

Robotic Tooling for DOE Environmental Management

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CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

The Department of Energy (DOE) has created nuclear weapons for defense for over forty years. During this time, hazardous and nuclear wastes have accumulated, and contamination of soils and groundwater have occurred throughout the United States, as environmental stewardship was not fully appreciated until recent times. Thousands of sites require clean up, and hundreds of facilities require decontamination and decommissioning. Environmental Restoration and Waste Management (EM), an agency under the Department of Energy, is charged with environmental restoration, waste management, technology development, and facility transition and management for both nuclear-and nonnuclear-related operations. Its purpose is to protect human health and safety; emphasize environmental responsibility within the DOE; and bring DOE sites into agreement with all applicable federal, state, and local regulations by the year 2019.

The Office of Technology Development (OTD), one of EM's constituents, assists this mission by developing new technology that is safer, more efficient, and less expensive than current processes. Developing new technology is seen as perhaps the most reasonable prospect to deal substantially with the immense environmental cleanup in a safe, financially feasible manner.

1.2 ROBOTICS FOR ENVIRONMENTAL MANAGEMENT

Within the OTD is the Robotics Technology Development Program (RTDP). Robotics allow for a "safer, better, quicker, and cheaper" operation in waste management. Safety is a major concern as and regulations require that radiation exposure be as low as can be reasonably achieved (ALARA). Robotic application reduces radioactive exposure to human operators. Less secondary waste is generated with a robotic process since protective clothing is not needed. A robot's efficient movement and automated processes results in more work in less time than human labor could achieve. The OTD has focused upon five primary areas where robotics technology can help EM fulfill its responsibility.

These five areas are: Tank Waste Retrieval (TWR), Contaminant Analysis Automation (CAA), Decontamination & Dismantlement (D&D), Mixed Waste Operations (MWO), and the Plutonium Focus Area (PFA).

The Tank Waste Retrieval focus area is carrying out a program of applied research and development of creative solutions for removing waste from underground storage tanks. The huge tanks created for storage of nuclear and toxic waste, many of which hold up to a million gallons, are at the end of their forty year design life and become unreliable. TWR seeks solutions which prove more cost and time effective, as well as safer, than present methods available.

To answer the need of characterizing the large number of radioactive and hazardous sites under DOE's charge, the Contaminant Analysis Automation team came into existence. Current methods of chemical analysis are not capable of characterizing the projected 10 million needed samples. The CAA team is developing robotic systems that automate the characterization process and are transportable to different sites.

Decontamination & Dismantlement of nuclear facilities is necessary as hot cells, canyons, glove boxes, and reactor facilities become obsolete and are shut down. D & D is preferable to long term surveillance and maintenance (S & M). Robotics can reduce the risk and cost associated with S & M and D & D.

The Plutonium Focus Area concerns problems associated with short term storage of fissile material from nuclear weapons. Some problems include excessive hydrogen gas generation, container pressurization, and increased ignition probability. Robotics is needed to survey and analyze materials and place them into long term storage.

Mixed Waste Operations deal with low level and transuranic mixed waste containing both hazardous and radioactive materials. It is the focus of this work, and is examined in detail.

1.3 MIXED WASTE OPERATIONS

1.3.1 Overview

The name transuranic (TRU) is derived from radionuclides of atomic number greater than uranium's 92. This waste generally results from the production of nuclear weapons and reprocessed spent fuel, and remains lethal for hundreds of years. Low-level mixed waste (LLMW) contains a wide assortment of wastes because it is a catchall category, containing radioactive waste not from transuranic waste, high-level waste, or uranium mill tailings. It is generated in many quarters, including hospitals, industrial plants, and nuclear facilities, and so takes many forms: contaminated wiping rags, filter sludge, hand tools, and parts of decommissioned nuclear facilities to name a few. Generally it is much shorter lived than TRU. Mixed waste comes in a vast variety of forms, including soil, bricks, clothing, car batteries, nuclear fuel processing residues, and chemicals that have been contaminated radioactively.

The Department of Energy (DOE) considers the management and disposal of mixed waste to be one of its highest priorities. Low-level mixed waste and transuranic mixed waste occupy over two and a half million cubic feet at 49 DOE sites in 22 states across the country (Ward 1994). In more tangible terms, 225,000 tons of waste are capable of filling a 16.5 mile stretch of railroad box cars ("Mixed Waste Focus Area Poised for Success" 1996). This volume continues to grow as waste is retrieved from normal nuclear related operations and decommissioned nuclear facilities. The reduction in waste volume or level of harmful constituents, or the complete transformation of the waste into an inert substance, is preferred over the endless costs and risks of simply storing the waste.

The Department of Energy's mixed waste focus area (MWFA) has categorized mixed waste into five basic types. They are: inorganic waste water/slurries, combustible organics, sludges/soil, solids/debris/soil, and special waste. MWFA keeps track of approximately 1,700 waste streams and their preferred treatments ("Mixed Waste Focus Area Poised for Success" 1996). The large differences among the wastes generally call

for a variety of treatment methods, which can be broken down into two basic operations: thermal treatment and non-thermal treatment.

1.3.2 Final Disposition

A wide variety of methods are available in non-thermal treatment of waste. Solidification of the waste with the addition of cement immobilizes the hazardous and radioactive components. Decontamination cleans items that have been contaminated, often by washing with water, or by blasting with pellets. Encapsulation contains waste in an asphalt type matrix or in a polymer.

Thermal treatments apply high temperatures to destroy and/or reduce waste. The vitrification processes melts waste with electrodes to form a glass like substance which is stable and takes up less volume. The VAC*TRAX vacuum dryer uses a lower temperature to separate organic contaminants from solids, leaving them chemically inactive.

The plasma hearth process is a promising thermal treatment. It is able to vitrify, or reduce to a glassy slag, a broad diversity of mixed wastes. The process does so by destroying the organic components and confining the inorganic components and radionuclides in a stable waste form. Importantly, extensive characterization of mixed wastes is not needed with this operation. However the process is unable to handle hazardous inorganics like mercury and lead. Still, the plasma hearth has the potential to significantly reduce the amount of mixed waste in storage.

In the plasma hearth process, waste is heated to temperatures of 3,000 °F. Concerns about the release of hazardous gases have prompted an investigation into a monitoring process which checks for small amounts of hazardous substances before venting any gases.

Because of the intrinsic blend of mixed waste, it must be characterized and sorted before treatment can begin. Robotics is sought for waste handling, characterization, and separation. Waste handling includes the opening and closing of waste containers.

Mixed waste is stored in a variety of containers: 30, 55, and 85 gallon drums, metal bins, and wooden boxes. Most of the volume, however, is contained in 55 gallon storage drums, and much of this is in the form of heterogeneous dry solids (DOE 1993), as shown in figure 1. This work focuses on the 55 gallon drums containing heterogeneous dry solids. The 55 gallon drums' weights vary from 100 to 600 pounds. They are not packed by weight but by their level of radioactivity, which does not exceed 300 mR./hr (Ward 1996). The objective of this research is to use a robot to open waste drums non-destructively. Hazardous waste can be removed and then drums can be resealed for a final process - the plasma hearth.



Figure 1 Waste Drums in Storage

CHAPTER 2. OPENING OF WASTE DRUMS

2.1 MANUAL CLOSING AND OPENING OF DRUMS

The waste drums have been sealed manually. After the lid cover was placed on the drum, the drum's closure ring (c-ring) was slid around the lid, fastening the lid to the drum. Then the c-ring was clamped tight with a bolt and nut in four steps:

1. First the bolt was put through the clearance eyelet hole of the right c-ring tab.
2. Then the nut (which works as a jam nut) was screwed onto the bolt.
3. Next the bolt was screwed into the threaded eyelet tab, tightening the c-ring around the drum lid. The torque applied may have been as high as 130 ft-lb with the use of a pneumatic wrench (Exum 1996). It is not uncommon for a mallet to impact around the c-ring as this tightening process occurs to assist in an evenly and thoroughly tightened c-ring.
4. Finally the jam nut was turned tight against the threaded eyelet (approximately 70 ft-lb applied by a hand wrench) to keep the bolt from turning so that it would not shake loose (Exum 1996).

The fastened bolt assembly is shown in figure 2. The jam nut works in conjunction with the threaded c-ring tab to preload the bolt and to eliminate backlash in the bolt. Figure 3 shows the threads of the threaded tab and nut are against different sides of the bolt's thread.

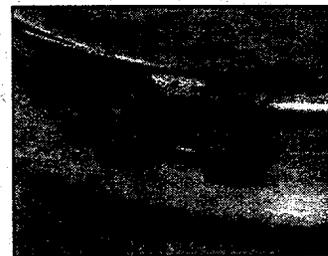
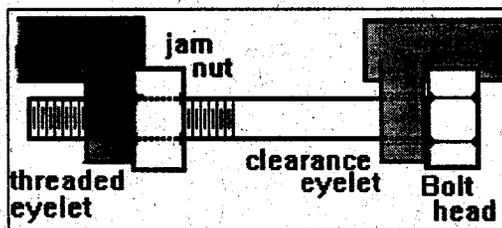


Figure 2 Secured Bolt Assembly Graphic / Photograph

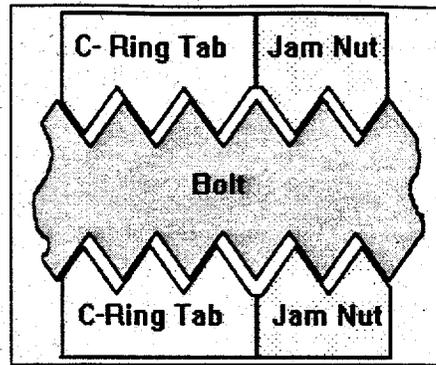


Figure 3 Preloading on the Bolt by C-Ring Tab and Jam Nut

The manual opening process is essentially the reverse of the closing process. Because the drums have been sitting for many years, the bolts and jam nuts should be sprayed or doused with a lubricant (such as Liquid Wrench or WD-40) to facilitate unscrewing. The lubricant should be applied hours before attempting to unscrew the assembly in order to allow penetration.

At the start of the actual unscrewing process, the jam nut would need to be loosened first (approximately a quarter turn) before the bolt could be unscrewed from the threaded eyelet. If this is not done, there is a possibility the bolt could be sheared off during the attempt to unscrew it with an impact wrench. Stripping the bolt's threads in the threaded c-ring tab is another possibility if the jamnut is not first loosened.

