FINAL REPORT

SIZE DISTRIBUTION AND RATE OF PRODUCTION OF AIRBORNE PARTICULATE MATTER GENERATED DURING METAL CUTTING

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LIST OF ACRONYMS

DOE	Department of Energy
D&D	Deactivation and Decommissioning
FIU	Florida International University
FIU-HCET	Florida International University's Hemispheric Center for Environmental Technology
FY00	Fiscal year 2000
FY01	Fiscal year 2001
GSD	Geometric Standard Deviation
HCET	Hemispheric Center for Environmental Technology
MMAD	Mass Median Aerodynamic Diameter

EXECUTIVE SUMMARY

During deactivation and decommissioning activities, thermal cutting tools, such as plasma torch, laser, and gasoline torch, are used to cut metals. These activities generate fumes, smoke and particulates. These airborne species of matter, called aerosols, may be inhaled if suitable respiratory protection is not used. Inhalation of the airborne metallic aerosols has been reported to cause ill health effects, such as acute respiratory syndrome and chromosome damage in lymphocytes. In the nuclear industry, metals may be contaminated with radioactive materials. Cutting these metals, as in size reduction of gloveboxes and tanks, produces high concentrations of airborne transuranic particles. Particles of the respirable size range (size < 10 μm) deposit in various compartments of the respiratory tract, the fraction and the site in the respiratory tract depending on the size of the particles.

The dose delivered to the respiratory tract depends on the size distribution of the airborne particulates (aerosols) and their concentration and radioactivity/toxicity. The concentration of airborne particulate matter in an environment is dependent upon the rate of their production and the ventilation rate. Thus, measuring aerosol size distribution and generation rate is important for 1) the assessment of inhalation exposures of workers, 2) the selection of respiratory protection equipment, and 3) the design of appropriate filtration systems.

Size distribution of the aerosols generated during cutting of different metals by plasma torch was measured. Cutting rates of different metals, rate of generation of respirable mass, as well as the fraction of the released kerf that become respirable were determined. This report presents results of these studies. Measurements of the particles generated during cutting of metal plates with a plasma arc torch revealed the presence of particles with mass median aerodynamic diameters of particles close to 0.2 μm, arising from condensation of vaporized material and subsequent rapid formation of aggregates. Particles of larger size, resulting from ejection of melted material or fragments from the cutting zone, were also observed. This study presents data regarding the metal cutting rate, particle size distribution, and their generation rate, while using different cutting tools and metals. The study shows that respirable particles constitute only a small fraction of the released kerf.

1.0 INTRODUCTION

In industry, different thermal cutting tools (e.g., cutting, plasma torch, gasoline torch) are used to cut metals. These cutting methods generate particles of different sizes, which become airborne and are inhaled by workers. Inhalation of mixed metal fumes from various materials, such as aluminum, antimony, beryllium, cadmium, copper, iron, zinc, lead, magnesium, manganese, platinum, selenium, silver, tin, and vanadium, has been reported to cause ill health effects, such as acute respiratory syndrome (Steiner et al. 1988; Ellenhorn 1997; Taylor 1997). Jelmert et al. (1994) have reported chromosome damage in lymphocytes of stainless steel welders. Department of Energy's (DOE) deactivation and decommissioning (D&D) activities involving cutting of radioactive materials pose additional problems associated with inhalation of radioactive aerosols (Newton et al. 1981-82; Haper and Warren 1987; Bach et al. 1989; Onodera et al. 1991).

In DOE's D&D activities, workers' exposures are minimized by the use of suitable respirators. The type of respirator used for a particular operation depends on a number of factors, including the concentration of airborne radionuclides in the working environment and particle size distribution. The concentration of airborne particulate matter in an environment is dependent upon the rate of production and removal, the latter being dependent on ventilation (air changes per unit time). The rate of generation of the respirable particulate matter is determined by the rate at which different metals are cut by a cutting tool and the fraction of the metal that become respirable (aerodynamic diameter < 10 μm) when released in the kerf.

The particle size distribution determines what fraction of the inhaled particles will deposit in which compartment of the respiratory tract. Thus, for assessment of inhalation exposures due to metal cutting, it is important to determine rate of cutting of metals by different tools, rate of generation of particulates, the fraction of the particulate matter that becomes respirable, and the size distribution of the respirable fraction.

A number of studies have been conducted by various researchers (Newton et al. 1981-1982, 1987; Hoover et al. 1982, 1986; Windelberg et al. 1987; Steiner 1988; Lillienberg and Bromssen 1996) measuring properties of aerosols generated during metal cutting and providing valuable data needed for assessment of inhalation exposures of workers. The aim of the present work was to perform measurements with additional metals of different thicknesses. It will be useful to extend these studies to measurement of radioactive aerosols generated during D&D operations, e.g., size reduction of gloveboxes contaminated with transuranics. Measurements on contaminated metals should lend information about the radioactive matter that becomes airborne per unit surface contamination of the cut metal. At the facilities where it is difficult to access/cut radioactive metals it will be useful to perform studies with surrogates of radioactive contaminants on metals (Wong et al. 1981). These studies will be useful for 1) assessment of enhanced inhalation exposures and recommendation of suitable respirator protection; 2) optimizing the design of a ventilation system, including local ventilation systems; and 3) design of a pre-filter to reduce load on expensive HEPA filters (Steiner et al. 1988; Bishop 1989; Garreres 1989).

Initially this project was of two years, duration. At the end of the first year, it was decided to broaden the scope of the project. The project for FY01 will have a new number (D069) and a New Title Worker Health and Safety Research and Technology Development. The scope of new project for FY01, in addition to study of particles generated during metal cutting, will cover particles generated during cutting of surrogates of radioactive materials. It will also perform state-of-the art assessment of continuous air monitoring technologies and systems. The current project will end. This document is the final report on the project completed for FY00.

