaluated the costs of this innovative technology versus the costs of the baseline technology, plasma arc cutting.

The DWC demonstration was performed at PPPL from August 23rd to September 3rd, 1999. The majority of the demonstration was performed with water cooling. Water cooling was used on each surrogate (foam, Rheocell-15, mortar). As expected, the water cooling method performed well on both the Rheocell –15 and mortar filled surrogates. Rheocell-15 is a foaming agent that is added to a concrete and water matrix to form a concrete with a density of 30-50 lbs/ft3. Two diamond wire ropes were used to completion on these two surrogates to compare filler performance with respect to cutting rates.

The Rheocell-15 filled surrogate was selected for demonstration of the liquid nitrogen cooling method. The DWC vendor for the demonstration, Bluegrass Concrete Cutting, Inc. (BCCI), developed a proprietary method for deployment of the liquid nitrogen which provides for multiple cooling locations. The liquid nitrogen cooling was also successful and was performed to a 50% completion of the total cut area (beyond original scope as agreed upon by vendor and demonstration representatives). At this point, several wire failures were experienced at the ferrule (coupling) location. This is further discussed in Section 7.

Key Results

Key results of the demonstration are summarized below. Further details can be found in Sections 2 and 3 of this report

- Diamond Wire Cutting is expected to reduce the costs of TFTR segmentation to 37% of the expected baseline cost of plasma cutting.

- Rheocell-15 (low density concrete) is 3-5 times lighter than conventional concrete, which can lower shipping costs. In addition, this void filler flows similar to water and fills the smallest of cavities while providing adequate strength for cutting.

- The Rheocell-15 reduced wire friction and is believed to have enabled the liquid nitrogen cooling method. Conventional concrete provides significantly more friction (sand) and consequently more heat generation.

- Worker safety is significantly improved with this technology. Entry into the vacuum vessel is not required and cutting is performed by an operator outside of the containment, which reduces or eliminates:
  - Direct radiation exposure from gamma.
  - Potential from exposure from tritiated particulate.
  - Entry into confined space.
  - Use of supplied air breathing system.
  - PPE requirements.

- Void filling the vacuum vessel prior to cutting:
  - Enables the DWC technology.
  - Provides shielding from gamma radiation and is estimated to reduce those levels by 30-40%.
  - Places the segment in proper burial waste form.
  - Significantly reduces emanation of tritium during cutting.

- Water and liquid nitrogen cooling methods are both viable, but:
  - Particulate emissions are greater during cutting with liquid nitrogen (LN), which requires strict engineering controls and also require site specific evaluation for respiratory protection requirements.
  - Control of water is difficult and also requires good engineering controls. Collection and re-circulation of water is critical to minimizing waste and controlling radioactive liquid hazard. Periodic cleanup is necessary and prudent.

  - During the cutting operation the wire beads wear and reduce their diameter. This makes it difficulty to introduce new wires into the bottom kerf of the existing cut. "Wallowing", a means of wire rotation at near-zero tension, which widens the kerf, or frequent rotation of the wires should be considered to allow the wires to maintain a similar diameter during the entire cut.

Potential Markets

Diamond Wire Cutting can be a cost-effective and safer method of segmenting complex large metal structures, such as reactors, heat exchangers, tanks, and other unique structures. This technology can successfully cut varied layers of metals such as Inconel, stainless steel, and carbon steel while using concrete as a stabilizing matrix.

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Web Site

The TFTR D&D project can be found at http://dd.pppl.gov/

Licensing

No licensing activities were required to support this demonstration; however, Non- Disclosure Agreements were executed with Bluegrass Concrete Cutting, Inc by Florida International University, Princeton Plasma Physics Laboratory, and AEA Technologies, Inc. for the demonstration of the liquid nitrogen cooling system.

Permitting

No permitting activities were required to support this activity; however, NESHAPS should be evaluated on a case-by-case basis.

Other

All published Innovative Technology Summary Reports are available on the OST Web site at http://ost.em.doe.gov under “Publications.” The Technology Management System, also available through the OST Web site, provides information about OST programs, technologies, and problems. The OST reference number for “Diamond Wire Cutting Technology Assessment of the Tokamak Fusion Test Reactor Vacuum Vessel Surrogate” is #2389.

SECTION 2
TECHNOLOGY DESCRIPTION

Overall Process Definition

Demonstration Goals and Objectives -

The overall objective is to demonstrate the feasibility of diamond wire cutting for segmentation of the TFTR vacuum vessel. The baseline technology is considered to be excessive in cost and presents a high level of risk to personnel safety. The objectives of this project were as follows:

- Demonstrate the feasibility of cutting large stainless steel devices with internal steel impediments (Inconel and stainless steel) using a diamond wire.
- Compare cost and other performance factors of diamond wire cutting to the baseline technology.
- Demonstrate the structural and contaminant stabilizing ability of various void space fillers.
- Demonstrate the diamond bit cleaning action of the various void space fillers.
- Obtain data on the life and degradation of diamond wire cutting rope in cutting stainless steel.
- Demonstrate alternative coolants during application of diamond wire cutting.

Description of the Technology -

A diamond wire system provided by Bluegrass Concrete Cutting, Inc. was used for this demonstration. The diamond wire system, Figure 4, consists of a diamond matrix wire made to length for each individual cut and a hydraulic drive system. The diamond-embedded wire consists of wire rope, springs and synthetic diamonds bonded to the outside of a steel bead. The wire is strung through the inside of the beads and springs. Adjacent to every third bead, a ring is compressed around the wire to isolate the cutting beads, in groups.

To perform a cutting operation with the diamond wire rope, it may be necessary to drill a small hole at each end of the proposed cut. The wire is either passed through the two holes or wrapped around the object to be cut and then coupled together to envelope the cut area. The wire is then guided back to a drive wheel and around idler wheels that guide the wire. The wheel rotates and pulls the wire through the cut area. Water is typically used to cool the wire and to wash away the slurry created by the cutting operation. Wire tension is maintained via a hydraulic “stroke” cylinder that pulls the main drive wheel along its sliding carriage assembly. The main drive assembly is a simple flywheel that is either hydraulically or electrically driven.

Figure 4. The diamond wire system (hydraulic power unit is outside containment).

System Operation -

The diamond wire cutting system consists of three major components: hydraulic power unit, diamond wire drive unit (i.e., saw) and the diamond wire.

Hydraulic Power Unit

- 40 horse power electric motor
- 33 gpm flow, 3000 psi max
- 480 volt, 3 phase, 60 amp
- Dimensions: 56” L x 32” W x 25” H
- Weight: 1400 lb.

Diamond Wire Saw

- 32” diameter drive wheel
- 30.5” carriage stroke
- Wheel speed: 0-50 rpm
- Dimensions: 74” L x 31” W x 38” H
- Weight: 1200 lb.
- Heavy duty frame

- Available diameters: 10 mm, 13 mm, and 15 mm
- Electroplated diamond bond
- 10 mm wire was used for this demonstration

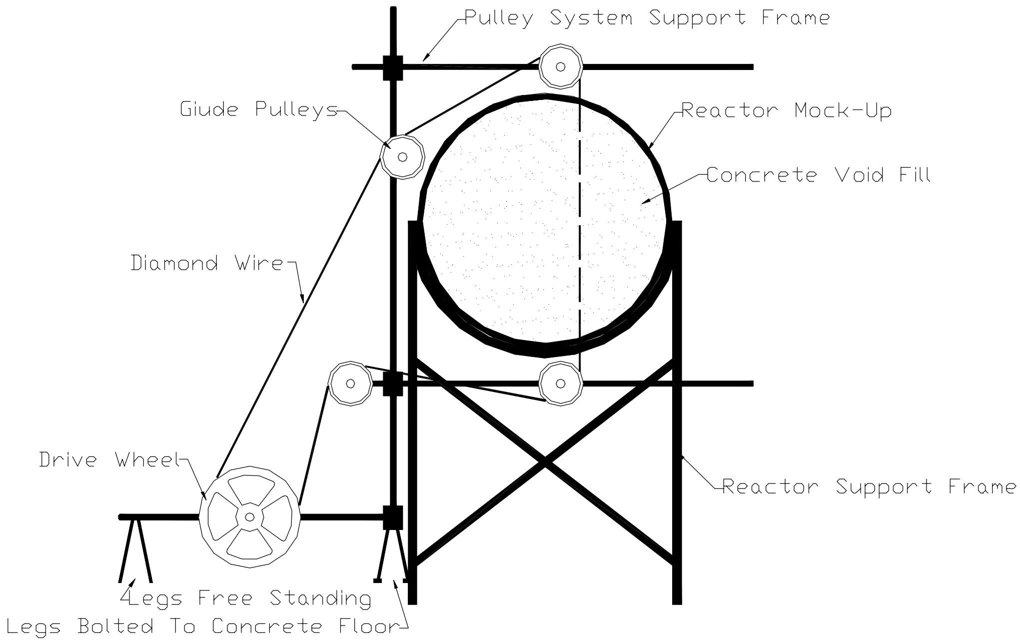
Maintenance - Required maintenance of the system is minimal. The hydraulic system is self-contained and requires checking of fluid level and inspection of hoses prior to use. The drive wheel may require replacement of a rubber belt that is in contact with the diamond wire. The guide pulleys may require replacement due to bushing wear which causes the pulley to wobble and effect wire fluctuations and movement. These pulleys are easily unbolted and replaced upon observation of excessive wire movement.