After the bolt assembly is unfastened, the c-ring can then be spread apart and slipped off the drum. The drum lid will often still be sealed to the drum, however, because of rust or corrosion that has occurred in areas between the lid and drum where the rubber gasket does not protect the contact surfaces. Often a mallet will be used to hammer the center or near the edge of the lid to help break the seal so the lid can be removed. Perhaps a screwdriver will be used to help pry the lid off as well.

2.2 DESTRUCTIVE DRUM OPENING

In 1993 at the Savannah River Site, drum opening technology as well as other relevant automated waste processing operations was demonstrated. The process begins

with a drum lifter, consisting of grasping straps controlled from an over-head crane, fitting around a 55 gallon drum. The drum lifter transports a drum to the drum opening cell and top loads it into a revolving chuck. Masts on either side of the drum engage cutting tools and idler supports that come into contact with the side of the drum wall. As the drum is rotated, the cutter, a sharp disk, is pressed onto the side, slowly cutting the drum as it revolves, like a huge pipe cutter. After the drum wall has been completely cut, the drum lifter removes the drum's top half, exposing the inner lining (.09" thick polyethylene) for the next cutting process. A stationary blade like a lathe cutter is then engaged into the liner side, cutting the liner in a similar fashion as used on the drum wall.

2.3 NON-DESTRUCTIVE DRUM OPENING

Although the technology of destructively opening the drums is robust and simple, the generation of secondary waste is a significant drawback because then the drums must be disposed of separately, perhaps in a larger 85 gallon drum. If the waste drums are opened in a non-destructive way, they can be resealed for one final use: transporting the appropriate sorted waste for final disposition in the plasma hearth. To reseat the drums, it is necessary that the lid and drum remain undamaged during the opening process. The inner plastic liner is no longer necessary for the last transportation of the drums. Similarly, the bolt assembly and the c- ring are of secondary importance. With just the drum and lid, waste suitable for the plasma hearth process can be repackaged inside the drum, with the lid glued or riveted on in an automated operation.

2.4 DESIGN CONSTRAINTS

2.4.1 Standard Industrial Robot

A standard industrial robot will be used for the non-destructive opening of the 55 gallon drums. According to Clyde Ward of the Savannah River Technical Center, possible candidates include Staubli, FANUC Robotics (figure 4), or ABB Flexible Automation (figure 5). Each of these satisfies the basic parameters of six degrees of

movement, a payload capacity from 50 to 100 lb., a six foot reach, and around $\pm 0.007''$ of repeatability.

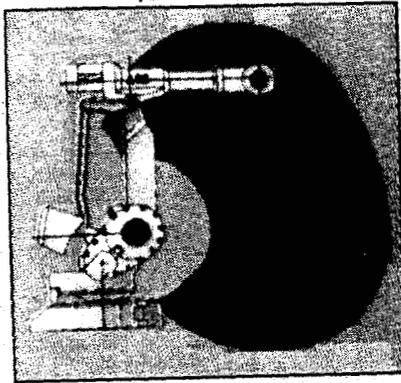


Figure 4 ABB Industrial Robot

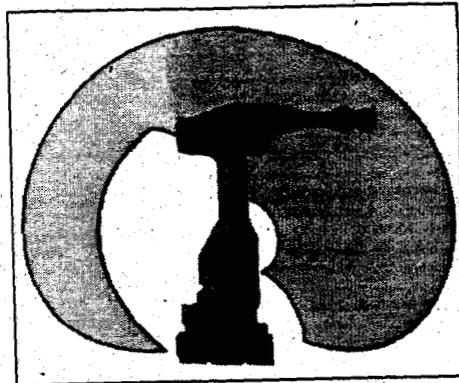


Figure 5 Fanuc Robot

2.4.2 Drum Lifter and Revolving Drum Chuck

The drum lifter and revolving drum chuck developed previously and demonstrated at Savannah River Technical Center will be used in this project. The drum lifter allows the transporting and top loading of the drums into workcells within the Mixed Waste Operations facilities. It is capable of precisely placing even deformed drums, and is used to load them into the revolving drum chuck. The drum chuck firmly grasps the drums at their base, and then can revolve the drums to whatever orientation is needed. This is a useful feature as a robot arm can reach any side of the drum without relocation of its base.

2.4.3 Tool Changer

A tool changer allows the robot to quickly and easily attach, and then exchange any number of end-effectors or robotic tools. One half of the tool changer is attached to the robot's tool face plate, and the other half is attached to the tool. The two halves are connected by a quick release cam. The tool changer supplies pneumatic and electrical contacts from the robot to power the end-effector. The Applied Robotics tool changer (figure 6) has been selected for this project. It has a weight of 22 lbs. with its center of mass 3.8" from the tool face plate. Its size and weight further restrict the tool design.

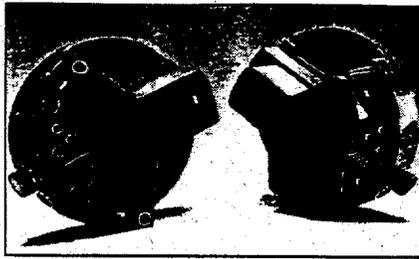


Figure 6 Applied Robotics Tool Changer

CHAPTER 3. END-EFFECTOR DESIGN FOR NON-DESTRUCTIVE DRUM OPENING

3.1 OVERVIEW

There are four steps involved in opening the drums so that they can be resealed in the future. First, the bolt assembly that secures the drum's closure ring (c-ring) must be disengaged by either cutting it or unscrewing it. The method used will affect the second task- c-ring removal, since parts of the bolt assembly may or may not be present in the c-ring tabs. After the c-ring is removed, the lid itself must be dislodged. This task is complicated by the significant seal that results with time, and the minimal leverage area available around the lid. And finally the top of the inside plastic liner must be cut out and removed. The liner top must be supported during this task to keep it from falling back inside the drum. Each task will require the design of one or more end-effectors, which will operate with the industrial robot through teleoperation. Therefore the designs should support as much automation as possible.

Designing for autonomous operation will be challenging because of slight size and shape variations among the drums. For example, a c-ring might be deformed, or a jam nut oriented differently from the previous drum's jam nut. And depending on the procedure used for unfastening the bolt, the bolt assembly may offer differences to the gripping interface of the end-effector, as the unfastening process may not produce identical results each time. For instance, the bolt could be cut in a slightly different place, producing a shorter or longer threaded rod left in the threaded eyelet. Although any major anomalies could be handled manually, the end-effector design should be as robust as possible.

3.2 BOLT REMOVAL

3.2.1 Unscrewing the Bolt

The first step in unscrewing the bolt assembly, after application of a lubricant, would be loosening the jam nut used to keep the bolt from turning. The nut loosening process will be challenging. Perhaps a gripper would force its teeth around the nut like pliers shown in figure 7, gripping it no matter what the orientation of the nut. And then another actuator would turn the grippers and nut the quarter turn required to loosen it (Nagle 1996). Or the nut could be split open. A nut splitter, hydraulically actuated, is available on the market for removing rusty or frozen nuts. This device forces two pointed teeth into the top and bottom surfaces of the nut, until the nut is broken apart. After the operation, the broken parts need to be recovered.

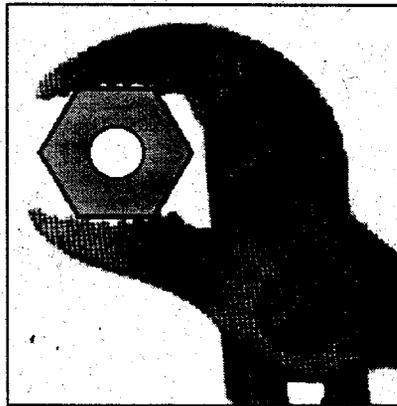


Figure 7 Pliers grip on jam nut

The nut does not need to be fully removed from the bolt to allow the c-ring to be removed (see figure 8). It just needs to be loosened so that the bolt can be unfastened from the threaded eyelet, making it possible to spread the c-ring apart and remove it. Partial unscrewing has the added advantage of keeping the bolt assembly attached to the c-ring, thus being one less part to handle. The advantageous geometry (2 open eyelets) for removing the c-ring in the next task step is no longer present, however.



Figure 8 Partially Unscrewed Bolt Assembly

Unscrewing the bolt from the threaded eyelet once the nut has been loosened or split apart could be achieved with a pneumatic impact wrench. Pneumatic impact wrenches are capable of applying well over the 130 ft-lb estimated requirement. The tool changer for the robot can provide 90 psi compressed air. A long socket over the bolt would avoid moving or feeding the end-effector backwards as the bolt unscrewed. The wrench can be engaged with the bolt head by lining up the wrench to the bolt and applying a small force into the bolt while activating the wrench (Hanna 1996).

3.2.2 Cutting the Bolt

Cutting the bolt between the tabs is a simpler process than unscrewing. A large range of methods are available for cutting the bolt assembly and must be considered. Whatever cutting method is used, the top half of the bolt will be loose in the clearance tab and will need to be retrieved. This will result in a c-ring with one open eyelet, and with a half bolt and nut tightly screwed into the other eyelet. Because of this, the bolt should be cut as close to the jam nut as possible to make room for the c-ring removal end-effector.

3.2.3 Comparison of Cutting or Unscrewing the Bolt Assembly

Unscrewing the bolt has two advantages to cutting. One, it will immediately make the c-ring usable for repackaging the sorted waste for final disposition. This advantage, however, is questionable as the c-rings may not be used for repackaging since a 'permanent' sealing process such as gluing or riveting the drum shut would be simpler and easier for robotic automation. The other advantage is that if the bolt were completely unscrewed and removed from the c-ring, the c-ring would be left with two good

geometric features (the open eyelets) to dock with an end-effector for removal of the c-ring. The disadvantages to unscrewing the bolt are many: the process will take longer to accomplish, is more complicated as it would almost certainly require the design of more than one end-effector, and may easily have a high failure rate if bolts are so rusty they end up being sheared apart.

Cutting the bolt has the advantages of being a quick and robust process. However, the cut half of the bolt may fall loose from the c-ring, and so must be dealt with in the design. Also, cutting the bolt will leave half of the bolt assembly in the threaded eyelet, making the gripping action for removal of the c-ring more difficult. This difficulty exists if the bolt assembly is partially unscrewed as well. Because of the complexity required in an unscrewing process, cutting is the preferred method. Comparison of cutting and unscrewing is listed in Table 1.