2.0 PROJECT DESCRIPTION

Different cutting tools (e.g., laser, plasma torch, gasoline torch) used at DOE sites to cut metals generate particles of different sizes, which become airborne and are inhaled by workers. The harmful effects from the inhalation of these airborne particles depend on their concentration, particle size distribution, solubility, and toxicity/radioactivity. Respirators are donned to control inhalation exposures. For given respiratory equipment, the higher the concentration of airborne particles, the higher the quantity of material that is likely deposited in the respiratory tract. The fraction of inhaled airborne particulate matter that deposits in the human respiratory tract depends on the size distribution of the particles. It is thus important to measure concentration and size distribution of airborne particles that are generated during the cutting of metals.

Decontamination and decommissioning (D&D) of contaminated structures and facilities in the DOE complex results in release of large quantities of contaminants that become airborne and thus could be inhaled by the workers. In order to adequately protect the workers during D&D operations, there is a need to evaluate various parameters contributing to inhalation exposures.

This project is based on the following Environment Management needs:

NEEDS IDENTIFICATION NO.:	TITLE
RL-DD025-S	Effluent Capture
RL-DD02	GloveBox Size Reduction for PFP
RF-DD03	Improved Interior Airborne Particulate Control
AL-00-01-07-DD	Ex-Situ GloveBox Size Reduction System
CH-DD06-99	Size Reduction of Massive Metal Structures

OBJECTIVES

The overall objective is to determine cutting rates of tools used for cutting various metals and to measure the rate of production of airborne particulates and their size distribution. The completion of this project will include the following:

Reviewing information about

- Tools used in DOE for cutting metals
- Metals used and cut by these cutting tools
- The cutting rates of different metals by these cutting tools.

Selecting a cutting tool and cutting different metals to determine

- Cutting rates for metals
- Particle generation rate
- Size distribution of the generated particles.

This one-year project began on November 1, 1999. Given below are the tasks for FY00 and their status.

3.0 FY00 TASKS AND THEIR STATUS

Task 1. Review of metal cutting technologies

Review of different cutting tools (plasma arc saw, laser, gasoline torch) used in DOE and industry for cutting metals will be performed from literature review, Internet, and personal contacts with site personnel. This review will give information about the metal cutting methods, different metals cut, their thicknesses and cutting rates. Information available on the concentration and size distribution will also be compiled. The selection of a metal cutting technology is based on a number of factors: cost (includes capital cost, cutting rate cost, and cost of safety equipment), type of metal and thickness, cutting rate, versatility of the cutting device, ease of operation, and safety issues. Decision as to which cutting technology and metals to use for year one will be made.

A review of the metal cutting technologies used in DOE as well as commercially available was performed and is presented in Table 1. Table 2 gives the characteristics of the aerosols produced during metal cutting. Table 3 presents commercial metal cutting technologies based on information obtained from technology vendors.

Task 2. Design of test chamber

A test chamber with a suitable ventilation system will be designed and built for the studies. Metals and cutting tools to be used for the study will be identified and procured.

A 6.1 m x 4.9 m x 3.7 m high chamber, made of stainless panels supported on mild steel frames (stainless steel covering on the inside face), was built for the studies. It has entry doors, and 10 portals on the roof to allow external lighting. The chamber has inlet and outlet ports. Filtered conditioned air enters the containment through the inlet port. The outlet port is connected to a high capacity suction pump. Inside the containment, the outlet port is connected to a 4.5 m long x 0.2 m diameter anti-static flexible hose. A 50-amp Dayton air plasma torch was used for cutting steel, stainless steel, and aluminum of various thicknesses.

Task 3. Experimental study

Experiments for measuring the concentration and size distribution of airborne particulate matter will be initiated; measurements will be performed using suitable instruments, and data will be analyzed.

Different types of metals, such as mild steel, stainless steel, and aluminum, of different thicknesses were cut by plasma torch and gas cutting tools. Size distribution and other relevant parameters were measured and data was analyzed. Two types of measurements - laboratory and field measurements - were performed. Laboratory measurements were performed in an enclosure. Technology demonstrations that could not be done inside the enclosure were conducted in an open area. At Florida International University's Hemispheric Center for Environmental Technology (FIU-HCET), various technology vendors brought their equipment for demonstration and evaluation to determine their suitability to DOE's D&D needs.

4.0 MATERIALS AND METHODS

Different types of metals, such as mild steel, stainless steel, and aluminum, of different thicknesses were cut by plasma and gas cutting tools. Two types of measurements - laboratory and field measurements - were performed. For experiments in the laboratory, metal plates were cut using plasma torch in an enclosure. Various parameters relevant for assessment of inhalation exposures were measured. At Florida International University's Hemispheric Center for Environmental Technology (FIU-HCET), various technology vendors brought their equipment for demonstration and evaluation to determine their suitability to DOE's D&D needs. During these demonstrations, different metal objects of different thicknesses were also cut, and measurements on the generated aerosols were performed. Cutting operations that could not be performed inside the enclosure were conducted in an open area.

The FIU-HCET containment is 6.1 m x 4.9 m x 3.7 m high, made of stainless panels supported on mild steel frames (stainless steel covering on the inside face). It has entry doors and 10 portals on the roof to allow external lighting. In the north and east areas of the containment, there are ports for air inlet and outlet. Filtered conditioned air enters the containment through the inlet port. The outlet port is connected to a high-capacity suction pump. Inside the containment, the outlet port is connected to a 4.5 m long x 0.2 m diameter anti-static flexible hose. The other end of this hose, the air inlet, is of conical shape and extends to 0.3-m (12-inch) diameter (Figure 1). The hose is mounted on a wheeled trolley, and the conical shaped stainless steel inlet of the hose is placed over the metal cutting tool. The inlet is moved as the tool moves so that it is always over the tool. The hose under suction draws airborne particles into it. A multi-stage impactor (Moudi) with stage diameters from 0.05 μm to 18 μm collects samples from this hose. Its inlet faces the direction of airflow. The Moudi operates at a flow rate of 30 L/min, and air enters the impactor at a velocity of 2.54 m/s. The velocity of air in the duct is matched to that of impactor to have isokinetic sampling.