Wire repair/replacement - A ferrule (coupling) is used to join the wire after it is wrapped around the object. A hand operated crimping tool is used to crimp each end of the ferrule onto the wire. In the event of a coupling failure (during cutting) entry into the area is necessary to cut the wire and reconfigure the spring arrangement. A new ferrule is then re-installed.

Replacement of a diamond wire is accomplished by cutting the wire, attaching a new wire to the old wire with a ferrule, pulling the new wire into the groove using the old wire, and then cutting the old wire and crimping both ends of the new wire.

Water Cooling Operation -

Water cooling was the primary cooling media selected for initial cutting and evaluation of the various void filler media. Tap water was directed to the wire entry point, at the top of the surrogate, with a flow rate of approximately 1 gallon-per-minute. The water becomes entrained in the wire and kerf. As the wire exits the surrogate, the water then falls. During the demonstration a water collection system was developed to contain and collect the water. Reinforced PVC sheeting was suspended under the surrogate below the wire and guide pulleys. The majority of water was contained in the containment which then drained to a rectangular plastic pan. The water collected in the pan was then periodically pumped to a series of three 55-gallon drums. Collected water was pumped to the first drum where sediments would settle to the bottom. As the water rose to a pre-set height, a sump pump pumped the water into the second drum. The process continued in the same manner into the third drum, which in turn, provides constant metered flow to the cut location. This system provided for a quasi “closed system” water flow in order to conserve water and consequently reduce the amount of radioactive liquid generation. The system does not entirely contain the water. A small amount of water remains entrained with the wire and it misted in several directions according to the pulley configurations. The containment was maintained at negative pressure with a 2000 cubic feet per minute (cfm) HEPA filtered ventilation system to collect particulate, and provide air change, and to simulate the evacuation of tritium containment.



Water cooling set-up – Figure 5

Table 1. Operational parameters and conditions of the Diamond Wire Cutting demonstration

Working Conditions	
Work Area Location	RESA Building, PPPL..
Work Area Description	Indoor Area.
Work Area Hazards	Rotating equipment, high pressure hydraulics, noise, and projectiles.
Labor, Support Personnel, Specialized Skills, Training	
Work Crew	DWC equipment operator, laborer, health physics technician.
Additional Support Personnel	Full-time demonstration data taker.
Training	No additional training was required, as the D&D laborers were already working at the site.
Equipment Specifications, Operational Parameters, and Portability	
Equipment Design Purpose	Provide high speed wire rotation at prescribed pressure (tension) to cause friction, wear, and removal of material from object being cut.
Dimensions	System set-up is dependent on object to be cut.
System Materials	Diamond wire beads crimped on a wire rope with springs between beads, electro-hydraulic power unit, rotating wire drive unit, support piping, clamps, and guide pulleys.
Portability	Forklift required to unload power unit, power and drive unit is on wheels, all other material is portable.
Illumination	Portable lighting needed inside containment

Materials Used	
Personal Protective Equipment	Poly-cotton coveralls, shoe covers, latex gloves, safety glasses, hearing protection (outside containment).
Utilities/Energy Requirements	
Utilities	480V, 60 amp power supply 2- 120V, 15 amp power supplies

SECTION 3
PERFORMANCE

Problem Addressed

Segmenting of the TFTR VV using the baseline technology provided unacceptable risk at considerable cost. Throughout the DOE, and at many commercial nuclear sites faced with decommissioning, removal and subsequent size reduction of large heat exchangers, pressure vessels and reactor vessels present significant challenges with regard to personnel safety, cost, contaminant stabilization, void filling, waste acceptance, and transportation. The use of DWC technology significantly reduces many, and in some cases all, of these challenges. Historically, plasma or other types of torch cutting technology have been generally used for cutting metals. Objects cut with these technologies are typically single layer and can be cut cost effectively using appropriate engineering controls, assuming the hazards present allow personnel access. In cases where personnel access is not possible, robotics can be applied in combination with video cameras and engineering controls, albeit at significantly increased costs.

The purpose of this demonstration was to perform a complete cut of a multi-layer reactor vessel surrogate (TFTR) with multiple steel content (Inconel, stainless steel alloys) by integrating the use of various void fillers with the DWC system

Demonstration Plan

Site Description -

A test bed was designed and constructed to accommodate different and multiple cutting scenarios. The vacuum vessel surrogates were fabricated from ½" 304 stainless steel, Inconel, and graphite, and were of the same geometric shape as the TFTR vacuum vessel. The test bed provided structural support during the cutting and allowed for the removal of the expended vessel surrogate section and installation of a new section. The surrogate section of each vessel consisted of a cylinder that was approximately 48 inches in width and 90 inches in height. The support structure was inter-changeable with each surrogate section.

The surrogate filled with Rheocell-15 was placed on a support structure to simulate the relative conditions (height, accessibility) of the TFTR VV. The support structure was designed for ease of disassembly and re-use for each vessel surrogate section and capable of independently supporting each half of a surrogate section when completely severed.

Water collection containment was constructed with a portable filtration system for re-circulation and conservation of contaminated water (simulated). A BCCI-designed cooling system was also utilized to provide the proper cooling for water circulation. PPPL provided for filtration of the effluent prior to discharge to the PPPL storm sewer system, at the completion of each test.

A radiological containment was constructed to simulate the environment that would exist to contain airborne contaminants and water from the cutting.

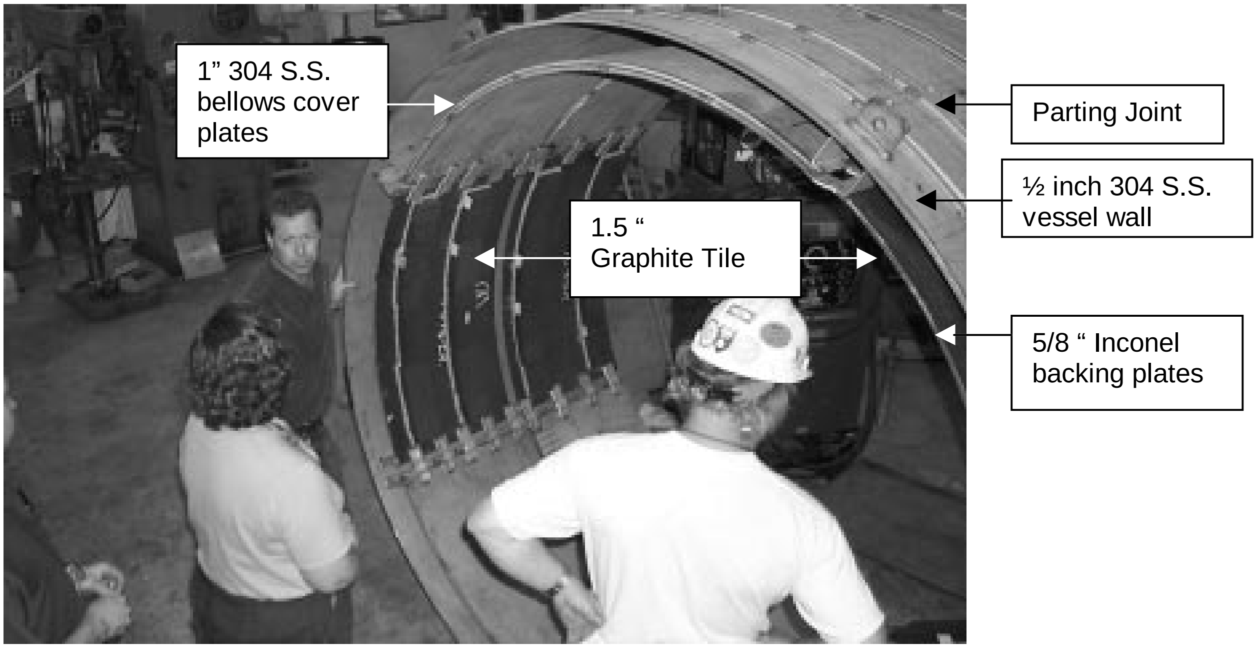


Figure 6 Vacuum vessel surrogate prior to fillling

Figure 7 Picture of Vacuum Vessel Surrogate filled with Rheocell-15

Major Objectives

The objective of this evaluation was to determine if available diamond wire cutting technology is suitable for cutting a surrogate section of the TFTR vacuum vessel and other stainless steel devices that require or will require D&D. In addition, the evaluation attempted to optimize the following variables:

- Personnel safety.
- Optimum void space filler material for the vacuum vessel.
- Optimum coolant for the diamond wire cutting technology.