Table 1 Comparison of Cutting and Unscrewing for C-Ring Removal		
Method	Advantages	Disadvantages
<u>Cutting the Bolt Assembly</u>	<ol style="list-style-type: none"> 1. Quick process 2. Robust operation 	<ol style="list-style-type: none"> 1. Loose half bolt with bolt head must be taken into account 2. Bolt assembly remains in one eyelet so that gripping of c-ring is more difficult
<u>Unscrewing the Bolt Assembly in General</u> (These apply to both partially or completely unscrewed)	C-ring reusable immediately (if needed)	<ol style="list-style-type: none"> 1. Complicated design 2. Requires more than one end-effector 3. Possible low success rate 4. Requires lubrication
Partially Unscrewed	Less complex than complete removal	Bolt assembly remains in one eyelet so that gripping of c-ring is more difficult
Completely Unscrewed	Will be simpler process to remove c-ring	Will need to deal with loose parts of bolt and nut

3.2.4 Survey of Cutting Methods

Four senior engineering students from Worcester Polytechnic Institute (WPI) worked on the problem of unfastening the bolt assembly during the spring semester of

1996 (Davis et al. 1996) as a joint project with N.C. A & T State University. This work made up their Major Qualifying Project, in partial fulfillment of an engineering degree from WPI. They conducted a survey of possible unfastening methods. They also ran a number of experiments, from obtaining the hardness of the bolt, to testing a number of cutting blades with variable feed rates and cutting speeds.

A number of cutting methods were discarded quickly. These include the bandsaw, the reciprocating saw, and the cutoff wheel. The bandsaw and reciprocating saw have clearance problems; the drum wall may be damaged before the bolt is completely cut. The cutoff wheel blade wears out very quickly and requires frequent changing. The more promising cutting methods are examined below.

Rotary Saw

WPI's proposal was to cut the bolt assembly with a pneumatically driven rotary saw made of high speed steel. This method requires feeding the blade as the cut is made. The metal chips that are generated would need to be vacuumed.

Laser

A laser unit to cut the bolt would not be attached to the robot because it is too large. But lasers could be placed overhead on a short liner track, cutting the bolt assembly from above. Laser systems require minimal maintenance (Patterson 1996). The laser would require an input of 480 volts to power. The output would be between ten to 20 kilovolts. A basic metal cutting unit, capable of cutting the 9/16" diameter of the bolt, would cost around .5 million dollars. Vaporized metal and molten metal fumes would result from the cutting operation (Kempka 1996).

Shearing

Shearing has a number of advantages. Once the blades have docked with the bolt assembly, they simply need to be activated, not fed through the cut as required in all other cutting operations. Shearing also does not generate any chips or dust. It requires around 10,250 lb of force to shear a 9/16" bolt (see Appendix A for calculations), however,

which suggests the need for hydraulic power given the weight constraints. With electrical power, a ball screw drive could handle this force, however its weight exceeds the 20 lb target by over 20 lb. Two shearing methods are examined next.

Hydraulic Rod Cutter

H. K. Porter manufactures a hydraulically actuated cutterhead (shown in figure 9) used in semi-production cutting. It produces over 14,000 pounds of cutting force and weighs about 22 pounds. It can handle hard metals up to .5". The medium hardness of the 9/16" bolt should not pose a problem.

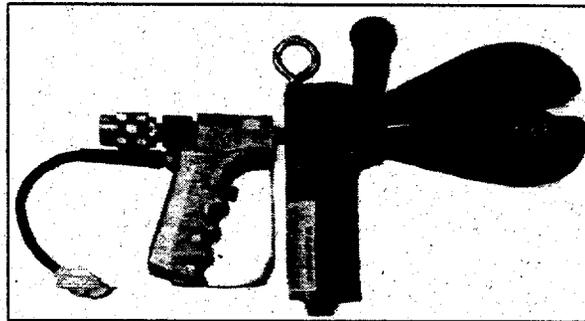


Figure 9 H.K Porter Hydraulic Rod Cutter

'Jaws of Life' Rescue Cutters

Hale Products Inc. manufactures the Mini-Cutter (in figure 10), used in rescue operations. It generates a cutting force of 17,000 lb, with a 1.5" open jaw. The tool is less than 10" in length and 4" in depth. The entire system includes a manual hydraulic pump and weighs only 21 lbs. The cutter and hose alone can be connected to a powered unit supplying hydraulic pressure (Hurst 1996). This tool would need to be modified in order to handle the tight clearances between the bolt assembly and drum.

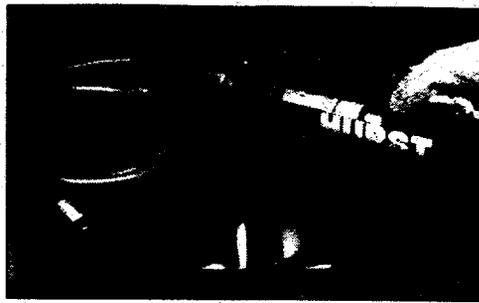


Figure 10 Hurst Mini-Cutter

3.2.5 Conceptual Design Selection

Shearing the bolt has several advantages over sawing: it is a quick operation, with minimal blade wear, and does not generate any chips or dust that must be recovered. Similarly laser cutting is also a quick and chipless operation, without any blade wear whatsoever. Sawing has one advantage over shearing or laser cutting. It can be easily accomplished with a common power tool. It does however have three disadvantages: a blade may break during operation, blades will wear and need to be changed, and the process is more complicated since it includes feeding the blade as the cut is made.

Five important parameters were chosen to select the best cutting method: safety, reliability, cost, maintenance and availability. Safety and reliability ranked the highest in importance. Both reflect why robotics is considered the best choice for this waste management operation. The categories cost and maintenance rank second in importance. Cost refers to initial cost. Maintenance is significant because it concerns continual cost and downtime. Downtime is not only expensive, but requires humans to interface with the workcell. Off the shelf availability primarily affects how quickly the design can be developed. It also affects cost and reliability. This decision process is summarized in Table 2. The hydraulically actuated Mini-Cutter outscored other cutting methods.

Table 2 Bolt Cutter Decision Matrix											
	Off the Shelf		Maintenance		Reliability		Safety		Cost		Total
Weight ==>	5		7		10		10		7		Points
Cut off Wheel	10	50	3	21	5	50	2	20	10	70	211
Rotary Saw	9	45	5	35	5	50	3	30	10	70	230
Laser	8	40	10	70	9	90	10	100	1	7	307
Hydrau. Shear	10	50	8	56	8	80	9	90	8	56	332
Hydrau. Mini-Cutter	7	35	10	70	9	90	10	100	7	49	344

3.3 C-RING REMOVAL

3.3.1 Design Considerations

The c-ring can be removed by cutting it off. However, cutting the c-ring off is problematic: its 'c' shaped cross section envelopes the outer edge of the lid and drum. Cutting it without damaging the drum seal would be very difficult and is not considered in this design.

Several facts help illuminate the problem of removing the c-ring:

1. The c-ring clamps the lid to the drum; the tighter the c-ring, the tighter the lid is pushed onto the drum, making a secure seal.
2. The c-ring has a spring constant of around 5.75 lb/in for the first 2 inches of displacement (see Appendix B for experimental data).
3. The c-ring's eyelets are approximately 1.75" apart from one another when the c-ring is in an untensioned position.
4. The c-ring must be spread at least two inches more from the untensioned position to clear the lid. This requires a force of approximately 11.5 pounds and brings the eyelets 3.75" apart. Therefore the bolt assembly can not be attached to both eyelets, as the bolt limits the spread of the tabs to approximately 3.3".

3.3.2 Removing the C-ring

The c-ring can be removed by spreading it apart and then lifting it off the drum. Spreading the c-ring apart can be accomplished in two ways. One way is by 'grabbing'

one eyelet and pulling. The other eyelet is held to the drum by friction. This method would require the robotic arm to apply a type of corkscrew motion, stripping the c-ring off the drum. The other end would snap off the drum when it becomes free. This uncontrolled snapping action may damage the robot and its hoses. The more stable method is for both eyelets to be grabbed at the same time and be spread apart.

3.3.3 End-Effector Design

Background

Before c-ring removal, the bolt is assumed to be sheared apart by a hydraulic cutter as close to the jam nut as possible. However, a shearing action generally cannot cut flush to the nut like a laser or sawing action can. Space between the cut bolt and clearance eyelet tab after the c-ring has lost most of its tension is only about 1.3".

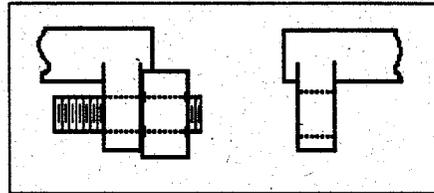


Figure 11 Bolt Assembly Sheared with Bolt Head Removed

This gap is an advantageous place to apply a pushing force in order to expand the c-ring. The bolt head is removed by an electro-magnetic end-effector from the clearance hole. The remaining bolt and jam nut remain in place.

Design Requirements

The end-effector will be attached to the Applied Robotics tool changer.

Keep the weight and size as low as possible.

Keep the design as simple as possible. Reduce the number of moving parts and actuators.

The end-effector's grasping points should allow the c-ring to swing freely. If a fixed restraint is required at the grasping points, the moment load caused by the weight of the c-ring to the tool changer will likely exceed the load capacity of the tool-changer.

A pneumatic piston is preferred. A linear actuator (pneumatic or hydraulic piston) is preferred to spread apart the c-ring. Since the force required is less than 20 lb, hydraulic power is more than necessary, and a pneumatic piston is lighter and cheaper. Electric motors are heavier since they will either need a linkage mechanism, a rack-and-pinion or worm gear to convert the rotary motion into linear motion.

The end-effector should be able to release the c-ring to a storage rack at the end of the task.

Sensors are needed to send signals to a robot controller to sequence the motion.

The end-effector should be able to grab the large majority of c-rings securely, and take them off. The remaining can be handled manually.

Function requirements

The two tabs need to be pushed 3" apart to remove the c-ring from the drum. Although it is possible to remove the c-ring with just a 2" spread, 3" gives more clearance and is easier to work with.

Maximum pushing force is 20 lb.

The end-effector should weigh under 10 lb since the c-ring is already 3.5 lb.

Pneumatic manifold is need^{ed} to merge several pneumatic ports of the tool changer to provide sufficient air flow.

Design

MEEN 565 Machine Design class of Spring 1996 had the c-ring removal end-effector as their class project. The class created many designs, and helped in shaping this final design.