The impactor has 11 stages, numbered 0 to 10 with 50% cut-off aerodynamic diameters of 18, 10, 5.6, 3.2, 1.8, 1.0, 0.56, 0.32, 0.18, 0.10, and 0.056 μm. At the end of these stages is a filter that collects particles that escaped collection. Aluminum foil substrate was used for each stage. Aluminum foils and a filter paper were weighed before and after sample collection, and the mass collected was determined from the difference between the mass after and before sample collection. From the masses collected on the various stages and on the filter paper, the mass median aerodynamic diameter of the particles was determined. A set of 5 aluminum foils and 5 filter papers was used as controls. These were weighed each time, along with substrate aluminum foils and filter paper used with impactor, to quantify any errors in weight measurements or variations in weight of filter due to changes in relative humidity.

5.0 MEASUREMENTS

During laboratory experiments, metal plates of different thicknesses were cut by a plasma torch, and measurements of various parameters relevant for the planned studies were made.

The plasma torch used was a Dayton 50 amp air plasma cutter model 5Z031B. Preliminary experiments were conducted on a 6.35-mm (0.25-inch) mild steel plate. These were conducted in open air and provided only particle size distribution. In these experiments, a metal funnel was attached to the impactor inlet and was moved over the tip of the plasma torch. Experiments were repeated in the containment. During these experiments, air was drawn through a cone into a flexible hose, and samples were collected from the duct with a multi-stage impactor during the metal cutting operation. The conical part of the hose was moved over the part of the metal that was being cut by the torch. Pre-weighed aluminum foil substrates were loaded in the stages, and a filter was loaded in the impactor filter holder. Particles escaping the final stage were collected on a filter paper. The impactor was operated at a flow rate of 30 L/min. The impactor was run throughout the cutting period. Aluminum foils and a filter paper were weighed before and after sample collection, and mass collected was determined from the difference between the mass after and mass before sample collection. From the masses collected on the various stages and on the filter paper, the mass median aerodynamic diameter of the particles was determined.

Particle size distribution measurements were also performed during technology demonstrations. The demonstrations used an oxygen torch, plasma torch or a diamond wire to cut steel tanks, glovebox, or steel pipes.

6.0 ANALYSIS

Table 4 gives the mass of the particles collected on various stages of the MOUDI impactor during cutting of a 6.35-mm thick mild steel plate with a 50-Amp air plasma torch. Column 1 of Table 4 gives stage number. Column 2 gives the stage diameter, that is, the stage cut-off diameter. For an impactor, all particles collected on a given stage, regardless of shape and density, have aerodynamic diameters larger than the cut-off diameter of that stage. Column 3 shows the mass of particles collected on that stage. This is the difference between the mass of the aluminum foil substrate after and before sample collection. The foils and filters are weighed on a micro-balance before loading and are weighed again 24 hours after sample collection to allow moisture in samples to equilibrate with the ambient air. A set of 5 aluminum foils and 5 paper filters were used as controls. These were weighed each time along with the sampling foils and filter used in each experiment.

The particles escaping collection on the stages are collected on the filter, which is mounted immediately after the last stage. Column 3 also shows the total mass collected on stages and the filter paper. Column 4 shows the mass collected on a stage as percentage of the total mass collected. Particles collected on a stage (say, stage X) are of a size larger than the stage diameter (D). Particle collected on the next stage (stage X + 1) are of diameter less than the diameter (D) of stage X. Column 5 shows cumulative percentage less than the stated size (undersize). Starting from the last stage (10A), percentage of the particles of size less than of this stage, i.e., 0.051 μm, are those collected on the following stage, that is, the filter paper. This is obtained from column 4 and is 2.92%. Cumulative percentage of particles of stage 9A (size 0.091 μm) is obtained from the sum of percentages of the stage 10A and filter paper (6.79% + 2.92%) and is shown as 9.71% in column 5 against stage 9A. Proceeding in the same manner, the cumulative percentage for stage 0 is the sum of all stages 1 through the filter paper.

Column 3 of Table 4 shows that mass of the particles collected on a stage first increases from nearly 1.6 mg on stage 0 and 1A to 2.533 mg at stage 2 and then decreases continuously until the stage 6A before increasing again from the stage 7A. This shows that particle size distribution may be bimodal. To analyze the bimodal distribution behavior of particles, Table 4 was divided into two tables, Table 4(a) and Table 4(b). The mass corresponding to sizes shown in both Tables 4(a) and 4(b) - namely, 0.58 μm and 0.36 μm - was obtained by extrapolating masses on the remaining stages.

A plot of the cumulative percent less than a stated size and the natural logarithm of the size is a sigmoid curve in rectangular coordinates. However, this plot in adjusted coordinates (probability coordinates) is a straight line. Log-probability graph is usually used to obtain the particle size distribution (mass median aerodynamic diameter [MMAD] and geometric standard deviation [GSD]) of the particles. An analytical method called method of probits (Finney 1947) was used to determine the particle size distribution. In this method, a probit value of 5.0 corresponds to a cumulative 50%. Similarly, probit values of 4.0 and 6.0 correspond to nearly cumulative 16% and 84%, respectively. Tables 4(a) and 4(b) show the values of probits (Finney 1947) corresponding to cumulative percentages.

Figures 2 and 3 show plots based on data in Tables 4(a) and 4(b), respectively. In these figures, natural logarithm of the stage diameter is plotted on the Y-axis against the probit, and a least square line is fitted for the data points. Then the value of Y is obtained for X = 5 (probit for 50%

cumulative mass). This value of Y is natural logarithm of the MMAD. Anti-logarithm of Y gives MMAD. For example, in Figure 2, for X = 5, Y = 1.98. Anti-log of 1.98 is 7.26. Thus, MMAD is 7.26 μm. The geometric standard deviation of the distribution is obtained from the absolute value (sign ignored) of the slope of the fitted straight line. In Figure 2, the slope of the line is 1.064. Anti-logarithm of 1.064 is 2.90, the geometric standard deviation. In a similar manner, MMAD and GSD of the distribution for data in Table 4(b) are found.