Major Elements of the Demonstration –

- A Diamond Wire Cutting system was provided and operated by Bluegrass Concrete Cutting, Inc. (BCCI) for this demonstration.
- A containment structure was erected to contain the emissions and possible projectiles from wire failure.
- The cutting and support equipment was mobilized to the site and installed
- Diamond Wire Cutting was performed on the Rheocell-15 surrogate at two locations using water and liquid nitrogen cooling separately. Cutting was performed until two wires were expended.
- A complete cut was performed using water cooling through the entire surrogate section to evaluate the critical issue of kerf (cutting path) closure. During this phase, the diamond wire was changed, as needed, to complete the entire cut.
- Evaluation personnel collected data on the rate of cutting, maintenance, performance, waste generation, cost, and health and safety aspects of the diamond wire technology.

Results

The Diamond Wire Cutting technology was performed successfully using liquid nitrogen or water cooling. The DWC provided significant improvements in worker safety and cutting performance as compared to the baseline. A performance comparison between the two technologies is listed in Table 2.

Table 2: Performance comparison between the DWC and the baseline technology

Performance Factor	Baseline Technology	Diamond Wire Cutting
Number of personnel required in vacuum vessel	2 to 3 people (2 workers to remove tiles, remove other internal components and operate plasma system)	0 person
Number of personnel required outside contamination area	8-9 people (4 support people for air system ops, IH, and safety oversight, 2-3 RCT to monitor radiation readings and survey equipment out of contamination area)	2 people (1 worker to operate DWC, 1 RCT to survey equipment out of contamination area)
Time to assemble and setup technology	72 hrs	46 hrs
Time to segment vacuum vessel (avg.)	35 hrs	24 hrs
Expected total whole body exposure	1380 mRem	20 mRem
Expected release of tritium	23 Curies	8 curies

Performance Factor	Baseline Technology	Diamond Wire Cutting
PPE requirements	Air supplied bubble suits	Coveralls, hood, etc. (respirators possible)
Superior capability	• Plasma cutting is preferable for single layer cutting of metal plate and structural steel provided that proper health and safety controls can be implemented.	• DWC is operated remotely and provides significant reduction in personnel exposure and radionuclide emissions. • DWC, when combined with lightweight concrete void fillers, is the only technology capable of cutting complex structures with multiple layers of steel, including hardened steel such as inconel.

SECTION 4
TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Competing Technologies

Baseline Technology

Diamond Wire Cutting is not typically used for the cutting of metals. The competing technology for this application is plasma arc cutting. Plasma arc cutting utilizes an electrical power pack at 120, 240 or 480V and compressed air or gas, and through an umbilical, forms a plasma in a hand-held torch to perform cutting. The power requirements and type of gas are dependent upon the material and material thickness. When used in radiological environments, engineered ventilation, containment, respiratory protection, eye protection (flash/arc) and general safety requirements are developed based upon site-specific conditions.

Specific to PPPL and others, the plasma arc cutting technology needs to be remotely operated which requires special fixtures, engineering, and detailed planning and training.

Other Competing Technologies

Oxy-gasoline and oxy-acetylene are typical torch cutting devices to cut metals. Laser cutting technology is in development but has not been demonstrated in this application. Reciprocating and band saws can be considered for application, although the size of the TFTR VV prohibits this.

Technology Applicability

Diamond wire cutting technology is fully developed and deployed for size reduction of large concrete structures containing carbon steel in radiological environments. This technology has now demonstrated the ability to cut large metal structures containing softer metals, such as stainless steel, and one of the hardest metals, Inconel, in conjunction with a concrete-matrix. Lighter weight concrete, such as Rheocell-15 increased the capability of this technology while providing for radionuclide stabilization, strength, and shielding. This technology is superior to plasma arc cutting for large metal vessels and heat exchangers, and is particularly advantageous to those objects that are too large to ship or possess significant radiological hazards

Patents/Commercialization/Sponsor

Diamond wire cutting systems are commercially available. Vendors, as a service to a particular project, typically perform DWC. The types of DWC equipment are standard although the fabrication, type and orientation of the diamond wire rope vary from vendor to vendor.

SECTION 5
COST

Introduction

This cost analysis compares the innovative Diamond Wire Saw Technology, using both water and liquid nitrogen as coolants, with the baseline Plasma Torch Cutting Technology. These technologies are used to size reduce metal, including, stainless steel and inconel. When all factors are carefully considered, the cost to use the innovative technology, with either coolant, is approximately 37% of the cost to use the baseline for similar tasks under similar conditions.

Methodology

The cost analysis for the innovative technology is based mostly on recorded data performance and published vendor prices. The demonstration of the diamond wire saw was performed in a non-radiological environment at PPPL; however, the cost analysis is based on a radiological environment. Therefore, some of the elements were modified to reflect this and are based on data from other PPPL radiological work. For the baseline technology, the cost analysis is derived from multiple sources. The costs for containments, vacuum vessel entries, personnel, and PPE are based on a recent vacuum vessel entry performed at PPPL in September 1999. Production rates for the plasma cutting torch are from reference 1 in Appendix A. The diamond wire saw was demonstrated in several separate tests making a partial cut through the TFTR mockup, each varying the void fill or coolant until an optimum set of conditions were determined. Then, using the optimum void fill (Rheocell-15) and coolant (water), a full cut of 4.15 m^2 (44.7 ft^2) was performed. The liquid nitrogen coolant test was performed as a partial cut of 1.24 m^2 (13.3 ft^2). The data for the partial liquid nitrogen cut was extrapolated to a full cut for the purposes of this cost analysis. Production rates and cutting times are listed in Table 4.

For the baseline technology, the reactor mockup would be empty and contain no void fill. The plasma torch makes three cuts around the circumference of the reactor (two inside and one outside) for a total linear cut length of 21.8 m (71.5 ft). Production rates and cutting times are listed in Table 4.

During the demonstration, the crew size for the innovative technology remains constant and is based on the vendor providing the equipment and personnel to perform the cutting. The crew size for the baseline technology fluctuates and is based on the recent TFTR vacuum vessel entry performed at PPPL in September 1999. The labor rates for site personnel are based on standard rates for the PPPL site. The equipment costs for the innovative technology are based on vendor supplied information. The baseline technology, plasma torch, is a custom-made technology designed specifically for cutting the TFTR and will be disposed of afterwards. To determine the baseline equipment cost per cut for this cost analysis, the estimated purchase price is divided by the number of cuts required to fully dismantle the TFTR. Additional details of the basis of the cost analysis are described in Appendix B.

Cost Data

Costs to Purchase, Rent, or Procure Vendor-Provided Services

The innovative technology is available from the vendor with optional components. The purchase price of the basic equipment and optional features used in the demonstration are shown in Table 3. Rental of the equipment is available from the vendor.

Table 3. Innovative technology acquisition costs

Acquisition Option	Item	Cost
Equipment Purchase	1. Drive wheel, hoses, and pulley wheels	$15,000
	2. Hydraulic power pack	$18,000
	3. Required accessories	$10,000
	4. Plated diamond wire per foot	$78
	5. Liquid nitrogen coolant equipment	$5,000
Vendor Provided Service	1. Mobilization and demobilization/travel	$3,000
	2. Two operators and equipment	$2,000
	- per day, excludes per diem (water coolant)	
	- per day, excludes per diem (liquid nitrogen coolant)	
	3. Diamond-wire charge per square foot of cut [1]	$70
Equipment Rental	1. Mobilization and demobilization/travel	$2,000
	2. Daily rental (exludes HEPA filtration)	
	- water coolant system	$250
	- liquid nitrogen coolant	$1,000
	3. Weekly rental (exludes HEPA filtration)	
	- water coolant system	$1,000
	- liquid nitrogen coolant	$4,000
	2. Monthly rental (exludes HEPA filtration)	
	- water coolant system	$3,000
	- liquid nitrogen coolant	$16,000

[1] This charge is calculated by determining the total length of wire used for the cut divided by the total square foot of cut area and then multiplying this number by the $75 per linear foot to determine the cost per square foot that will be charged.

The baseline technology is a custom-made piece especially designed for the PPPL TFTR vessel vacuum. The total cost of this technology is estimated to be $500,000. This technology would be used for the dismantlement of the TFTR and then would be disposed as low-level radioactive waste. A total of 10 cuts would be made to complete the dismantlement of the reactor. Therefore, for the purposes of this cost analysis, the purchase price of the plasma torch was divided by 10 for an equipment cost per cut.