A common design of the grasping arrangement of many class design groups consists of a cup over the jam nut and the bolt, and a pin into the clearance hole in the c-ring. After the contact is secured by the cup and pin, they will be pushed outward to spread the c-ring. The c-ring is allowed to swing down by at the contact (cup and pin). However, the design requires more clearance than may be available because of the size of the cup.

A revised design (Rommel D. Simpson's group) changes the cup to a slender tab to push against the cut bolt. A ring tab is used to envelope the bolt end as it is pushed out, as shown in Fig. 16. This requires less gap space between the c-ring tabs, and takes advantage of the severed bolt assembly, instead of viewing the half-bolt as a liability. Or, from another perspective, the new design breaks the two functions of the cup (pushing and holding) into two separate parts. The slender tab is for pushing, and the ring tab is for holding.

Most designs require the two tabs to be pushed apart at the same time. This requires either two actuators or one double actuating actuator. Rommel D. Simpson's group presented a simple idea using a single actuator to push the left tab to expand the c-ring while holding the right tab. This operation will require a coordinated robot motion to compensate for the unsymmetric c-ring expansion when lifting the c-ring.

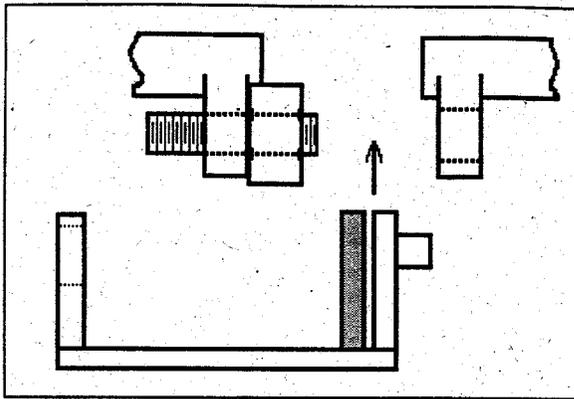


Figure 12 Step 1 of C-Ring Removal

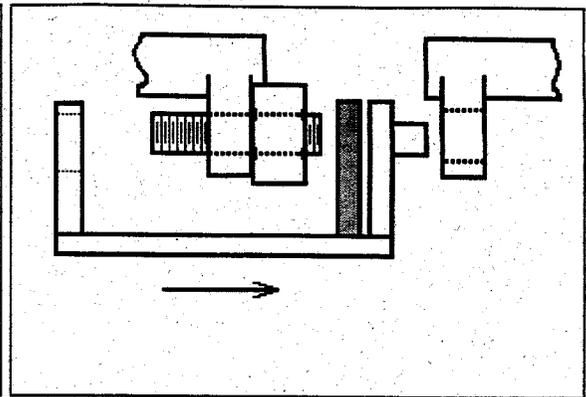


Figure 13 Step 2 of C-Ring Removal

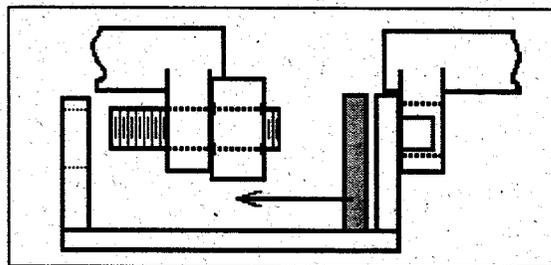


Figure 14 Step 3 of C-Ring Removal

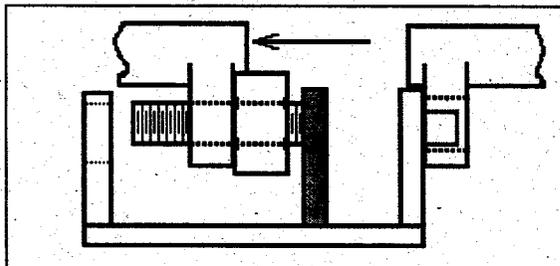


Figure 15 Step 4 of C-Ring Removal

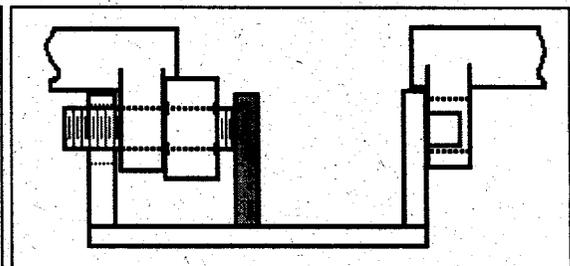


Figure 16 Step 5 of C-Ring Removal

In figure 12, the robot prepares to dock the end-effector. Figure 13 shows the robot placing the pin and plate into the gap. Then the robot moves to the right until the pin is in the clearance hole, as shown in figure 14. The piston is then pushed to the left for a stroke of 3" (figure 15), forcing the bolt into the left ring tab (figure 16). The robot will then move to the left so that the clearance is symmetric about the center (figure 17).

Finally, the robot will lift the c-ring from the drum. Once the c-ring clears the drum, the robot is responsible for placing the c-ring on a rack.

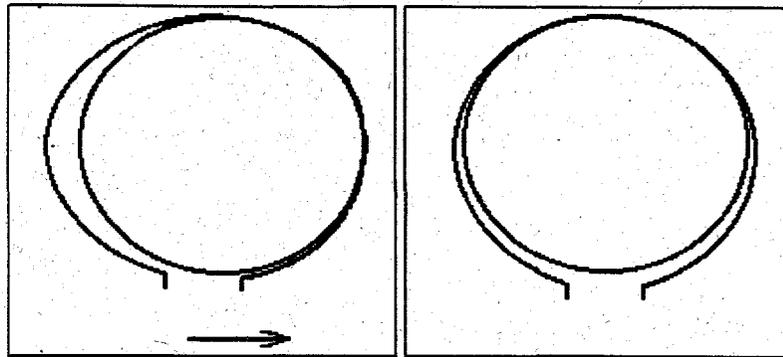


Figure 17 Step 6 of C-Ring Removal

3.4 LID REMOVAL

3.4.1 The Problem

After having a c-ring clamped around it for up to 40 years forcing it onto the drum, the lid is essentially sealed to the drum. Removing the lid becomes a two step process: breaking the seal and then removing the loosened lid. In manual operations, a sealed lid is hit a number of times with a hammer, both at the center and around the rim, to help break this seal. A screwdriver may then be wedged in-between the lid and drum to help break this seal. However, there is very little clearance between the lid and drum (.035") for robotic operations. A little more substantial is a lip overhang from the width of the lid's thickness (.065"). The lid itself weighs 7.5 pounds.

3.4.2 Lid Removal Methods

Because the clearance between the lid and drum (.035") is so small, some effort was made to find possible ways to increase this gap. An experiment was conducted to see if placing a large force in the center of the lid would bow the lid enough to force the perimeter up and away from the drum so that a tool can wedge in and finish the job of lid removal. However, the lid proved inflexible, with no perceptible bending occurring with

a weight of 200 lb, either at the center or near the edge of the perimeter. The lid and drum are shown in figure 18.

It is possible that hooks from an overhead crane could be placed around the lid's edge as the drum is held in the chuck. The hooks could pull up and just detach the lid from the drum with raw force in one step. A large pulling force is required to break the seal.

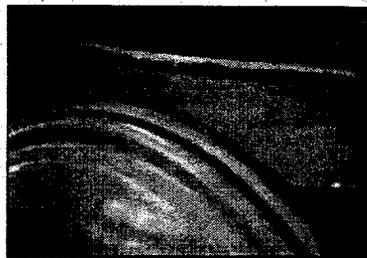


Figure 18 Underside of Lid Revealing Gasket and Leaning on Drum

The manual operation of removing the lid includes impacting a screwdriver from the bottom while its tip is wedged between the lid and drum. This method employs impact force to break the lid's seal. An impact chisel as shown in figure 19 could do the same thing.

3.4.3 Conceptual Design Selection

Breaking the seal



Figure 19 Pneumatic Chisel with Bit



Figure 20 Chisel Impacting Lid

An end-effector composed of a pneumatic chisel with a flat edge bit could be brought to the lid's perimeter to apply an impact force at the lip overhang as shown in

figure 20. A roller could be attached to the end-effector to keep it stable with the side of the drum as the chisel strikes the lid. The drum could be rotated as needed, starting from the weaker joined locations. In this manner, the impacts could vibrate the lid, tearing and breaking the areas which are sealed. The bit has the tendency to chip off paint from the drum. To avoid this problem, the bit could be given a protective coating such as Teflon, or made out of rubber.

This end-effector could be useful in other drum opening operations as well. After the bolt assembly has been sheared apart, the c-ring may have a residual frictional cling to the drum, keeping the c-ring tabs too close together for the c-ring removal operation. The chisel could strike the c-ring, relaxing it, and allowing the c-ring tabs to spread apart.

This method of lid removal was demonstrated at Savannah River Technical Center on July 30, 1996 on a drum left outside for three years. During the three years a substantial seal of rust had developed between the metal contact surfaces between the lid and drum not separated with the rubber gasket. Within three minutes the seal was broken, allowing the removal of the lid. The procedure was also performed on a drum sealed with super glue, an excellent bonding adhesive on both metal and rubber. The adhesive was applied between the rubber gasket and metal drum rim to simulate a seal resulting from time and exposure. The experiment showed the impact chisel can break up the glue seal.

Removing Loosened Lid

After the lid's seal is broken, the loosened lid can be removed. Vacuum cups could be employed. However an electromagnetic end-effector would be less likely to lose its effectiveness from a dented or soiled lid. Also, an electromagnetic end-effector is needed to retrieve the cut half bolt from task one of unfastening the bolt assembly.

3.5 PLASTIC LINER REMOVAL

3.5.1 The Problem

An .090" thick inner plastic lining is the final obstacle to reaching the stored mixed waste. The liner's round plastic cover has been 'permanently' secured by coating its perimeter with an epoxy and then force fitting the cover into the lining. A one inch diameter hole in the cover's center is present to vent any gas. The top of the liner can be cut out because it does not need to be used again in a 'sealed' condition.

1. The top of the liner must be supported as it is cut so that it does not drop into the drum after the cut.
2. The supported cut piece will then need to be lifted out.

Because the drum will be in the rotating chuck, the cutting tool can remain stationary while the drum turns, creating a circular cut. The circular cut, with a radius smaller than 12", can possibly pose a problem for some cutting methods. For example, if a reciprocal cutting method is adopted, the blade would need to be thin, similar to a jigsaw blade, to avoid binding.