The sum total of the mass in column 3 of Table 4 gives the mass that becomes airborne and is collected in the impactor. Particles of 18 μm are not respirable. The respirable mass collected in the impactor is that collected on all stages 2A through filter paper (< 10 μm). The total mass that becomes respirable during a cutting operation is the product of the respirable mass collected by the impactor and the ratio of the flow rates of air in the duct to that in the impactor. To account for particle losses in the duct, a software called Deposition-4 developed by Texas A&M University (MacFarland 1996) was used. This software gives penetration of particles of various sizes through straight and bent tubes. At the flow rates of about 5000 L/min in the duct, nearly 92% and 100% of the particles of geometric median diameter 7 μm (GSD 3) and 0.1 μm (GSD 2.5), respectively, penetrate the duct.

Only a small fraction of the total cutout metal (kerf release) becomes airborne. The remaining settles on the floor. Thin metal sheets were spread on the floor to collect the mass that does not become respirable. From the total respirable and non-respirable mass, the fraction of the mass of metal that becomes respirable was determined.

Table 5 shows impactor data obtained from cutting a section of a mild steel tank during a technology demonstration using an oxygen-torch technology. This table shows only one mode of particle size distribution, so only one analysis was performed.

7.0 RESULTS AND DISCUSSION

Tables 6 and 7 show a summary of measurements performed. These include laboratory experiments of cutting mild steel, stainless steel, and aluminum plates of different thicknesses with a Dayton 50-amp plasma air torch (Table 6) and technology evaluation involving cutting a mild steel tank, glovebox, and pipe with an oxygen torch, diamond wire, plasma torch, and shear. These tables show metal cutting rate, particle size distribution, respirable mass (mass corresponding to aerodynamic diameter less than 10 μm), total mass of metal released from a certain length of metal and the percent respirable. For some studies, which include exploratory studies and technology demonstrations by vendors, only limited data could be collected.

Cutting rate depends on the experience and skills of the person performing the cutting operation. Generally, cutting rate is higher for soft metals than for hard metals; e.g., cutting rate increases from stainless steel to mild steel to aluminum. Cutting rate also increases as the metal thickness decreases. It is interesting to note that only a small percent of the cut-out (released) mass becomes respirable. For mild steel, respirable fraction is about 2%. For stainless steel, respirable mass varied from 0.2% to about 4%, depending on the metal thickness, values increasing with decrease in metal thickness. For aluminum, respirable fraction varied from 0.3% to 6.2%. Here again, respirable fraction was higher for thin aluminum. Small respirable mass means less inhalation exposures. During cutting of 5-mm stainless pipe by plasma torch, Newton et al. (1987) observed the fraction of respirable part as 2 to 7% of the total release. Their respirable fraction was 3 to 8% of the release for an oxy-acetylene cutting torch.

When cutting metals by high temperature techniques, particles are produced through two main mechanisms: condensation of vaporized material and subsequent rapid formation of aggregates and ejection of melted material or fragments from the cutting zone (Taronni 1986). In the present studies, the cutting of metals with a plasma torch was observed to generate large-size particles as well as particles in the submicron size range. The bimodal size distribution behavior could clearly be seen for some of the samples. The MMAD of the larger size particles was generally greater than 5 μm with a geometric standard deviation of about 3. The particles of the smaller size group showed a MMAD in the range 0.05 to 0.5 μm with a GSD of about 2.5. Some of the metal fragments were larger in size than 1 mm. If the generated particles are of large size, they may be deposited on the floor or in the sampling system and may not be presented to the impactor. For particle sizes larger than the useful range of the impactor, the impactor may not yield the correct value of MMAD, or it may not be possible to resolve the size of the large particle size group.

As seen in Table 5 for oxygen torch cutting of tank metal, it was difficult to resolve the large and small size modes. This is evident from the large values of GSD for both tank and pipe cutting with oxygen gas. Newton et al. (1987) have reported only unimodal size distribution with MMAD values between 0.2 and 0.3 for plasma torch and between 0.1 and 10.3 for oxy-acetylene torch. Our measurements show the size distribution of small-size particles comparable with those of Newton et al. (1987). Wong et al. (1981) reported that gas-cutting operations produced a multi-component, multi-modal, respirable-sized aerosol. Novick et al. (1996) performed aerosol measurements from plasma torch cuts on stainless steel, carbon steel, and aluminum and observed bimodal size distributions with one mode at about 0.2 μm and the other at about 10 μm.

Oxygen gas cutting and plasma torch technologies used for technology demonstration were very aggressive and it was not possible to collect the entire mass of the particles generated; hence, only information about the particle size distribution and cutting rate could be obtained. Further, sampling instrumentation had to be placed away from the metal. Diamond wire cutting, depending on the cutting speed and thickness of the metal or obstructions, produced particles with larger geometric standard deviation.

These studies form the basis for size distribution and other relevant parameters needed for determining exposure of workers in any industry. These studies will be extended to cover aerosols generated during cutting of metals, such as gloveboxes and tanks, contaminated with radioactive materials or their surrogates. Size reduction of gloveboxes and other large equipment is important for D&D operations.

8.0 CONCLUSIONS

Thermal methods of cutting metals generate particles by vaporization of metals and subsequent condensation of the fumes. These particles are of submicron size and are respirable. A large fraction of the metal particles produced during cutting arise from ejection of molten metal. These are of very large size and settle in a short time. These are not respired. Only a small fraction of the metal released from the kerf becomes respirable. Thus, while assigning exposure time to workers in an atmosphere contaminated with aerosols generated due to cutting of metals or of metals contaminated with radioactive/toxic substances, only a fraction of the aerosols that are respirable should be considered, not the entire released kerf.

Knowledge of the size distribution of particles generated due to cutting metals is important for designing a filtration system. Since a large fraction of the particles can be easily removed from the air stream by use of pre-filters, pre-filters are used to reduce load on the expensive HEPA filters and to extend their life. The data on the size distribution obtained from this study will be useful in designing a proper pre-filter for use in the metal processing/cutting industry. Knowledge of the particle size distribution is also useful for designing a local ventilation system, which removes most of the airborne particles before they disperse to the entire enclosed space.