Costs

Tables 4 lists the unit costs to perform one complete cut through the vacuum vessel for the innovative and baseline technologies. The unit costs are based on the detailed costs in Tables B-2, B-3, and B-4. Tables 5 and 6 show a relative percentage for each activity of the demonstration. This percentage represents each activity's cost relative to the total cost of the job. Additionally, the site-specific conditions that can affect the cost of the activity are identified on the right side of the table.

Table 4. Unit cost for each technology to perform one complete cut through the vacuum vessel

Technology	Total Cost	Cutting Rate	Cutting Time
Diamond wire saw – water coolant	$45,531	0.32 m^2/h (3.42 ft^2/h)	13 h
Diamond wire saw – LN coolant	$52,046	0.32 m^2/h (3.42 ft^2/h)	13 h
Plasma torch	$123,391	200 mm/min (39.3 ft/h)	1.8 h

Table 5. Breakdown of innovative technology total cost

Activities	Percent of Total Cost (Water Coolant)	Percent of Total Cost (LN Coolant)	Site Specific Conditions
Cut Reactor Mockup	44.5	53.4	Cut 44.7 ft^2 of stainless steel and inconel (includes liquid nitrogen cost of $0.77/L)
Erect Enclosure	10.2	8.9	Size 24.5 ft L x 8.25 ft W x 16 ft H
Additional Productivity Activities	6.8	7.8	8.6 h (water), 12.2 (LN) non-cutting activities
Transport To and From Site	6.6	5.8	Vendor provided cost
Disassemble Equipment	5.7	5.0	8 h decontamination and survey of equipment
Void Fill Reactor	5.4	4.8	6.5 yd^3 Rheocell-15
Solid Waste Disposal	4.1	2.0	34 ft^3 (water), 19 ft^3 (LN)
Vendor Matriculation	4.0	4.4	GET, Rad Worker, Cryogenic training (for LN only)
Treatment of Water and Slurry	4.0	0	65 gallon water to be solidified
Remove Enclosure	3.4	3.2	12 h to remove
Setup Equipment	2.5	2.4	Includes water containment system or LN lines
Replace/Splice Diamond Wire	2.4	2.1	9 coupling changes and 6 wire changes
Load Equipment	0.3	0.2	0.5 h to load equipment
Unload/Move Equipment to Work Area	0.1	0.1	0.25 h to unload equipment

Table 6. Breakdown of baseline technology total cost

Activities	Percent of Total Cost	Site Specific Conditions
Setup Equipment	43.3	Includes price for custom-made remotely operated plasma torch.
Erect Enclosure for Vessel Entry	10.2	1000 ft^3 PVC enclosure.
Remove Bellows Cover Plates	9.8	16 h to unbolt stacked bars on outside of VV
Floor Installation in VV	8.3	8 h install, includes lighting
PPPL Worker Training	4.7	Mockup training and air-fed PPE suit training for 19 site personnel
Erect Enclosure Outside VV	3.9	Size 24.5 ft L x 8.25 ft W x 16 ft H
Reposition Equipment	3.5	6 h to reposition from inside to outside VV
Remove Materials from Internal	3.1	8 h for 7 D&D workers
Solid Waste Disposal	2.6	59 ft^3 includes plasma torch
Remove VV Entry Enclosure	2.5	16 h to remove
Remove Graphite Tiles	2.4	4 h to remove prior to cutting
Void Fill Reactor	2.0	6.5 ft^3 after cutting
Decontaminate, Package Equipment	1.8	16 h to decontaminate and survey equipment
Remove Remaining Enclosure	1.3	12 h to remove
Cutting of Circumference	0.4	7.87"/min cutting rate (200mm/min.), 23.8 ft cut length
Cutting of Internal Components	0.2	2 parallel cuts, 47.6 ft length

Payback Period

For this demonstration, the innovative technology saves approximately $70,000 over the baseline for a similar job size. At this rate of savings, the purchase price for the diamond wire saw would result in a total equipment cost of $66,700, which would be recovered in the first job using the innovative technology.

- saw and equipment ($43,000) Re-use
- 240 ft of plated diamond wire ($18,720) Consumable
- liquid nitrogen coolant equipment ($5,000) Re-use

Observed Costs for Demonstration

Figure 9 summarizes the costs observed for both innovative technologies and the baseline technology for cutting 44.7 ft^2 of the TFTR mockup. The details of these costs are shown in Appendix B, which includes tables B-2 through B-4. These tables can be used to compute site-specific costs by adjusting for different labor rates, crew makeup, etc.

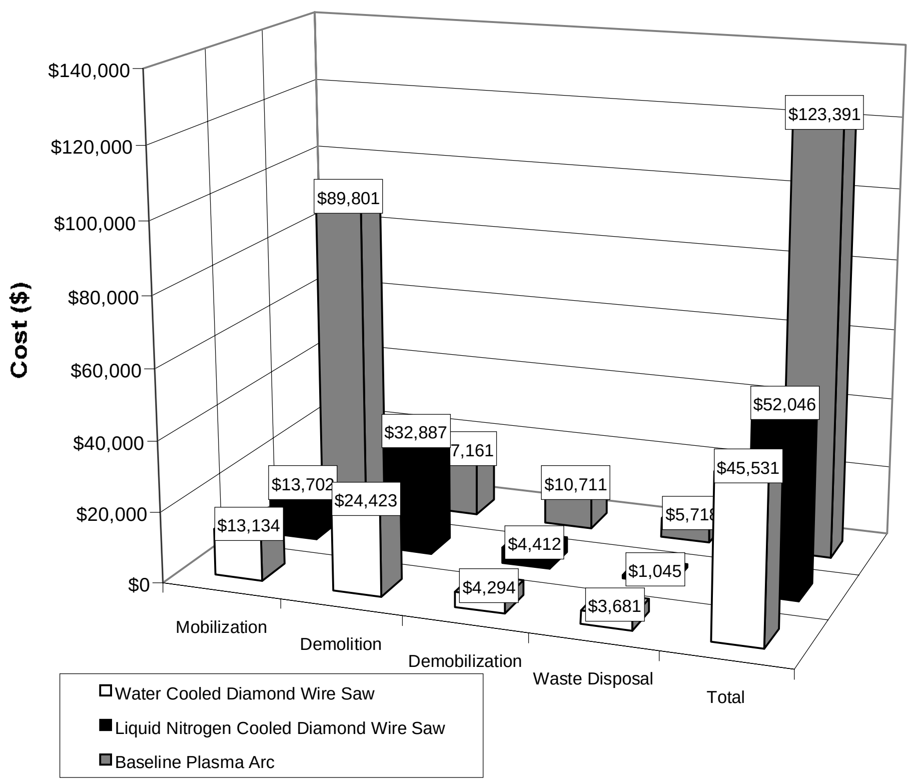


Figure 8 Summary of technology costs.

Cost Conclusions

The cost to use the innovative technology, diamond wire with water coolant, is approximately 87% of the cost of using the liquid nitrogen coolant with the innovative technology and approximately 37% of the cost of using the baseline technology for this demonstration. The savings from baseline result from the fact that when using the innovative technology, no internal components of the vessel vacuum has to be removed prior to cutting, and the vacuum vessel will be void filled prior to cutting encapsulating the tritium in concrete. This reduces the number of containments required for the cut and the number of personnel at the work site.

Cutting of the TFTR mockup would be performed in different ways for the two technologies. The innovative technology, diamond wire saw, would cut through the reactor and void fill for a total cut area of 4.15 m^2 (44.7 ft^2). The baseline technology, however, would make three cuts around the circumference of the reactor (two inside and one outside) for a total linear cut length of 21.8 m (71.5 ft). Two parallel cuts, approximately 6 inches apart, inside the vacuum vessel are necessary to remove the internal plates to provide access to the vessel wall for further cutting. Cutting rates for the two technologies are therefore expressed in different units. The diamond wire saw has a cutting rate of 0.32 m^2/h (3.42 ft^2/h). This cutting rate is the same for both water-coolant or liquid nitrogen coolant. The plasma torch's cutting rate is 12 m/h (39.3 ft/h).

The major difference in the costs for the innovative and baseline technologies is the necessity for personnel to enter the reactor vessel during the baseline technology. This is necessary to complete the following activities:

- remove graphite tiles prior to cutting since the plasma torch will not cut through graphite,
- remove the tile backing plates, protective plates, etc. in order to cut the outer vessel wall.
- setup the remotely operated plasma torch equipment,
- reposition on the outside of the reactor after the internal cutting is completed, and
- remove all debris and cut media at the end.