3.5.2 Survey of Methods

Cutting

Stationary Blade

The 1993 destructive drum opening process demonstrated at Savannah River Technical Center used a stationary blade to cut through the side of the liner with progressive feeding. Although it took a number of revolutions to accomplish the cut, the method did not produce shavings. This new task, however, involves opening the liner from the top. Since the blade will be cutting a circular path, a narrow blade is needed to prevent binding. Also, the blade would need to be fed down into the liner during the cut.

Spiral Saw

A spiral saw (figure 21), which cuts like a portable mini- milling machine, can accomplish this task in one pass. It weighs about a pound, and would constitute the main part of the robotic end-effector. A vacuum could be added if needed to retrieve the plastic shavings as they are created.



Figure 21 Spiral Saw

Liner Support

Vacuum cups

Vacuum cups, can easily be attached to the top of the liner, however they would need to straddle the center hole. They would also need to be attached to a bearing so that they could freely rotate in relation to the turning drum as the cut is made.

Toggle Mechanism

A toggle mechanism can take advantage of the center venting hole. It can be actuated by a solenoid. In its activated state, the toggle contracts so that it can enter the center hole. Then it is deactivated so that a spring spreads the toggle out, supporting the liner from underneath. This fail-safe mode would keep the mechanism from dropping the liner if power were suddenly cut off. The liner would not have any trouble rotating relative to the toggle support.

3.5.3 Prototype Design

A spiral saw with a toggle mechanism attached is shown in figure 22. This prototype was built to test the liner opening. The simple toggle used had only two

prongs, but three prongs would allow for a more stable handling of the liner top. Also, this generic toggle requires a minimal depth penetration of about 2" into the drum in order for the prongs to operate. A more robust design using a different toggle design would cut the minimal clearance to a fraction of that, perhaps 1/8".

The end-effector is positioned over the liner so that the toggle be dropped down into the center hole. As the toggle enters the hole and deactivates to its support position, the spiral saw can be activated, making an initial plunging cut into the liner. The drum chuck is then rotated, causing the stationary cutter to make a circular cutting path while the toggle gives support at the center of the liner. After the drum has turned 360 degrees, the cut is complete and the spiral saw can be turned off. With the toggle still attached, the end-effector then lifts out the liner top. At the appropriate place of delivery, the toggle activates and drops the top.

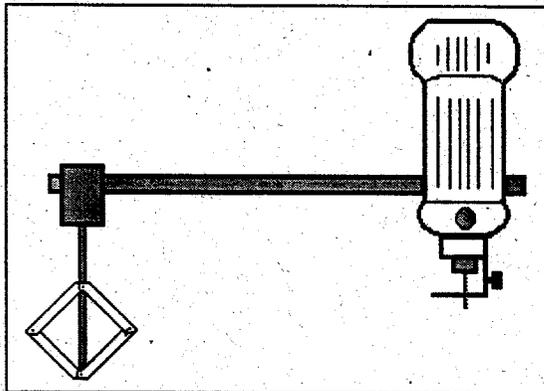


Figure 22 Toggle and Spiral Cutter

CHAPTER 4. SUMMARY AND CONCLUSION

A demonstration was made at Savannah River Technical Center on July 30th, 1996 to show the conceptual design of the c-ring, lid, and inner liner top removal with handheld powertools. A short video was made to demonstrate these tasks. The demonstration was successful.

Sensors and an accompanying control system should be developed to help make the process as automated as possible. Sensors should be added to the end effectors to allow automatic docking with the drum. An automated system not only places less demand on the operator, but helps to speed up the overall process.

Since work was begun on the non-destructive drum opening procedure, the plasma hearth thermal process has fallen out of favor. Public concerns about environmental pollution have kept states from allowing the process within their borders. Therefore the need for a non-destructive operation that accommodates a final permanent sealing process for final disposal is also shelved.

However, a new non-destructive drum opening need has arisen in Idaho. The 55 gallon mixed waste drums stored there must be brought into the required safety standards, and then shipped to another storage location. Many drums will need to be opened so that items such as compressed gas and ignitable materials, which do not meet the waste acceptance criteria, can be removed; after which the drums will be sealed again. This means the liner, as well as the drum, will need to be opened non-destructively, and then resealed. Another situation is that the metal drum itself may be rusted or damaged. In this case, just the inner liner could be removed intact, and placed in a new drum.

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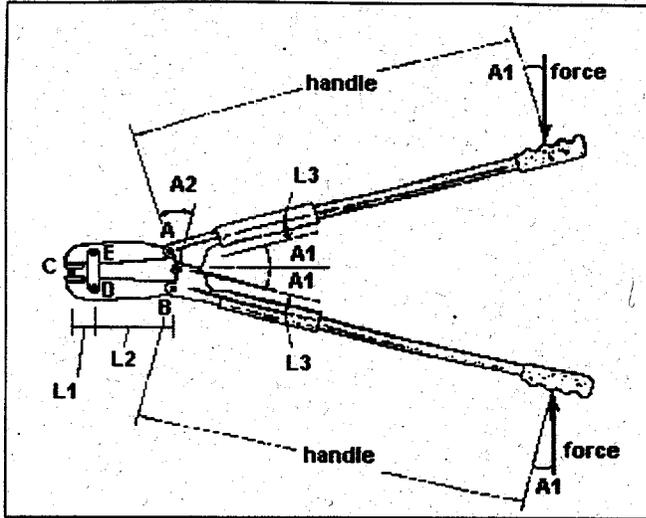
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Appendix A

General Force Analysis of Bolt Cutter



Given:

handle = 36-in

L1 = 1.181-in

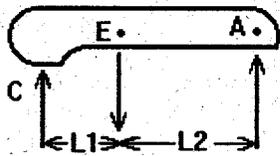
L2 = 3.15-in

L3 = .787-in

A1 = 15-deg

A2 = 30-deg

Diameter = $\frac{9}{16}$ in



Free body diagram of Upper Jaw

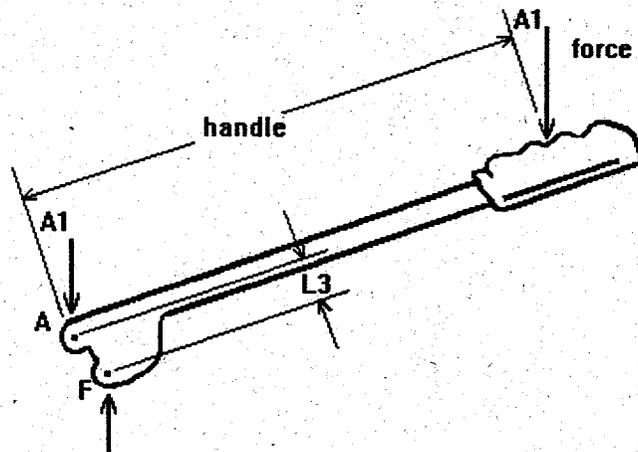
Upper Jaw :

ForceOut = FC

ForceOut equals force at C, which is what the bolt experiences.

FC * L1 = FA * L2

Force balance for the horizontal Jaw



Free body diagram of Handle

Handle :

Summing moments about handle :

FA * L3 * sin(A1) =

force * (handle * cos(A1) - L3 * sin(A1))

Force balance for the slanted handle

General Force Analysis of Bolt Cutter

$$FA := \frac{FC \cdot L1}{L2}$$

Solving for FA

$$\text{force} := \frac{FA \cdot L3 \sin(A1)}{\text{handle} \cdot \cos(A1) - L3 \sin(A1)}$$

Solving for force

Determining Shear Force Needed :

$$s_y := 55 \text{ ksi}$$

Estimated
yield strength
of bolt

$$s_{us} := s_y \cdot 0.75$$

Estimated
ultimate strength
in shear of bolt

$$s_{us} = 41.25 \text{ ksi}$$

$\tau_{ave} := s_{us}$ Let the average shear
equal the bolt's ultimate strength in shear

$$\tau_{ave} := \frac{P}{A}$$

$$P := \tau_{ave} \cdot A \quad \text{Solve for P}$$

$$P = 1.025 \cdot 10^4 \text{ lbf}$$

Shearing Force

$$A := \frac{\text{Diameter}^2 \cdot \pi}{4}$$

Area of bolt cross
section

$$FC := P$$

Shearing force
equals force in
shear equation

Substituting into one equation :

$$\text{force} := \frac{\frac{FC \cdot L1}{L2} \cdot L3 \sin(A1)}{\text{handle} \cdot \cos(A1) - L3 \sin(A1)}$$

$$\text{force} = 22.645 \text{ lbf}$$

$$\text{Torque} := \text{force} \cdot \text{handle}$$

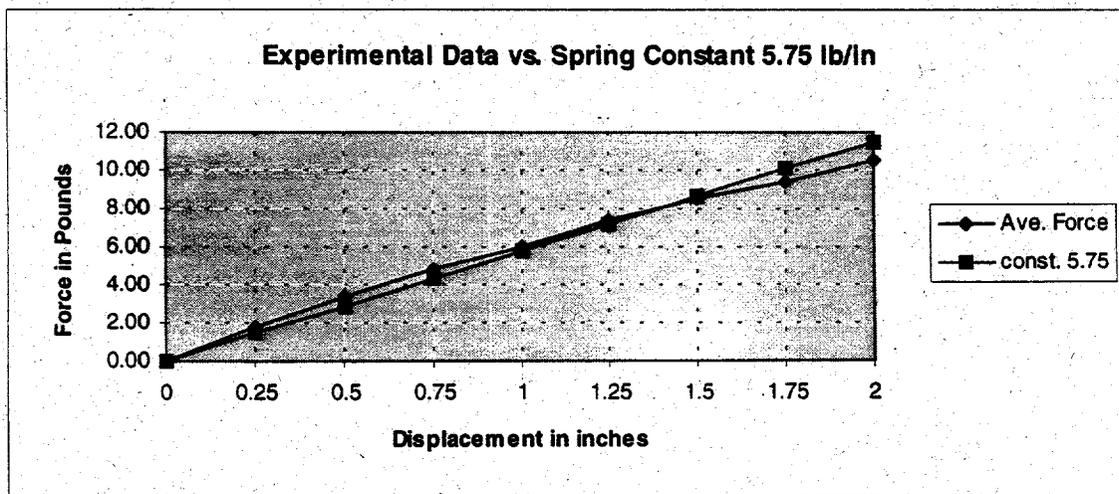
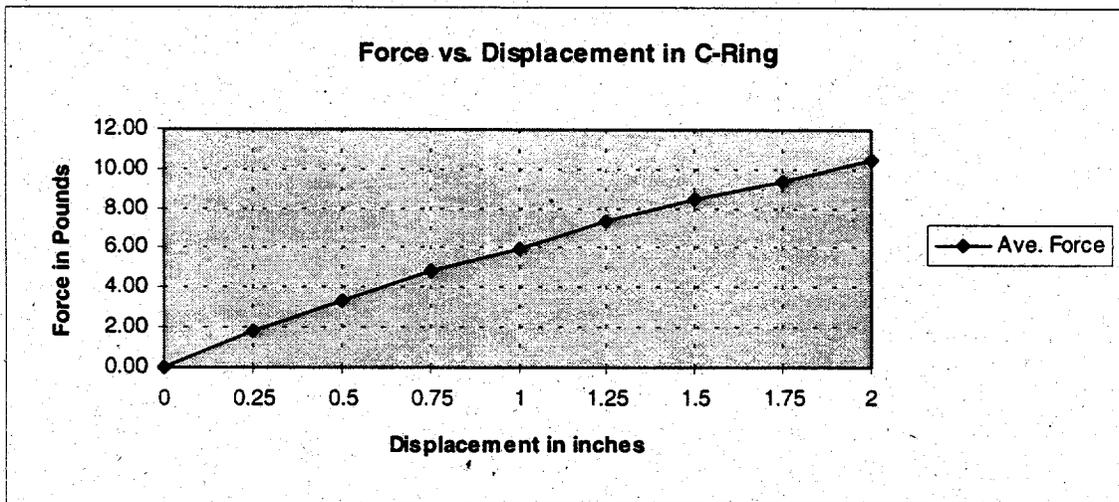
$$\text{Torque} = 67.935 \text{ ft} \cdot \text{lbf}$$