9.0 ACCOMPLISHMENTS

During FY00, different metals were cut in the laboratory using a plasma torch, and important parameters needed for assessment of inhalation exposures and for design of the pre-filter or ventilation system were measured. These parameters are size distribution of the particles, metal-cutting rates, mass of the metal released in the kerf, and generation rate of fraction of the mass that becomes respirable. Measurements were also performed during demonstration, and evaluation of metals cutting technologies from different vendors and data obtained were analyzed. All the tasks and milestones of the project were completed.

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Table 1.
Metal cutting technologies used in DOE sites

Technology	Material	Location	Equipment Cut	Reference
Plasma torch	Stainless Steel, Coated/ Uncoated Carbon Steel	Hanford		EM Need No. RL-DDO25-S
Laser	Stainless Steel, Coated/ Uncoated Carbon Steel	Hanford		EM Need No. RL-DDO25-S
Different cutting tools	Different types of metals	Hanford	GloveBox, Piping, Ducting	EM Need No. RL-DD02
Different cutting tools	Different types of Steel	Hanford	Tanks, Racks, Pipes	EM Need No. RL-DD08
Plasma Arc	Different types of metals	Argonne National Laboratory	Piping, Tanks, Flat stock, Pressure Vessels Structural Steel	EM Need No. CH-DD06-99
Oxyacetylene	Different types of metals	Argonne National Laboratory	Piping, Tanks Flat stock, Pressure Vessels, Structural Steel	EM Need No. CH-DD06-99
Different cutting tools	Carbon Steel 25-33 cm thick with a stainless steel cladding 0.635 cm thick on the inner surface		Reactor components	Newton et al. 1987
	Stainless Steel		Piping, Structure Shielding, Internal components	
	Carbon Steel		Ancillary components -Pipe hangers and supporting beams	
	Aluminum		Low-power test reactor vessels and internal components	
	Stainless Steel		Reprocessing plants/ Acidic waste tanks, gloveboxes	
	Steel		Reprocessing plants/ Alkaline waste tanks	
Plasma Arc (70 Amp)	Stainless Steel (0.5 inch thick)		Elbow section of a pipe contaminated with radioactive materials	Fogle,

Table 2.
Characterization of aerosols produced during metal cutting processes typically used in Decommissioning operations

Technology	Material	Cutting Time (min)	MMAD (µm)	Geometric Std. Deviation (σg)	Measured Concentration (mg/m^3)	Reference
Oxy-Acetylene Torch	5 cm Schedule 40, type 304 L, Stainless Steel Pipe	3.6	0.1 – 0.3	2.3	15 ± 11	Newton et al. 1987 Newton et al. 1981-82.
Plasma Torch		0.6	0.2 – 0.3	2.7	60 ± 80	
Cut Rod		0.8	0.4 – 0.8	1.8	53 ± 30	
Pulsed Nd:YAG Laser of energies up to 20 J/pulse, pulse rates up to 300 Hz	Stainless Steel shim stock, and rod and block samples of aluminum and stainless steel		Primary particles with smaller diameters on the order 0.01µm and Primary particles with larger diameters on the order 0.1µm		250 µg/min	Hoover et al. 1986

MMAD = Mass Median Aerodynamic Diameter

Table 3. Commercial thermal metal cutting technologies

Table 3a.
Plasma metal cutting technologies

Company Name/Address/Tele No./Fax/e-mail	Technical Description	Technology Name	Power	Rate of Cutting	Thickness of Metal	Type of metal	Cost $
Hypertherm/Etna Road, P.O. Box 5010 Hanover, NH 03755 603-643-5352 603-643-5352 fax	Dual gas Air/Air Plasma Cutter	MAX100D	100 amp 15 Kw	6in/min	1 ¼ in	Mild steel	12,500
	Air portable plasma cutter	Powermax 1100	30-80 amps	20 in/min cutting mild steel	¾ in recommended	Mild steel, stainless, aluminum	
	Air/Nitrogen plasma cutter	Powermax 900	55 amps	35 in/min cutting mild steel	3/8 in	Mild steel, stainless, aluminum	
	Air/Nitrogen plasma cutter	Powermax 600	40 amps	25 in/min cutting mild steel	3/8 in recommended	Mild steel, stainless, aluminum	
	Air plasma cutter	Powermax 350	25 amps	17 in/min cutting mild steel	¼ in recommended	Mild steel, stainless, aluminum	
Datona MIG/1821 Holsonback Dr. Daytona Beach, FL 32117 (800) 331-9353 or (904) 274-1245 fax (904) 274-1237	Air Plasma Cutter	Prof 36m	35 amps	15 in/min	½ in	Steel and aluminum	1,425
		Prof 52m	50 amps		½ in	Steel and aluminum	1,990

Table 3a.
Plasma metal cutting technologies (continued)

Company Name/Address/Tele No./Fax/e-mail	Technical Description	Technology Name	Power	Rate of Cutting	Thickness of Metal	Type of metal	Cost $
HTP America Inc. 3200 Nordic Road Arlington Heights, IL 60005-4729 Phone: 1-800-USA-WELD (847)357-0700 Fax:1-877-HTPS-FAX (toll free) (847)357-0744 E-mail: jnoland@htpweld.com	Plasma air cutter	MicroCut 250	28 Amps	sheet metal - 100 inches per minute	1/4" steel	stainless steel and aluminum	699
Farley Cutting Systems Australia Pty Ltd./ 7-9 Walter Street Glenroy Victoria 3046 Australia/ phone 61-3-9306-3055/ fax 61-3-9300-3308	Plasma cutter engraver marker inkjet character, spot drill, laser position	Rapier	20- 200 Amps	800 in/min	6.6 in	stainless steel and aluminum	
	Plasma cutter engraver marker inkjet character, spot drill	Phoenix	20- 1000 Amps	1000 in/min	13 in	stainless steel and aluminum	
Farley Cutting Systems Australia Pty Ltd./ 7-9 Walter Street Glenroy Victoria 3046 Australia/ phone 61-3-9306-3055/ fax 61-3-9300-3308	Plasma and gas, external and internal coolant systems, engraver marker inkjet character	Fabricator	20 -1000 Amps	800 in/min	12 in	Stainless steel and aluminum	
	Plasma cutter (multi heads)	Neptune	100- 1000 Amps	1000 in/min	30 in	Stainless steel and aluminum	
	Plasma cutter (multi heads)	Nautilus	100- 1000 Amps	1000 in/min	13 in	Stainless steel and aluminum	