These activities require additional containment and ventilation, a higher level of PPE protection (Level A), and additional personnel due to increased risk of tritium contamination.

SECTION 6
REGULATORY AND POLICY ISSUES

Regulatory Considerations

The regulatory/permitting issues related to diamond wire cutting, as well as the baseline technology, are as follows:

- Occupational Safety and Health Administration (OSHA) 29 CFR 1926
- Occupational Safety and Health Administration (OSHA) 29 CFR 1910
- National Environmental Policy Act (NEPA) of 1969 (PL 91-190) and Amendments
- 10CFR21 – DOE NEPA Guidelines
- 40 CFR 61 Subpart H – National Emission Standards for Hazardous Air Pollutants
- 10 CFR 835 – Occupational Radiation Protection

Safety, Risks, Benefits, and Community Reaction

The benefits listed below were realized in the demonstration of diamond wire cutting technology. These benefits will be incorporated into the plan to segment the TFTR VV.

- Significantly reduced fumes and airborne contamination.
- Minimized personnel exposure resulting from remote operation of the saw unit and the associated reduction in dose rate from the additional shielding from the void filler.
- No pre-dismantling work would be required inside the vacuum vessel, which eliminates the requirements for confined space entry and use of supplied air breathing equipment.
- Reduced risk of spread of tritium contamination.
- Reduced overall costs compared to plasma arc cutting.
- Provided a technical solution to a difficult and complex disassembly and segmentation of the TFTR vacuum vessel.

SECTION 7
LESSONS LEARNED

Implementation Considerations

Diamond wire cutting is a mature technology for concrete cutting applications. As a result of this demonstration, the technology has also proven to be applicable to size reduction of large metal vessels such as, reactors, heat exchangers, and tanks when combined with some form of concrete matrix. The technology is particularly advantageous when there are significant health and safety concerns with the baseline technology. Utilization of a skilled and experienced operator/vendor is critical to the cutting success and performance. Selection of a concrete filler that meets the cutting, stabilization and shipping constraints is also critical to the success of the project

Strong consideration must be given to the selection of water or liquid nitrogen as the cooling media. This decision must be based upon particular radionuclide hazards and their application to feasible engineering controls for each media. Liquid waste generation and the subsequent solidification and treatment can be costly and difficult. In contrast, the airborne dry particulate generated when using LN cooling is also of concern along with oxygen deficiency. Removal of the graphite tiles at the cutting locations is also receiving strong consideration in future planning to reduce emissions during cutting.

The TFTR segmentations were limited to a 10 mm wire diameter due to the width of the parting joint. The use of a larger diameter wire would result in cutting through the shoulders of the parting joint which increases the amount of material (stainless steel) to be cut before cutting of the actual vessel wall. If the structure (to be cut) allows the use of a larger diameter wire, greater tension can be placed on the wire, which can increase cutting rate.

Technology Limitations and Needs for Future Development

Object must be solid in nature or be filled with a material of strength in excess of 100 psi.

Need for an improved ferrule to minimize periodic entry for inspection and replacement. Welding of wire to replace ferrule is being considered.

The TFTR D&D project is also considering removal of the graphite tiles at the cut locations. This will reduce metal tritide emissions associated with the cutting. An ALARA analysis will be performed to evaluate the exposure concerns.

Improved methods to contain water.

Technology Selection Considerations

Based upon the demonstration at PPPL on the TFTR surrogate, the diamond wire cutting technology is superior to the baseline technology for both cost and safety considerations. The combination of void filling with this cutting technology will significantly reduce personnel radiation exposure through shielding, remote operation (normal application of this technology), and radionuclide stabization.

Both low-density concrete and mortar proved to be acceptable void fillers and provide numerous benefits, both for health and safety, and technical performance.

Liquid nitrogen and water proved to be effective cooling media. The choice of either will depend upon evaluation of the radioisotopes of concern and associated hazards presented by the methods of engineering control, respiratory protection, and waste management.

APPENDIX A
REFERENCES

1. Bach, Fr.-W, Steiner, H, and Pilot, G., Year. Analysis of Results obtained with different cutting techniques and associated filtration systems for the dismantling of radioactive metallic components. *Journal* volume information: pgs. 680-700.

2. Litka, Tom J., Advances Consulting Group, Inc. for PPPL, "TFTR Vacuum Vessel Segmentation Approaches Study, December 1994".

APPENDIX B
COST COMPARISON

ASSUMPTIONS:

- Where work activities were performed by site personnel, the overhead and general and administrative (G&A) markup costs are not included. Indirect costs were omitted from the analysis since overhead rates can vary from contractors and locations.
- Site-specific costs such as engineering, quality assurance, administrative costs and taxes were omitted from this analysis.
- Vendor-provided service hourly rate for the innovative technology, diamond wire equipment, and personnel was calculated using the formula:

  ($2000 daily rate/10 h/day) + ($148 per diem/10 h/day * 2 workers) = $200/h labor + $29.60/h per diem = $229.60/h
- Plasma arc for the baseline technology must be custom built to work inside the TFTR, therefore, it would be purchased by PPPL and discarded at the end of the dismantlement of the TFTR. For the purposes of this cost estimate, the total purchase price of $500,000 would be divided by the number of cuts (10) to totally dismantle the TFTR. The price per cut has been applied to the cost estimate in Table B-4.
- Forklift hourly rates are based on construction equipment estimates taken from RSMeans, *Building Construction Cost Data*, 1999.
- Hourly rates for site-owned equipment was based on a straight-line depreciation of purchase price. Assumed 5 y expected useful life of equipment at 2000 h/y.
- Baseline cost analysis is based on actual observation from PPPL entry into the vessel vacuum in September 1999 and the document *TFTR Vacuum Vessel Segmentation Approaches Study, December 1994*.
- This analysis assumes that the work area was radioactively contaminated during cutting although, in fact, the surrogate was not.

MOBILIZATION (WBS 331.01)

<u>Erect Enclosure</u>:

Innovative technology: (Tables B-2 and B-3)

This activity is the observed time for constructing a 92.5-m^3 (3,267-ft^3) enclosure.

- The dimensions of the enclosure were 24.5 ft L x 8.25 ft W x 16 ft H.
- Three site D&D workers took four days to construct the wood, herculite®, and lexan® enclosure.

Same activity for water-cooled and LN-cooled technology.

Baseline technology: (Table B-4)

Multiple enclosures and a wooden work platform needed to be constructed prior to cutting using the plasma arc technology.

- A PVC tent with a dual chamber is required at the entry point for the vacuum vessel.
- A 2-1/2 in. wide wood flooring inside the vacuum vessel is needed

to prevent injury and provide a work platform.

- An enclosure outside the vacuum vessel in the same dimensions and material as the innovative technology.

This element also includes rental costs for ventilation systems for both enclosures and two truckloads of Grade D breathing air required for the air-fed suits.

Void Fill Reactor:

Innovative technology: This activity is the observed time to add Rheocell-15 to the reactor surrogate. Includes vendor time and equipment for the pump, hoses, and site personnel. Only site personnel would be wearing PPE (without a respirator) during this activity. Same activity for water-cooled and LN-cooled technology.

Baseline technology: This activity is the same for the innovative technology, except that this happens after the cutting is completed.

Reactor Preparation:

Innovative technology: No additional preparation required.

Baseline technology: This activity involves entry into the vessel vacuum and the removal of graphite tiles at the cut location. An 8 in. wide path of tiles along the circumference of the reactor will be removed. This is necessary because the plasma arc cannot cut through these tiles.

Transport To and From Site:

Innovative technology: This activity includes the transportation of vendor's equipment and personnel from their location to PPPL and back to the vendor. This is based on a quote from the vendor. Same activity for water-cooled and LN-cooled technology.

Baseline technology: Not applicable. Equipment will be owned and operated by PPPL.

Training (Vendor Matriculation):

Innovative technology: This activity includes all site training and badging of vendor personnel. Includes GET, Radiation Worker, and Cryogenic Training (for liquid-nitrogen cooled technology only).

Baseline technology: Assumed that all PPPL personnel were already trained for GET and Radiation Worker. This activity includes the following training:

- air-fed (bubble) suits
- mockup training on installation of plasma torch
- mockup training on removal of bellows cover plates

Unload/Move Equipment to Work Area:

Innovative technology: This activity is the observed time for unloading equipment from the vendor's flatbed truck with a forklift operated by a site D&D worker and moving it to the work area. Same activity for water-cooled and LN-cooled technology.

Baseline technology: Not applicable.

Setup Equipment:

Innovative technology: This activity involves preparation of the vendor equipment and site ventilation unit in the work area prior to operation and is based on observed duration.

- For water-cooled technology, includes cost and time for setup of water containment system.
- For LN-cooled technology, includes setup of LN lines from trailer to work area.