(for the handle, or first lever)

Appendix B

Data for Spring (K) Experiment on C-Ring

Distance (in)	0	0.25	0.5	0.75	1	1.25	1.5	1.75	2
Trial 1	0	2	3.5	4.5	6	7.5	9	9.5	11
Trial 2	0	1.5	3	5	6	7.5	8.5	9.5	10.5
Trial 3	0	2	3.5	5	6	7	8	9	10
Average (in)	0.00	1.83	3.33	4.83	6.00	7.33	8.50	9.33	10.50



ROBOTIC END-EFFECTORS FOR NON-DESTRUCTIVE OPENING OF WASTE DRUMS

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ABSTRACT

Mixed waste, much of which is stored in 55 gallon drums, consists of both radioactive and toxic waste. Tens of thousands of waste drums will have to be processed in waste treatment facilities. One of the promising processes is plasma hearth, a thermal process. Some toxic waste (lead and mercury) can not be effectively handled by this process, and therefore must be disposed of separately.

A nondestructive drum opening process is pursued in this research so that drums can be resealed after toxic waste has been retrieved for final disposition. The whole process requires four tasks. First, the bolt assembly that secures the drum's closure ring (c-ring) must be disengaged. Afterwards, the c-ring, which clamps the lid to the drum, must be removed. Then the lid itself must be dislodged. Finally the top of the inside plastic liner must be cut out and removed. Each task will require the design of one or more end-effectors, used with an industrial robot.

I. INTRODUCTION

The Department of Energy (DOE) has created nuclear weapons for defense for over forty years. During this time, hazardous and nuclear wastes have accumulated, and contamination of soils and groundwater have occurred, as environmental stewardship was not fully appreciated until recent times. Thousands of sites require clean up, and hundreds of facilities require decontamination and decommissioning.

Mixed Waste Operations deal with low level and transuranic mixed waste containing both hazardous and radioactive materials. Mixed waste occupies over two and a half million cubic feet at 49 DOE sites in 22 states across the country (Ward 1994). The reduction in waste volume or level of harmful constituents, or the complete transformation of the waste into an inert substance, is

preferred over the endless costs and risks of simply storing the waste.

The plasma hearth process is a promising thermal treatment. It is able to vitrify, or reduce to a glassy slag, a broad diversity of mixed wastes. The process does so by destroying the organic components and confining the inorganic components and radionuclides in a stable waste form. Importantly, extensive characterization of mixed wastes is not needed with this operation. However the process is unable to handle hazardous inorganics like mercury and lead. Still, the plasma hearth has the potential to significantly reduce the amount of mixed waste in storage.

Mixed waste is stored in a variety of containers: 30, 55, and 85 gallon drums, metal bins, and wooden boxes. Most of the volume, however, is contained in 55 gallon storage drums, and much of this is in the form of heterogeneous dry solids, as shown in figure 1.

This work focuses on the 55 gallon drums containing heterogeneous dry solids. The 55 gallon drums' weights vary from 100 to 600 pounds. They are not packed by weight but by their level of radioactivity, which does not exceed 300 mrem/hr (Ward 1996). The objective of this research is to use a robot to open waste drums non-destructively. Hazardous waste can be removed and then drums can be resealed for a final process - the plasma hearth.



Figure 1 Waste Drums in Storage

II. OPENING OF WASTE DRUMS

The waste drums have been sealed manually. The lid cover was first placed on the drum. The drum's c-ring was then slid around the lid, fastening the lid to the drum. Then the c-ring was clamped tight with a bolt and nut in four steps.

First the bolt was put through the clearance eyelet hole of the right c-ring tab. Then the nut (which works as a jam nut) was screwed onto the bolt. Next the bolt was screwed into the threaded eyelet tab, tightening the c-ring around the drum lid. The torque applied may have been as high as 130 ft-lb with the use of a pneumatic wrench (Exum 1996). It is not uncommon for a mallet to impact around the c-ring as this tightening process occurs to assist in an evenly and thoroughly tightened c-ring.

Finally the jam nut was turned tight against the threaded eyelet (approximately 70 ft-lb applied by a hand wrench) to keep the bolt from turning so that it would not shake loose (Exum 1996).

The fastened bolt assembly is shown in figure 2. The jam nut works in conjunction with the threaded c-ring tab to preload the bolt and to eliminate backlash in the bolt. Figure 3 shows the threads of the threaded tab and nut are against opposite sides of the bolt's thread.

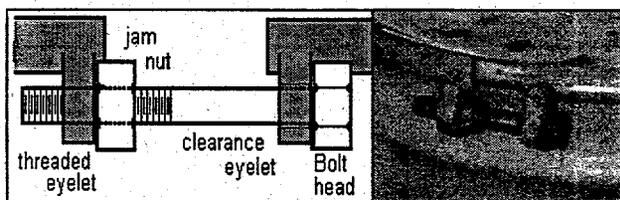


Figure 2 Secured Bolt Assembly

The manual opening process is essentially the reverse of the closing process. Because the drums have been sitting for many years, the bolts and jam nuts should be sprayed or doused with a lubricant (Liquid Wrench or WD-40) to facilitate unscrewing. The lubricant should be applied hours before attempting to unscrew the assembly in order to allow penetration.

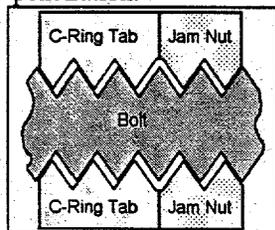


Figure 3 Preloading on the Bolt and Jam Nut

At the start of the actual unscrewing process, the jam nut would need to be loosened first (approximately a quarter turn) before the bolt could be unscrewed from the threaded eyelet. If this is not done, there is a possibility the bolt could be sheared off during the attempt to unscrew it with an impact wrench. Stripping the bolt's threads in the threaded c-ring tab is another possibility if the jam nut is not first loosened.

After the bolt assembly is unfastened, the c-ring can then be spread apart and slipped off the drum. The drum lid will often still be sealed to the drum, however, because of rust or corrosion that has occurred in areas between the lid and drum where the rubber gasket does not protect the contact surfaces. Often a mallet will be used to hammer the center or near the edge of the lid to help break the seal so the lid can be removed. Perhaps a screwdriver will be used to help pry the lid off as well.

In 1993 at the Savannah River Site, destructive drum opening as well as other relevant automated waste processing operations was demonstrated (DOE 1993). The process begins with a drum lifter, consisting of grasping straps controlled from an overhead crane, fitting around a 55 gallon drum. The drum lifter transports a drum to the drum opening cell and top loads it into a revolving chuck. Masts on either side of the drum engage cutting tools and idler supports that come into contact with the side of the drum wall. As the drum is rotated, the cutter, a sharp disk, is pressed onto the side, slowly cutting the drum as it revolves, like a big pipe cutter. After the drum wall has been completely cut, the drum lifter removes the drum's top half, exposing the inner lining (.09" thick polyethylene) for the next cutting process. A stationary blade like a lathe cutter is then engaged into the liner side, cutting the liner in a similar fashion as used on the drum wall.

Although the technology of destructively opening the drums is robust and simple, the generation of secondary waste is a significant drawback because then the drums must be disposed of separately, perhaps in a larger, 85 gallon drum. If the waste drums are opened in a non-destructive way, they can be resealed for one final use: transporting the sorted waste for final disposition in the plasma hearth. To reseat the drums, it is necessary that the lid and drum remain undamaged during the opening process. The inner plastic liner is no longer necessary for the last transportation of the drums. Similarly, the bolt assembly and the c-ring are of secondary importance. With just the drum and lid, waste suitable for the plasma hearth process can be repackaged inside the drum, with the lid glued or riveted on in an automated operation.

Design constraints for the non-destructive opening of the 55 gallon drums include incorporating a standard

industrial robot, a drum lifter and revolving drum chuck, and a tool changer. Possible candidates for the industrial robot include FANUC S-700 and the ABB Flexible Automation IRB 4400. Each of these satisfies the basic parameters of six degrees of movement, a payload capacity from 50 to 100 lb., a six foot reach, and around $\pm 0.007''$ of repeatability.

The drum lifter and revolving drum chuck developed previously and demonstrated at Savannah River Technical Center will be used in this project. The drum lifter allows the transporting and top loading of the drums into workcells within the Mixed Waste Operations facilities. It is capable of precisely placing even deformed drums, and is used to load them into the revolving drum chuck. The drum chuck firmly grasps the drums at their base, and then can revolve the drums to whatever orientation is needed. This is a useful feature as a robot arm can reach any side of the drum without relocation of its base.