Table 3a.
Plasma metal cutting technologies (continued)

Company Name/Address/Tele No./Fax/e-mail	Technical Description	Technology Name	Power	Rate of Cutting	Thickness of Metal	Type of metal	Cost $
ESAB/ P.O. Box 100545 411 South Ebenezer Rd. Florence, SC 29501/ 1-800-ESAB-123/ fax 843-664-4258	Plasma air cutter with PT-26 torch	Duece Pack 150	300 amps	7 in/min cutting a 4 in carbon steel	4 in	Carbon steel, stainless steel, aluminum	20,273
	Plasma air cutter/ torch required = PT-31XL	PCM-SMi	7-14 Amps	10 in/min cutting 1/8 in	1/8 in	Carbon steel, stainless steel, aluminum	
ESAB/ P.O. Box 100545 411 South Ebenezer Rd. Florence, SC 29501/ 1-800-ESAB-123/ fax 843-664-4258	Plasma air cutter/ torch required = PT-25, PT-20AM, PT-19XLS/ can cut air/air or H-35/N_2	PCM 150 Plasmarc system	150 Amps	25 in/min cutting ¾ in of stainless steel using H-35/N_2	2 in	Carbon steel, stainless steel, aluminum	
	Plasma air cutter/ torch required =, PT-19XLS/ can cut air/air or N_2/plasma air, or argon/ hydrogen plasma/air	ESP-200 Smart Plasm arc	50-200 Amps			Carbon steel, stainless steel, aluminum	

Table 3b.
Gas metal cutting technologies

Company Name/ Address/ Telephone No. /Fax/ e-mail	Technological description	Name of the technology	Current/ power rating	Profiling cutting speed	Type of material	Material thickness	Cost $
Messer Welding Products Filler Materials N94 W14355 Garwin Mace Drive Menomonee Falls USA - Wisconsin 53051 Tel.: +1-262 255 55 20 Fax: +1-262 255 55 42 E-mail: saleswp@messer-mg.com	O_2 metal cutting	Strip welders KONTINUMAT	100 Amps 15 kW		Mild and stainless steel	Up to ¾ inch	
ESAB Welding & Cutting Products 801 Wilson Ave., Dept. TR, P.O. Box 517 Hanover, PA 17331 USA	Oxy acetylene metal cutters	Trade Master	100 Amps		Mild and stainless steel	Up to 8 inches	724
Thermadyne Industries, Inc. 101 S. Hanley Rd., Suite 300 St. Louis, MO 63105 3406 USA Tel: 314-721-5573 Fax: 314-721-4822	Oxy acetylene metal cutting	Portable Torch Outfit			Mild and stainless steel and nonferrous metals	Up to 3/16 inch	505
Cypress Welding Equipment, INC. P.O. Box 690168 Houston, TX 77269 # 1-281-469-0746 fax #1-281-469-9354. E-mail cypressweldequipt@worldnet.att.net	Programmable saddle and elbow oxy- fuel cutter	SE-4P		47 in/min	Steel, Stainless steel, brass, copper and aluminum	Up to 12 inches	

Table 3b.
Gas metal cutting technologies (continued)

Company name/ address/ telephone No. /fax/ e-mail	Technological Description	Name of the technology	Power Rating	Profiling Cutting Speed	Type of Material	Material Thickness	Cost $
Bernie Cragg. 1608 Lehigh Station Rd. Henrietta NY. 14467 Phone and fax # 716-334-8858	Oxy- acetylene cutter	MQT-21012 Marquette Star-Jet	20 Amps		Steel, stainless steel, brass, copper and aluminum	Up to 5 inches	349
		MQT-20022 Marquette Super-Jet			Steel, stainless steel, brass, copper and aluminum	Up to 6 inches	399
Farley Cutting Systems Australia Pty Ltd./ 7-9 Walter Street Glenroy Victoria 3046 Australia/ phone 61-3-9306-3055/ fax 61-3-9300-3308	Gas cutter, oxy fuel up to 6 flame torches, engraver marker inkjet character, spot drill	Stiletto/Trident	20-1000 Amps		Stainless steel and aluminum	30 in	
	Oxy fuel up to 6 flame torches, engraver marker inkjet character, spot drill	Phoenix	20-1000 Amps		Stainless steel and aluminum	13 in	

Table 3c.
Laser metal cutters

Company Name/ Address/ Telephone No. /Fax/ e-mail	Technology	Name	Details	Power Rating	Cutting Area	Profiling Cutting Speed	Type of Material	Material Thickness	Cost
Jamieson Manufacturing Co., Inc. 2500 South Main St. P.O.Box 966 Torrington, CT 06790 Tel: (860)482-6543 FAX 860-482-4051	Laser Cutter	LC2 Laser Center		110 Watt		Rapid motion to, contouring 2400 inch per min to 500 inch per min	Steel and acrylic		$104, 800
Jamieson Manufacturing Co., Inc. 2500 South Main St. P.O.Box 966 Torrington, CT 06790 Tel: (860)482-6543 FAX 860-482-4051	Laser Cutter	LC2 Laser Center		220 Watt		Rapid motion to 2400 inch per min, contouring to 500 inch per min	Steel and acrylic		$123,400
G S USA, Inc. 1680 Roberts Blvd, Suite 401, Kennesaw, Georgia. 30144Tel: 877-424-9776 Fax: 770-424-4458 Email: sales@gs-usa.com	Laser cutters	FB750	50 watt CO_2 laser with water chiller	300 Watts	725 x 995 (mm^2)		Stainless steel, Vinyl	Up to 25 mm thick	
		FB7100	100 watt CO_2 laser with water chiller	300 Watts	725 x 995 (mm^2)		Stainless steel, Vinyl	Up to 25 mm thick	
		FB1525	25 watt CO_2 laser with water chiller	300 Watts	1475 x 995 (mm^2)		Stainless steel, mild steel, carbon steel	Up to 25 mm thick	