Baseline technology: This activity involves installation of a specially designed and engineered fixture that allows for 360 degree rotation as a cutting platform for the plasma torch.

DECOMMISSIONING (WBS 331.17)

Cut Reactor Surrogate:

Innovative technology: This activity includes only the observed duration for the diamond wire to cut the surrogate. Activities such as changing the wire or the coupling, moving the pulley wheels, etc., are included in activities listed below. Since the equipment operators can be located up to 100-ft from the work area, no PPE is required during cutting.

- The total area of the reactor surrogate cut was 4.15 m^2 (44.7 ft^2).
- Cutting time was observed to be 13 h.
- Total cutting rate was calculated as 0.32 m^2/h (3.42 ft^2/h).
- Wire usage rate is calculated as follows:
  - *6 wires * **40** ft/wire = 240 linear feet of wire used*
  - *240 feet/44.7 ft^2 of cut area = 5.37 ft/ft^2 wire*
  - *5.37 ft/ft^2 * $70/linear ft = **$375.90/ft^2 wire usage rate***
  - *$375.90/$ft^2$ *44.7 ft^2 cut area = **$16,803 wire usage cost***

The cutting rate was consistent for both the water-cooled and LN-cooled technology. However, LN costs were included as follows:

- rental of 1500 gal nitrogen truck which holds 139,665 ft^3 of LN = $50/day. Assumed rental for 9 days.
- LN = $1.00/100 ft^3
- Wire usage rate is calculated as follows:
  - *6 wires * **55** ft/wire = 330 linear feet of wire used*
  - *330 feet/44.7 ft^2 of cut area = 7.38 ft/ft^2 wire*
  - *7.38 ft/ft^2 * $70/linear ft = **$516.60/ft^2 wire usage rate***
  - *$516.60/$ft^2$ *44.7 ft^2 cut area = **$23,092 wire usage cost***
- delivery vendor personnel for setup = $374
- measured LN consumption was 375 L/m^2 (9.19 gal/ft^2) for a total of 1556.25 L (~37,250 ft^3).
- unit cost calculated for LN to be $0.77/L.

Baseline technology: This activity is for the cutting time of both internal materials and the circumference of the vacuum vessel wall. This includes the following:

- purchase of the specially designed plasma arc system (see Assumptions), cost per cut $50,000.
- operation of equipment by PPPL personnel.
- cutting rate of 200 mm/min.
- Two parallel cuts will be made of the internal components for a total of approximately 14,500 mm (92.5 ft) cut length.
- The circumference cut will be a single cut for a total of 7250 mm (47.6 ft) cut length.

Replace/Splice Wire:

Innovative technology: This activity includes the observed time to replace the diamond wire, change the coupling on an existing wire, or shorten an existing diamond wire. PPE with respirator is required during this activity.

- Avg time to change coupling = 6 min.
- Avg time to change wire = 14 min.
- Coupling changed nine times and wire changed six times during cut.

Same activity for water-cooled and LN-cooled technology.

Baseline technology: Not applicable.

Additional Productivity Activities:

Innovative technology: This activity covers additional non-cutting activities that are necessary to complete the cutting. These include moving the pulley wheels, wallowing old wires to allow the new wires to fit in the cut-line, modifying the water collection system, addition of water to the collection system barrel, etc. Time is based on observed duration. PPE with respirator is required for all portions of this activity performed within the containment.

Additional time is added for the LN-cooled technology, which includes time for the LN to flow freely through the lines for every system startup and allowing time for the LN to dissipate for proper oxygen levels before entering containment.

Baseline technology: This activity includes the removal of 25 ft^2 of bellows cover plates after cutting the internal components and repositioning of the plasma arc for the circumference cut.

DEMOBILIZATION (WBS 331.21)

Remove Internal Material:

Innovative technology: Not applicable.

Baseline technology: This activity includes the removal of all material from the cut location and clean-up of debris left inside the vacuum vessel.

Disassemble Containment:

Innovative technology: This activity includes the disassembly, decontamination (if applicable), and radiological survey of the containment. This number is estimated and is based on past experiences with similar types of work. PPE without respirators is required for all personnel.

Additional time is added for the LN-cooled technology for removing the LN lines from the nitrogen truck to the work area.

Baseline technology: For the plasma arc technology, two containments must be disassembled. PPE without respirators is required for all personnel.

- enclosure for vacuum vessel entry.
- enclosure around the cutting area.

Disassemble Equipment:

Innovative technology: This activity includes the disassembly, decontamination, and final radiological survey of the diamond wire equipment within the work area. This number is estimated and is based on past experiences with similar types of equipment. PPE without respirators is required for all personnel. Same activity for water-cooled and LN-cooled technology.

Baseline technology: This activity is the same as the innovative technology.

Load Equipment:

Innovative technology: This activity is the observed duration for moving the equipment from the work area and loading the diamond wire equipment on a flatbed truck using a forklift operated by PPPL personnel. Same activity for water-cooled and LN-cooled technology.

Baseline technology: Not applicable.

WASTE DISPOSAL (WBS 331.18)

Treatment of Liquid Waste and Slurry:

Innovative technology: This activity involves the solidification of all water and slurry from the Water Containment System used during the cutting. Due to tritium contamination, all water is to be solidified. Based on demonstration, it is estimated that 65 gal will be generated from each cut. Solidification agent costs $10/lb with a 30 part water, 1 part solidifier ratio.

Does not apply to LN-cooled technology.

Baseline technology: Not applicable.

Disposal of Solid Waste:

Innovative technology: This activity is the disposal of all solidified water, compactible waste, and pieces of vendor equipment that could not be decontaminated. Includes all PPPL costs as well as Hanford disposal rate. Breakdown of disposal includes:

- 15 ft^3 of solidified water/slurry (water-cooled technology only)
- 15 ft^3 of compactible waste from containment (wood is expected to be non-contaminated and is not included).

- 4 ft^3 of waste from cutting activities and/or decontamination of vendor equipment. Includes equipment pieces that could not be decontaminated.

Baseline technology — Same as the innovative technology. Totals of waste for the plasma arc include:

- 40 ft^3 compactible waste from tent and enclosure material.
- Approximately 4 ft^3 of waste from the demonstration and equipment decontamination.
- 15 ft^3 of waste from contaminated plasma torch.

Personal Protective Equipment
The PPE requirements for the innovative and baseline technologies are very different. For the innovative technologies, Level C protection is required. Some tasks for the innovative technologies (either water-cooled or LN-cooled), however, do not require the respirator. PPE requirements for the baseline, Plasma Arc, technology are for Level A protection. An air-fed suit is required due to the chance for internal uptake of tritium. Table B-1 below defines the PPE and their associated costs. PPPL hires a laundry service to clean various PPE items.

Table B-1. PPE Requirements

With Respirator	Unit	Quantity per box	Cost per box	Cost per unit	Disposed or Laundried	Laundry costs	Lifespan	Total cost
Cloth coveralls	ea			$5.90	L	$2.39	80	$6.02
Poly booties	pr	50	$16.95	$0.34	D	---	---	$0.34
Cloth overshoe	pr			$1.84	L	$0.27	80	$0.69
Cotton gloves	pr	100	$14.15	$0.14	D	---	---	$0.14
Rubber gloves	pr			$1.75	L	$0.32	80	$0.82
Cloth hood	ea			$1.16	L	$0.77	80	$1.93
Full-face respirator	ea			$174.00	L		200	$0.87
Respirator cartridges	pr			$11.74	D			$11.74
TOTAL With Respirator								**$22.55**
TOTAL Without Respirator								**$9.94**
TOTAL With Air-Fed Suit								**$309.94**