A tool changer allows the robot to quickly and easily attach, and then exchange any number of end-effectors or robotic tools. One half of the tool changer is attached to the robot's tool face plate, and the other half is attached to the tool. The two halves are connected by a quick release cam. The tool changer supplies pneumatic and electrical contacts from the robot to power the end-effector. The Applied Robotics tool changer has been selected for this project. It has a weight of 22 lbs. with its center of mass 3.8" from the tool face plate. Its size and weight further restrict the tool design.

III. END-EFFECTOR DESIGN

There are four steps involved in opening the drums so that they can be resealed in the future. First, the bolt assembly that secures the drum's c-ring must be disengaged by either cutting it or unscrewing it. The method used will affect the second task- c-ring removal, since parts of the bolt assembly may or may not be present in the c-ring tabs. After the c-ring is removed, the lid itself must be dislodged. This task is complicated by the significant that results with time, and the minimal leverage area available around the lid. And finally the top of the inside plastic liner must be cut out and removed. The liner top must be supported during this task to keep it from falling back inside the drum. Each task will require the design of one or more end-effectors, which will operate with the industrial robot. Therefore the designs should support as much automation as possible.

Designing for autonomous operation will be challenging because of slight size and shape variations among the drums. For example, a c-ring might be deformed, or a jam nut oriented differently from the

previous drum's jam nut. And depending on the procedure used for unfastening the bolt, the bolt assembly may offer differences to the gripping interface of the end-effector, as the unfastening process may not produce identical results each time. For instance, the bolt could be cut in a slightly different place, producing a shorter or longer threaded rod left in the threaded eyelet. Although any major anomalies could be handled manually, the end-effector design should be as robust as possible.

A. Bolt Removal

The first step in unscrewing the bolt assembly, after application of a lubricant, would be loosening the jam nut used to keep the bolt from turning. The nut loosening process will be challenging. Perhaps a gripper would force its teeth around the nut like pliers, gripping it no matter what the orientation of the nut. And then another actuator would turn the grippers and nut the quarter turn required to loosen it. Or the nut could be split open. A nut splitter, hydraulically actuated, is available on the market for removing rusty or frozen nuts. This device forces two pointed teeth into the top and bottom surfaces of the nut, until the nut is broken apart. After the operation, the broken parts need to be recovered.

The nut does not need to be fully removed from the bolt to allow the c-ring to be removed (see figure 4). It just needs to be loosened so that the bolt can be unfastened from the threaded eyelet, making it possible to spread the c-ring apart and remove it. Partial unscrewing has the added advantage of keeping the bolt assembly attached to the c-ring, thus being one less part to handle. The advantageous geometry (2 open eyelets) for removing the c-ring in the next task step is no longer present, however.



Figure 4 Partially Unscrewed Bolt Assembly

Unscrewing the bolt from the threaded eyelet once the nut has been loosened or split apart could be achieved with a pneumatic impact wrench. A long socket over the bolt would avoid moving or feeding the end-effector backwards as the bolt unscrewed. The wrench can be engaged with the bolt head by lining up the wrench to the bolt and applying a small force into the bolt while activating the wrench (Hanna 1996).

Cutting the bolt between the tabs is a simpler process than unscrewing. A large range of methods are available for cutting the bolt assembly and must be considered. Whatever cutting method is used, the top half of the bolt will be loose in the clearance tab and will need to be retrieved. This will result in a c-ring with one open eyelet, and with a half bolt and nut tightly screwed into the other eyelet, as shown in figure 5. Because of this, the bolt should be cut as close to the jam nut as possible to make room for the c-ring removal end-effector.

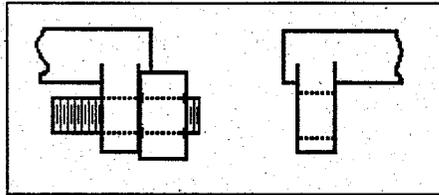


Figure 5 Sheared Bolt with Bolt Head Removed

Unscrewing the bolt has two advantages as compared to cutting. One, it will immediately make the c-ring usable for repackaging the sorted waste for final disposition. This advantage, however, is questionable as the c-rings may not be used for repackaging since a 'permanent' sealing process such as gluing or riveting the drum shut would be simpler and easier for robotic automation. The other advantage is that if the bolt were completely unscrewed and removed from the c-ring, the c-ring would be left with two good geometric features (the open eyelets) to dock with an end-effector for removal of the c-ring. The disadvantages to unscrewing the bolt are many: the process will take longer to accomplish with more than one end-effector, and may easily have a high failure rate if bolts are so rusty they end up being sheared apart.

Cutting the bolt has the advantages of being a quick and robust process. However, the cut half of the bolt may fall loose from the c-ring, and so must be dealt with in the design. Also, cutting the bolt will leave half of the bolt assembly in the threaded eyelet, making the gripping action for removal of the c-ring more difficult.

Four senior engineering students from Worcester Polytechnic Institute (WPI) worked on the problem of unfastening the bolt assembly during the spring semester of 1996 (Davis et al. 1996) as a joint project with N.C. A & T State University (A&T). This work made up their Major Qualifying Project, in partial fulfillment of an engineering degree from WPI. They conducted a survey of possible unfastening methods. They also ran a number of experiments, from obtaining the hardness of the bolt, to testing a number of cutting blades with variable feed rates and cutting speeds.

A number of cutting methods were discarded quickly. These include the bandsaw, the reciprocating saw, and the cutoff wheel. The bandsaw and reciprocating saw have clearance problems; the drum wall may be damaged before the bolt is completely cut. The cutoff wheel blade wears out very quickly and requires frequent changing. The more promising cutting methods, rotary saw, laser, and shearing, are examined below.

WPI's proposal was to cut the bolt assembly with a pneumatically driven rotary saw. This method requires feeding the blade as the cut is made. The metal chips that are generated would need to be vacuumed.

A laser unit to cut the bolt would not be attached to the robot because it is too large. But lasers could be placed overhead on a short liner track, cutting the bolt assembly from above. Laser systems require minimal maintenance. The laser would require an input of 480 volts, with a transformer to step the voltage up to 20 kilovolts. A minimum power of 1500 watts is needed, giving a cutting speed of five to ten inches a minute. A basic metal cutting unit, capable of cutting the 9/16" diameter of the bolt, would cost around a half million dollars. Vaporized metal and molten metal fumes would result from the cutting operation (Kempka 1996).

Shearing has a number of advantages. Once the blades have docked with the bolt assembly, they simply need to be activated, not fed through the cut as required in all other cutting operations. Shearing also does not generate any chips or dust. It requires around 10,250 lb of force to shear a 9/16" bolt, however, which suggests the need for hydraulic power given the weight constraints. H. K. Porter manufactures a hydraulically actuated cutterhead (shown in figure 6) which can meet the need.



Figure 6 H.K Porter Hydraulic Rod Cutter

Hale Products Inc. manufactures the Mini-Cutter (as shown in figure 7), used in rescue operations. It generates a cutting force of 17,000 lb, with a 1.5" open jaw. This tool would need to be modified in order to handle the tight clearances between the bolt assembly and drum.

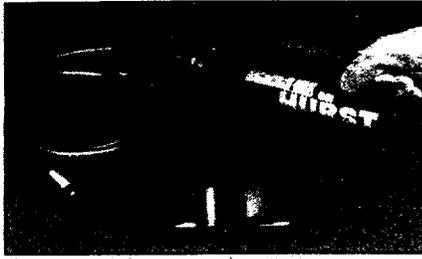


Figure 7 Hurst Mini-Cutter

B. C-Ring Removal

The c-ring can be removed by cutting it off. However, cutting the c-ring off is problematic: its 'c' shaped cross section envelopes the outer edge of the lid and drum. Cutting it without damaging the drum seal would be very difficult and is not considered in this design.

The c-ring can be removed by spreading it apart and then lifting it off the drum. Spreading the c-ring apart can be accomplished in two ways. One way is by 'grabbing' one eyelet and pulling. The other eyelet is held to the drum by friction. This method would require the robotic arm to apply a type of corkscrew motion, stripping the c-ring off the drum. The other end would snap off the drum when it becomes free. This uncontrolled snapping action may damage the robot. The more stable method is for both eyelets to be grabbed at the same time and be spread apart.

Before c-ring removal, the bolt is assumed to be sheared apart by a hydraulic cutter as close to the jam nut as possible. However, a shearing action generally cannot cut flush to the nut like a laser or sawing action can. Space between the cut bolt and clearance eyelet tab after the c-ring has lost most of its tension is only about 1.3".

This gap is an advantageous place to apply a pushing force in order to expand the c-ring. The bolt head is removed by an electro-magnetic end-effector from the clearance hole. The remaining bolt and jam nut remain in place. The design requirements are listed below:

- The end-effector will be attached to the Applied Robotics tool changer.
- Keep the weight and size as low as possible.
- Keep the design as simple as possible. Keep the number of moving parts and actuators as small as possible.
- The end-effector's grasping points should allow the c-ring to swing freely. If a fixed restraint is required at the grasping points, the moment load caused by the

weight of the c-ring to the tool changer will likely exceed the latter's load capacity.

- The end-effector should be able to release the c-ring to a storage rack at the end of the task.
- Sensors are needed to send signals to a robot controller to sequence the motion.
- The two tabs need to be pushed 3" apart to remove the c-ring from the drum.
- Maximum pushing force is 20 lb.
- A pneumatic piston is preferred.
- Pneumatic manifold is needed to merge several pneumatic ports of the tool changer to provide sufficient air flow.

MEEN 565 Machine Design class of Spring 1996 had the c-ring removal end-effector as their class project. The class created many designs, and helped in shaping this final design.

A common design of the grasping arrangement of many class design groups consists of a cup over the jam nut and the bolt, and a pin into the clearance hole in the c-ring. After the contact is secured by the cup and pin, they will be pushed outward to spread the c-ring. The c-ring is allowed to swing down by at the contact (cup and pin). However, the design requires more clearance than may be available because of the size of the cup.

A revised design (Rommel D. Simpson's group) changes the cup to a slender tab to push against the cut bolt. A ring tab is used to envelope the bolt end as it is pushed out, as shown in Fig. 12. This requires less gap space between the c-ring tabs, and takes advantage of the severed bolt assembly, instead of viewing the half-bolt as a liability. Or, from another perspective, the new design breaks the two functions of the cup (pushing and holding) into two separate parts. The slender tab is for pushing, and the ring tab is for holding.

Most designs require the two tabs to be pushed apart at the same time. This requires either two actuators or one double actuating actuator. Simpson's group presented a simple idea using a single actuator to push the left tab to expand the c-ring while holding the right tab.