Table 4.
Mass of particles collected on various impactor stages during cutting of a typical 6.35-mm thick mild steel plate using plasma torch, showing bimodal distribution

MOUDI Stage #	Stage diameter (μm)	Mass collected (mg)	Mass collected (%)	Cumulative mass undersize (%)	Natural logarithm of diameter
0	18	1.697	12.51	87.49	2.890
1A	9.9	1.509	11.12	76.37	2.293
2A	6.2	2.533	18.67	57.71	1.825
3A	3.1	2.073	15.28	42.43	1.131
4A	1.8	0.777	5.73	36.71	0.588
5A	1	0.425	3.13	33.57	0.000
6A	0.58	0.312	2.30	31.27	-0.545
7A	0.36	0.749	5.52	25.76	-1.022
8A	0.17	1.08	7.96	17.80	-1.772
9A	0.091	1.097	8.08	9.71	-2.397
10A	0.051	0.922	6.79	2.92	-2.976
Filter	<0.051	0.396	2.92		
	Total	13.57			

Table 4a.
Mass distribution of particles corresponding to the larger size fraction of the particles among the bimodal particle size distribution observed during cutting of 6.35-mm thick mild steel plate using plasma torch

Stage diameter (μm)	Mass collected (mg)	Mass collected (%)	Cumulative mass undersize (%)	Natural logarithm of diameter	Probit
18	1.697	18.07	81.93	2.89	5.92
9.9	1.509	16.07	65.85	2.29	5.40
6.2	2.533	26.98	38.88	1.82	4.72
3.1	2.073	22.08	16.80	1.13	4.04
1.8	0.777	8.28	8.52	0.59	3.63
1	0.425	4.53	3.99	0.00	3.25
0.58	0.250	2.66	1.33	-0.54	2.71
0.36	0.125	1.33			
Total	9.389				

Table 4b.
Mass distribution of particles corresponding to the smaller size fraction of the particles among the bimodal particle size distribution observed during cutting of 6.35-mm thick mild steel plate using plasma torch

Stage diameter (μm)	Mass collected (mg)	Mass collected (%)	Cumulative mass undersize (%)	Natural logarithm of diameter	Probit
0.58	0.062	1.49	98.51	-0.54	6.34
0.36	0.599	14.41	84.10	-1.02	5.67
0.17	1.08	25.99	58.11	-1.77	5.04
0.091	1.097	26.40	31.71	-2.40	4.43
0.051	0.922	22.18	9.53	-2.98	3.62
<0.051	0.396	9.53			
Total =	4.156				

Table 5.
Mass of distribution of particles collected on various impactor stages during cutting of 25-mm thick mild steel tank using oxygen torch

MOUDI stage #	Stage diameter (μm)	Mass collected (mg)	Mass percentage	Cumulative percentage undersize	Probit
0	18	0.179	2.39	97.61	6.98
1A	9.9	0.072	0.96	96.64	6.83
2A	6.2	0.694	9.28	87.36	6.145
3A	3.1	0.987	13.20	74.15	5.645
4A	1.8	0.205	2.74	71.41	5.562
5A	1.0	0.804	10.76	60.66	5.269
6A	0.58	0.803	10.74	49.91	4.998
7A	0.36	0.907	12.13	37.78	4.685
8A	0.17	0.869	11.63	26.15	4.36
9A	0.091	0.851	11.38	14.77	3.95
10A	0.051	0.44	5.89	8.88	3.65
Filter	<0.051	0.664	8.88		
	TOTAL	7.475			

Mass median aerodynamic diameter: 0.61 μm

Geometric standard deviation: 5.81

Table 6.
Summary of results for laboratory experiments: cutting of metal plates by plasma torch

Cutting tool	Metal cut (thickness)	Cutting rate (m/min)	MMAD	GSD	MMAD	GSD	Length cut (m)	Mass respirable (gm)	Total Mass (gm)	Percent respirable	Respirable mass generation rate (mg/min)
Plasma torch	Mild steel plate (6.35 mm)		0.11	2.39	8.39	2.48					
Plasma torch	Mild steel plate (6.35 mm)		0.07	2.42	11.02	1.89					
Plasma torch	Mild steel plate (6.35 mm)		0.05	8.52	6.86	2.35					
Plasma torch	Mild steel plate (6.35 mm)	0.34	0.18	2.54	7.26	2.9	3.66	1.94	126.51	1.53	180
Plasma torch	Mild steel plate (3.1 mm)	0.59	0.30	3.89			3.05	1.22	71.87	1.69	235
Plasma torch	Stainless steel plate (1.22 mm)	1.39	0.2	4.09			5.49	1.55	40.09	3.88	395
Plasma torch	Stainless steel plate (1.22 mm)	1.72	0.21	3.46			5.49	0.96	44.74	2.15	303
Plasma torch	Stainless steel plate (3.048mm)	0.256	0.07	5.89			4.572	2.85	217.62	1.31	160
Plasma torch	Stainless steel plate (3.048mm)	0.309	0.07	3.88			4.572	1.52	169.55	0.90	103
Plasma torch	Stainless steel plate (3.175 mm)	0.62	0.22	2.89			4.27	2.57	114.43	2.24	374
Plasma torch	Stainless steel plate (3.175mm)	0.52	0.21	3.52			4.27	1.80	121.45	1.48	218

Table 6.
Summary of results for laboratory experiments: cutting of metal plates by plasma torch (continued)