Table B-2. Diamond Wire Saw - Water Coolant

Work Breakdown Structure (WBS)	Unit	Unit Cost $	Qty	Total Cost $	Computation of Unit Cost						Comments
					Production Rate	Duration (HR)	Labor & Equipment Costs: Labor/Equipment Items	$/HR	Equipment/ Materials	Total $	
MOBILIZATION (WBS 331.01) Subtotal				$13,133.77							
Erect Enclosure	ft^3	$1.42	3,267	$4,628.65		32	3DD, 1/10 ENG	$108.24	Containment	$1,165	8.3 ft W x 24.5 ft L x 16 ft H
Void Fill Reactor	yd^3	$380.51	6.5	$2,473.30		3.75	2DD, ENG, 1/2 HP, Vendor	$238.25	Rheocell-15 PPE	$1,580	Includes stand-by time, & hose
Transport to and from Site	LS	$3,000		$3,000.00			BCC	$3,000.00		$0	Flat rate per vendor
Vendor Matriculation	LS	$1,837		$1,836.80		8	BCC	$229.60		$0	GET, Rad Worker
Unload/Move Equipment to Work Area	LS	$67		$67.46		0.25	BCC, DD, FL	$269.83			
Setup Equipment	LS	$1,128		$1,127.56		2.74	BCC, DD, 1/4 HP, VENT	$271.74	WCS, Filters	$383	WCS =Water Containment System
DEMOLITION (WBS 331.17.04) Subtotal				$24,422.56							
Cut Reactor Mockup	ft^2	$453.30	44.7	$20,262.39	3.42	13	BCC, 1/4 DD, 1/4 IH, 1/2 HP, VENT	$266.13	Diamond wire usage	$16,803	Wire usage = see text for explanation
Replace/Splice Diamond Wire	LS	$71.52	15	$1,072.79		2.25	BCC, 1/4 DD, 1/4 IH, 1/2 HP, VENT	$266.13	PPE	$474	9 coupling changes, 6 wire changes
Additional Productivity Activities	ft^2	$69.07	44.7	$3,087.39		8.55	BCC, 1/4 DD, 1/4 IH, 1/2 HP, VENT	$266.13	PPE	$812	Includes non-cutting activities such as moving pulley wheels, etc.
DEMOBILIZATION (WBS 331.21) Subtotal				$4,294.44							
Remove Enclosure	ft^3	$0.48	3,267	$1,562.06		12	3DD, 1/2 HP, VENT	$117.76	PPE	$149	
Disassemble Equipment	LS	$2,607.52		$2,607.52		8	BCC, 2DD, 1/2 HP, VENT	$313.52	PPE	$99	Includes decon and survey of equipment.
Load Equipment	LS	$124.86		$124.86		0.5	BCC, 1/2 DD, 1/2 FL	$249.72		$0	
WASTE DISPOSAL (WBS 331.18) Subtotal				$3,680.67							
Treatment of Water & Slurry	gal	$28	65	$1,810.67		3	2DD, 1/2 HP	$83.56	Solidifier	$1,560	Solidifier @ $10/lb
Solid Waste Disposal	ft^3	$55	34	$1,870			Disposal Fees	$55.00			Solidifed water, slurry, compactable waste
TOTAL				**$45,531.43**							

CREW AND EQUIPMENT FOR INNOVATIVE TECHNOLOGY (Both Water and Liquid Nitrogen Cooled)											
Crew Item	**Rate $/HR**	**Abbrevi-ation**	**Crew Item**	**Rate $/HR**	**Abbrevi-ation**	**Equipment Item**	**Rate $/HR**	**Abbrevi-ation**	**Equip Item**	**Rate $/HR**	**Abbrevi-ation**
Skilled labor	$33.84	DD	Industrial Hygienist	$47.33	IH	Forklift	$6.39	FL			
HP Technician	$31.75	HP	Vendor, void fill	$87.50	Vendor	Ventilation unit	$0.36	VENT			
Engineer	$67.19	ENG	(includes pump equip)								
Bluegrass Concrete Cutting	$229.60	BCC									
(includes equipment)											

Table B-3. Diamond Wire Saw - Liquid Nitrogen Coolant

Work Breakdown Structure (WBS)	Unit	Unit Cost $	Qty	Total Cost $	Computation of Unit Cost						Comments
					Production Rate	Duration (HR)	Labor & Equipment Costs				
							Labor/Equipment Items	$/HR	Equipment/ Materials	Total $	
MOBILIZATION (WBS 331.01) Subtotal				$13,701.51							
Erect Enclosure	ft^3	$1.42	3,267	$4,628.65		32	3DD, 1/10 ENG	$108.24	Containment	$1,165	8.3 ft W x 24.5 ft L x 16 ft H
Void Fill Reactor	yd^3	$380.51	6.5	$2,473.30		3.75	2DD, ENG, 1/2 HP, Vendor	$238.25	Rheocell-15 PPE	$1,580	Includes stand-by time, & hose
Transport to and from Site	LS	$3,000		$3,000.00			BCC	$3,000.00		$0	Flat rate per vendor
Vendor Matriculation	LS	$2,296		$2,296.00		10	BCC	$229.60		$0	GET, Rad Worker, Cryogenic Training
Unload/Move Equipment to Work Area	LS	$67		$67.46		0.25	BCC, DD, FL	$269.83			
Setup Equipment	LS	$1,236		$1,236.11		3.25	BCC, 3DD, 1/4 HP, VENT	$339.42	Filters	$133	
DEMOLITION (WBS 331.17.04) Subtotal				$32,886.90							
Cut Reactor Mockup	ft^2	$621.22	44.7	$27,768.66	3.42	13	BCC, 1/4 DD, 1/4 IH, 1/2 HP, VENT	$266.13	Wire usage, LN	$24,290	Wire usage = see text for explanation, Liquid nitrogen = $0.77/L
Replace/Splice Diamond Wire	LS	$71.52	15	$1,072.79		2.25	BCC, 1/4 DD, 1/4 IH, 1/2 HP, VENT	$266.13	PPE	$474	9 coupling changes, 6 wire changes
Additional Productivity Activities	ft^2	$90.50	44.7	$4,045.45		12.15	BCC, 1/4 DD, 1/4 IH, 1/2 HP, VENT	$266.13	PPE	$812	Includes non-cutting activities such as moving pulley wheels, etc.
DEMOBILIZATION (WBS 331.21) Subtotal				$4,412.29							
Remove Enclosure	ft^3	$0.51	3,267	$1,679.92		13	3DD, 1/2 HP, VENT	$117.76	PPE	$149	
Disassemble Equipment	LS	$2,607.52		$2,607.52		8	BCC, 2DD, 1/2 HP, VENT	$313.52	PPE	$99	Includes decon and survey of equipment.
Load Equipment	LS	$124.86		$124.86		0.5	BCC, 1/2 DD, 1/2 FL	$249.72		$0	
WASTE DISPOSAL (WBS 331.18) Subtotal				$1,045.00							
Solid Waste Disposal	ft^3	$55	19	$1,045			Disposal Fees	$55.00		$0	Compactable waste
TOTAL				$52,045.70							

Table B-3. Baseline – Plasma Torch

Work Breakdown Structure (WBS)	Unit	Unit Cost $	Qty	Total Cost $	Computation of Unit Cost						Comments
					Production Rate	Duration (HR)	Labor & Equipment Costs				
							Labor/Equipment Items	$/HR	Equipment/ Materials	Total $	
MOBILIZATION (WBS 331.01) Subtotal			$89,801.21								
Erect Enclosure for Vessel Entry	ft^3	$12.57	1,000	$12,567.98		24	3 DD, 1/2 HP	$117.40	See comment	$9,751	Containment, air system, and breathing air
Floor Installation in Vacuum Vessel (VV)	ft^2	$68.53	150	$10,278.88		8	6 DD, 2 HP, CR, HVAC	$330.04	See comment	$7,639	Flooring, lighting, PPE 2 1/2 ft wide floor
Erect Enclosure Outside VV	ft^3	$1.47	3,267	$4,796.59		32	3 DD, 1/10 ENG	$108.24	See comment	$1,333	Containment, ventilation unit
PPPL Worker Training	LS	$5,810		$5,809.52		8	10 DD, 5 HP, 2 IH, 2 ENG	$726.19		$0	Mockup training and air-fed suit training
Remove Graphite Tiles	ft^2	$184.43	15.8	$2,914.00		4	6 DD, 2 HP, ENG, IH	$381.06	PPE, tools, bags	$1,390	Remove 8" wide x circumference of mockup
Setup Equipment	LS	$53,434		$53,434.24		6	6 DD, 2 HP, ENG, HVAC	$365.48	See comment	$51,241	Plasma torch system, local ventilation, PPE
DEMOLITION (WBS 331.17.04) Subtotal			$17,160.87								
Cutting of Internal Components	ft	$9.15	47.6	$435.38		2	2 DD, 2 HP, ENG, HVAC	$230.12	PPE	$90	Cutting rate=200 mm/min Two parallel cuts.
Remove Bellows Cover Plates	ft^2	$483.56	25	$12,088.96		16	6 DD, 2 HP, IH, HVAC	$345.62	Tools, PPE	$6,559	
Reposition Equipment	LS	$4,328.50		$4,328.50		6	7 DD, 3 HP, IH, HVAC	$411.21	See comment	$1,861	Local ventilation, PPE
Cutting of Circumference	ft	$12.94	23.8	$308.03		1	3 DD, 2 HP, ENG, HVAC	$244.10	PPE	$113	Cutting rate=200 mm/min Single cut.
DEMOBILIZATION (WBS 331.21) Subtotal			$10,710.74								
Remove Materials from Internal	LS	$3,834.76		$3,834.76		8	7 DD, 3 HP, 3/4 IH, 3/4 HVAC	$391.44	See comment	$703	PPE (2 air fed suits, 8 Level C), HEPA Vac
Remove VV Entry Enclosure	ft^3	$3.03	1,000	$3,031.60		16	4 DD, HP	$167.11	PPE	$358	
Remove Remaining Enclosure	ft^3	$0.48	3,267	$1,567.78		12	3 DD, 1/2 HP	$117.40	PPE	$159	
Decontaminate, Package Equipment	LS	$2,276.60		$2,276.60		16	3 DD, 1 HP	$133.27	PPE, Misc.	$144	
WASTE DISPOSAL (WBS 331.18) Subtotal			$5,718.30								
Void Fill Reactor	yd^3	$380.51	6.5	$2,473.30		3.75	2DD, ENG, 1/2 HP, Vendor	$238.25	Rheocell-15 PPE	$1,580	Includes stand-by time, & hose
Solid Waste Disposal	ft^3	$55	59	$3,245			Disposal Fees	$55.00			Compactable waste & plasma torch
TOTAL			**$123,391.12**								

CREW AND EQUIPMENT FOR BASELINE TECHNOLOGY											
Crew Item	**Rate $/HR**	**Abbrevi-ation**	**Crew Item**	**Rate $/HR**	**Abbrev i-ation**	**Equipment Item**	**Rate $/HR**	**Abbrevi-ation**	**Equip Item**	**Rate $/HR**	**Abbrevi-ation**
Skilled labor	$33.84	DD	Industrial Hygienist	$47.33	IH						
HP Technician	$31.75	HP	Vendor, void fill	$87.50	Vendor						
Engineer	$67.19	ENG	(includes pump equip)								
HVAC Technician	$31.75	HVAC									
Craft	$31.75	CR									

APPENDIX C
COMPLETE DEMONSTRATION

Introduction

The demonstration of the DWC technology at PPPL in August 1999 described in the main part of this document was only a portion of the complete demonstration performed. As stated in Section 3 the purpose of the demonstration was to determine if the existing diamond wire cutting methods and technology are suitable for cutting a surrogate of a section of the TFTR vacuum vessel and other stainless steel devices that require, or will require, D&D. In addition, the demonstration was designed to optimize the following variables:

- The void-fill material for the vacuum vessel.
- The coolant for the diamond wire cutting technology.

Demonstration

The evaluation was divided into three phases. The first phase tested the various void fillers for use with the TFTR. The second phase concentrated on different coolant types. Four identical test surrogates of the TFTR vacuum vessel were designed and fabricated, each with a different void filler. Three of the four surrogates were filled, while the fourth remained empty.

- First surrogate was filled with a mortar and sand mixture, which had a density of approximately 120 lbs/ft^3; and strength of 1200 psi. (Figure B-1)
- Second was filled with Rheocell-15, a foamed concrete product with a density of ~35 lbs/ft^3 and strength of 128 psi. (Figure B-1)
- Third is filled with a rigid foam, Perma-Fill, which has a density of ~ 1 lb/ft^3 (Figure B-2).

Figure C-1. Rheocell – 15 and Mortar Void Filled Mockups..

Figure C-2. Perma-Fill Void Filled Mockup.

In Phase I, the vendor performed a partial cut through each of these sections until two plated diamond wires were totally spent or they cut through each of the material types found in the surrogate and a decision was made to stop. New diamond wire was used for each test section. For this part of the testing, water coolant was used.

Once this phase of the testing was complete, the optimum void filler, Rheocell-15, was used for the Phase II testing. Two additional cuts were made, each with new diamond wire, where different coolants (i.e., liquid nitrogen and air) were tested. The end point of the test was up to the discretion of the evaluation team working with the vendor.

Phase III was performed using the optimized void filler and cooling system. One of the cuts started during Phase II was performed to completion (cut all the way through the surrogate section) in order to evaluate the critical issue of kerf closure. During Phase III, the diamond wire was changed as needed to complete the entire cut.

Evaluation personnel collected data on the performance, waste generation, cost, and health and safety aspects of the diamond wire technology. Data was also collected on the void fillers and coolants tested.

Key Results

The results of the multiple tests are summarized in Table B-1 below:

Table C-1. Results of Phase I and II testing

Varied Void Fills and Coolants

	Rheocell-15 (low density concrete) – Water	**Mortar – Water**	**Perma-Fill (foam) – Water**	**Rheocell-15 (low density concrete) – Air**	**Rheocell-15 (low density concrete) – Liquid Nitrogen**
Cutting rate	0.19 m^2/h (2.06 ft^2/h)	0.14 m^2/h (1.55 ft^2/h)	NA	NA	0.19 m^2/h (2.08 ft^2/h)
Production rate	0.10 m^2/h (1.10 ft^2/h)	0.09 m^2/h (1.01 ft^2/h)	NA	NA	0.09 m^2/h (0.94 ft^2/h)
Area cut	0.82 m^2 (8.81 ft^2)	0.60 m^2 (6.49 ft^2)	NA	NA	1.24 m^2 (13.3 ft^2)
Coolant usage [1]	251 L/m^2 (6.16 gal/ft^2)	419 L/m^2 (10.3 gal/ft^2)	Not measured	NA	375 L/m^2 (9.19 gal/ft^2)
Water loss during cutting	105 L/m^2 (2.59 gal/ft^2)	157 L/m^2 (3.85 gal/ft^2)	Not measured	NA	NA
Wire wear rate (# wires/ft-depth)	1.20	1.18	Not measured	Not measured	1.21
Operation pressure [2]	60,80-85 bar (870-1233 psi)	70-85 bar (1015-1233 psi)	70-75 bar (1015-1088 psi)	70-75 bar (1015-1088 psi)	70-75 bar (1015-1088 psi)
Successful	Yes	Yes	No	No	Yes

1 This water was recycled throughout the cutting process. The majority of the water (minus the amount lost during cutting) would need to be treated at the end of a cut or could be recycled for use on a second cut.

2 Operating pressure is the pressure applied to the wire in order to force it into the work piece.

The optimum void fill was determined to be the low density cellular concrete, Rheocell-15. This decision was based on the ability of the void fill to support and clean the diamond wire during cutting as well as the fact that the lesser weight (see Table C-2) represents a significant cost savings over the harder mortar void fill. Cutting on the surrogate filled with Perma-Fill foam was unsuccessful. The foam did not have adequate strength to provide resistive force to the wire, which caused the wire beads and springs to catch on the sharp cutting edges as the wire penetrated the vacuum vessel wall (top and bottom) causing damage to the wire in several places (see Figure C-3). As a result of the foam demonstration, cutting of the empty surrogate was not performed.

Table C-2. Mockup weights.

Void Fill	***Mockup Weight***
None	2.50
Mortar	12.90
Rheocell-15	6.90
Perma-Fill	2.67

Figure C-3. Damaged wire from Perma-Fill cut.

Both the water and liquid nitrogen performed successfully as coolants. While the water-coolant was chosen for Phase III of this demonstration, the liquid nitrogen was performed to a 50% completion of the total cut area (beyond the original scope of the demonstration). At this point, several wire failures were experienced at the ferrule (coupling) location. The use of air cooling was not successful due to excessive heating of the wire which caused erratic and unsafe movement of the wire.

Conclusion

As a result of the five individual and partial cut tests performed, the Phase III testing was completed using the Rheocell-15 and water-coolant. However, the liquid nitrogen coolant test was considered successful and additional testing may be performed in the future to verify its ability to perform a full cut of the TFTR vacuum vessel vacuum. The water-coolant and liquid nitrogen coolant data are presented in greater detail in the main portion of this document.

APPENDIX D
ACRONYMS AND ABBREVIATIONS

BCCI	Bluegrass Concrete Cutting, Inc.
cfm	Cubic feet per minute
CR	Craft labor
D&D	Decontamination and Decommissioning
DDFA	Deactivation and Decommissioning Focus Area
DOE	Department of Energy
DWC	Diamond Wire Cutting
ea	each
ENG	Engineer
FETC	Federal Energy Technology Center
FL	Forklift operator
ft	Feet or foot
gal	gallon
GET	General Employee training
h	hour
HEPA	High Efficiency Particulate Air
HP	Health physics technician
IH	Industrial hygienist
in	inch
lb	pound
L	liter
LN	Liquid nitrogen
LS	Lump sum
m	meter
mm	millimeter
NA	Not applicable
NEPA	National Environmental Policy Act
OSHA	Occupational Safety and Health Administration
PPE	Personal protective equipment
PPPL	Princeton Plasma Physics Laboratory
pr	pair
PVC	Poly vinyl chloride
psi	pounds per square inch
TFTR	Tokamak Fusion Test Reactor
VENT	Ventilation operator/technician
VV	Vacuum Vessel
yd	yard