Cutting tool	Metal cut (thickness)	Cutting rate (m/min)	MMAD	GSD	MMAD	GSD	Length cut (m)	Mass respirable (gm)	Total Mass (gm)	Percent respirable	Respirable mass generation rate (mg/min)
Plasma torch	Stainless steel plate (6.35 mm)	0.27	0.34	3.17			3.66	0.49	219.75	0.22	39
Plasma torch	Stainless steel plate (6.35 mm)	0.35	0.21	3.69			4.27	1.34	283.68	0.47	111
Plasma torch	Stainless steel plate (6.35 mm)	0.50	0.20	2.96			4.27	0.60	85.84	0.70	69
Plasma torch	Aluminum plate (1.524mm)	0.85	0.28	3.09			5.33	1.21	19.96	6.07	193
Plasma torch	Aluminum plate (6.35 mm)	0.35	0.24	4.34			3.66	0.23	80.13	0.29	22
Plasma torch	Aluminum plate (6.35 mm)	0.42	0.52	3.81			4.27	0.54	103.15	0.53	54
Plasma torch	Aluminum plate (6.35mm)	0.508	0.32	4.64			4.267	0.79	108.52	0.73	94

MMAD = Mass Median Aerodynamic Diameter

GSD = Geometric Standard Deviation

Mass Respirable = Mass of the airborne particles of aerodynamic diameter < 10 μm

Total Mass = Total mass released in the kerf

Percentage Respirable = Percentage of the material that becomes respirable to that released in the kerf

Table 7.
Summary of results for technology demonstration: cutting of different metal objects by different cutting tools

Cutting tool	Metal cut (thickness)	Cutting rate (m/min)	MMAD	GSD	MMAD	GSD
Oxygen torch	Mild steel tank (25.4 mm)		0.61	5.81		
Oxygen torch	Mild steel pipe (7.1 mm)		0.71	6.23		
Nukem Wire	Glove box		0.04	6.05	4.74	2.75
Nukem Wire	Glove box		2.02	13.49		
Nukem Wire	Glove box		1.07	11.34		
Nukem Wire	Tank		0.17	3.16	11.66	3.04
Nukem Wire	Tank		0.21	2.45	5.51	2.75
Shear	Glove box & Tank		5.19	3.67		
Plasma torch	Tank	0.55	0.38	2.33	0.80	2.95
Plasma torch	Tank	0.55	0.82	2.30	1.35	2.41
Plasma torch	Tank	0.55	0.32	3.25	0.62	5.37

Figure 1. Arrangement for moving sampling hose over the metal to be cut.

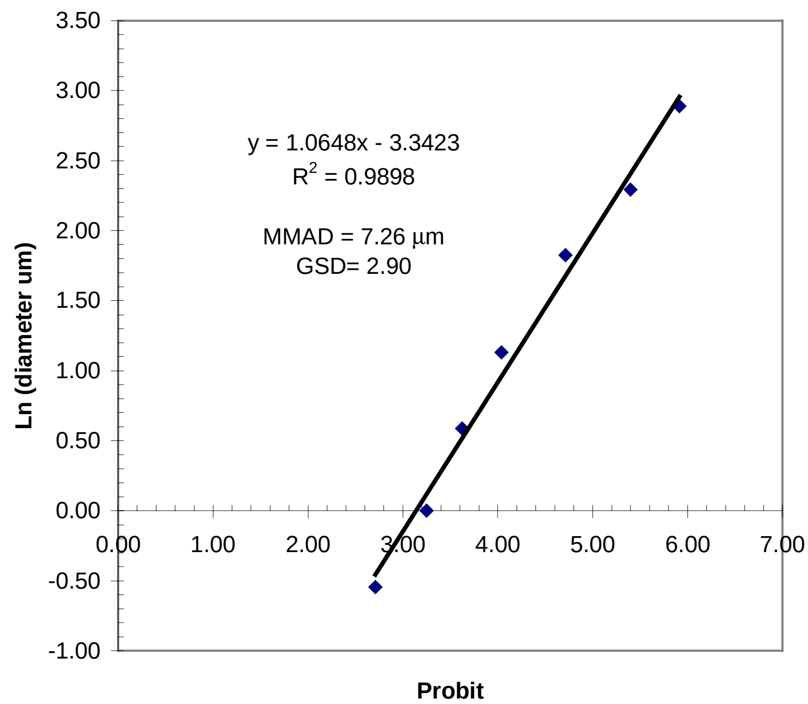

Figure 2. Cutting of 6.35-mm thick mild steel plate using plasma torch. Size distribution analysis of particles corresponding to the larger size fraction of the particles in the bimodal particle size distribution. Method of probits.

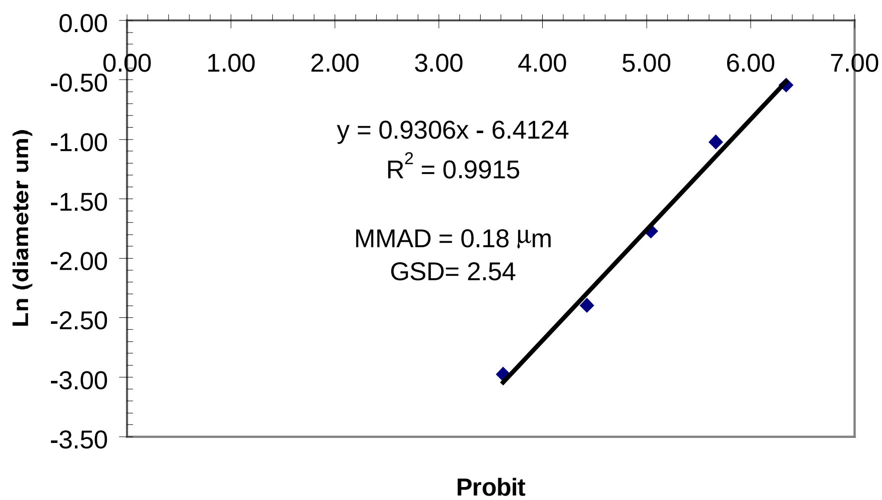

Figure 3. Cutting of 6.35-mm thick mild steel plate using plasma torch. Size distribution analysis of particles corresponding to the smaller size fraction of the particles in the bimodal particle size distribution. Method of probits.