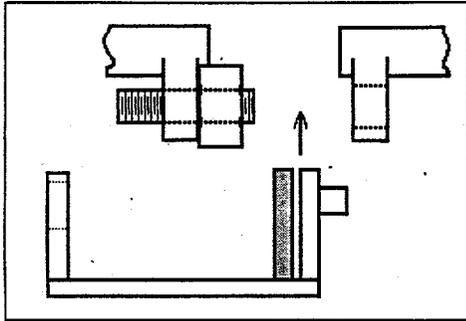


Figure 8 Docking the Tool

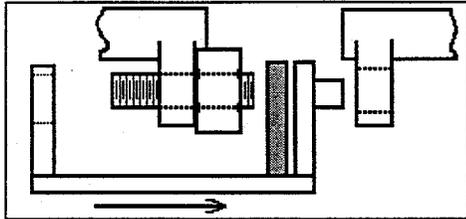


Figure 9 Moving into the Right Eyelet

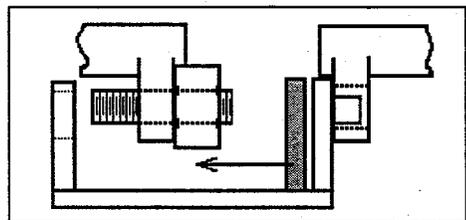


Figure 10 Engaging the Cut Bolt

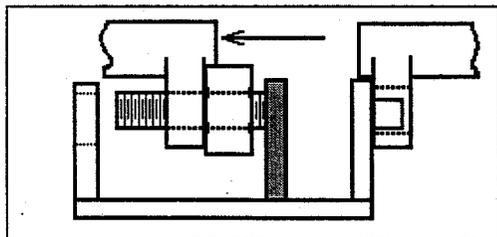


Figure 11 Pushing the C-Ring Apart

In figure 8, the robot prepares to dock the end-effector. Figure 9 shows the robot placing the pin and plate into the gap. Then the robot moves to the right until the pin is in the clearance hole, as shown in figure 10. The piston is then pushed to the left for a stroke of 3" (figure 11), forcing the bolt into the left ring tab (figure 12). The robot will then move to the left so that the clearance is symmetric about the center (figure 13). Finally, the robot will lift the c-ring from the drum. Once the c-ring clears the drum, the robot is responsible for placing the c-ring on a rack.

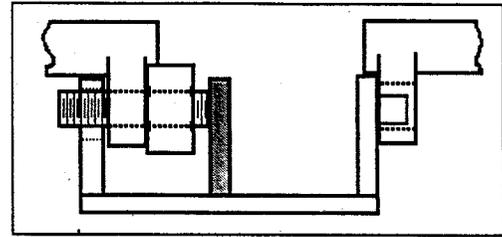


Figure 12 Holding the Bolt in the Ring Tab

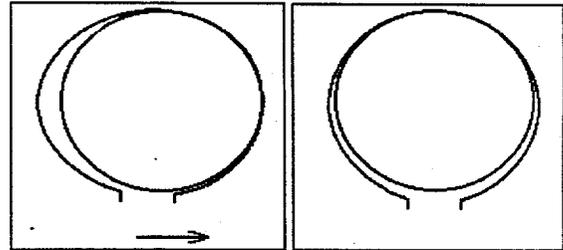


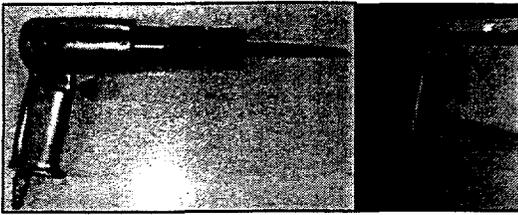
Figure 13 Centering the C-Ring

C. Lid Removal

After having a c-ring clamped around it for up to 40 years, the lid is essentially sealed to the drum. Removing the lid becomes a two step process: breaking the seal and then removing the loosened lid. In manual operations, a sealed lid is hit a number of times with a hammer, both at the center and around the rim, to help break this seal (Exum 1996). A screwdriver may then be wedged in-between the lid and drum to pry off the lid. However, there is very little clearance between the lid and drum (.035") for robotic operations. A little more substantial is a lip overhang from the width of the lid's thickness (.065"). The lid itself weighs 7.5 pounds.

It is possible that hooks from an overhead crane could be placed around the lid's edge as the drum is held in the chuck. The hooks could pull up and just detach the lid from the drum with raw force in one step. A large pulling force is required to break the seal.

An impact chisel with a flat edge bit, as shown in fig 14(a), could employ impact force to break the lid's seal like a screwdriver in manual operation. A pneumatic chisel could be brought to the lid's perimeter to apply an impact force at the lip overhang as shown in figure 14(b). A roller could be attached to the end-effector to keep it stable with the side of the drum as the chisel strikes the lid. The drum could be rotated as needed, starting from the weaker joined locations. In this manner, the impacts could vibrate the lid, tearing and breaking the areas which are sealed. The bit has the tendency to chip off paint from the drum. To avoid this problem, the bit could be given a protective coating such as Teflon, or made out of rubber.



(a) (b)
Figure 14 Pneumatic Chisel

This method of lid removal was demonstrated at Savannah River Technical Center on July 30, 1996 on a drum left outside for three years. During the three years a substantial seal of rust had developed between the metal contact surfaces between the lid and drum not separated with the rubber gasket. Within three minutes the seal was broken, allowing the removal of the lid. The procedure was also performed on a drum sealed with super glue, an excellent bonding adhesive on both metal and rubber. The adhesive was applied between the rubber gasket and metal drum rim to simulate a seal resulting from time and exposure. The experiment showed the impact chisel can break up the glue seal.

After the lid's seal is broken, the loosened lid can be removed. Vacuum cups could be employed. However an electromagnetic end-effector would be less likely to lose its effectiveness from a dented or soiled lid.

D. Plastic Liner Removal

An .090" thick inner plastic lining is the final obstacle to reaching the stored mixed waste. The liner's round plastic cover has been 'permanently' secured by coating its perimeter with an epoxy and then force fitting the cover into the lining. A one inch diameter hole in the cover's center is present to vent any gas. The top of the liner can be cut out because it does not need to be used again in a 'sealed' condition. The design must satisfy the following constraints:

- The top of the liner must be supported as it is cut so that it does not drop into the drum after the cut.
- The supported cut piece will then need to be lifted out.

Because the drum will be placed in the rotating chuck, the cutting tool can remain stationary while the drum turns, creating a circular cut. The circular cut, with a radius smaller than 12", can possibly pose a problem for some cutting methods. For example, if a reciprocal cutting method is adopted, the blade would need to be thin, similar to a jigsaw blade, to avoid binding.

The 1993 destructive drum opening process demonstrated at Savannah River Technical Center used a stationary blade to cut through the side of the liner with progressive feeding. Although it took a number of revolutions to accomplish the cut, the method did not produce shavings. This new task, however, involves opening the liner from the top. Since the blade will be cutting a circular path, a narrow blade is needed to prevent binding. Also, the blade would need to be fed down into the liner during the cut.

A spiral saw (figure 15), which cuts like a portable mini-milling machine, can accomplish this task in one pass. It weighs about a pound, and would constitute the main part of the robotic end-effector. A vacuum could be added if needed to retrieve the plastic shavings as they are created.

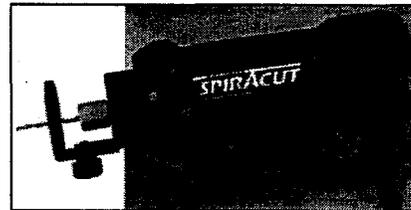


Figure 15 Spiral Saw

Liner support can be accomplished by vacuum cups or a supportive toggle mechanism. Vacuum cups, can easily be attached to the top of the liner, however they would need to straddle the center hole. They would also need to be attached to a bearing so that they could freely rotate in relation to the turning drum as the cut is made.

A toggle mechanism can take advantage of the center venting hole. It can be actuated by a solenoid. In its activated state, the toggle contracts so that it can enter the center hole. Then it is deactivated so that a spring spreads the toggle out, supporting the liner from underneath. This fail-safe mode would keep the mechanism from dropping the liner if power were suddenly cut off. The liner would not have any trouble rotating relative to the toggle support.

A spiral saw with a toggle mechanism attached is shown in figure 16. This prototype was built to test the liner opening. The simple toggle used had only two prongs, but three prongs would allow for a more stable handling of the liner top.

The end-effector is positioned over the liner so that the toggle can be dropped down into the center hole. As the toggle enters the hole and deactivates to its support position, the spiral saw can be activated, making an initial plunging cut into the liner. The drum chuck is then rotated, causing the stationary cutter to make a circular

cutting path while the toggle gives support at the center of the liner. After the drum has turned 360 degrees, the cut is complete and the spiral saw can be turned off. With the toggle still attached, the end-effector then lifts out the liner top. At the designated place of delivery, the toggle activates and drops the top.

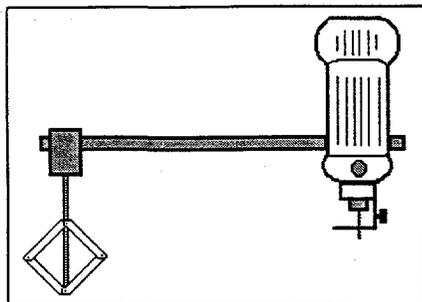


Figure 16 Toggle and Spiral Cutter

IV. SUMMARY AND CONCLUSION

A demonstration was made at Savannah River Technical Center on July 30, 1996 to show the conceptual design of end-effectors to remove the c-ring, lid, and inner liner top. A short video was made to demonstrate these tasks.

Sensors and an accompanying control system should be developed to help make the process as automated as possible. An automated system not only places less demand on the operator, but helps to speed up the overall process.

Since work was begun on the non-destructive drum opening procedure, the plasma hearth thermal process has fallen out of favor. Public concerns about environmental pollution have kept states from allowing the process within their borders. Therefore the related non-destructive drum opening is also shelved.

However, a new need has arisen in Idaho for non-destructive drum opening. The 55 gallon mixed waste drums stored there must be brought into the required safety standards, and then shipped to another storage location. Many drums will need to be opened so that items such as compressed gas and ignitable materials, which do not meet the waste acceptance criteria, can be removed; after which the drums will be sealed again. This means the liner, as well as the drum, will need to be opened non-destructively, and then resealed. Another situation is that the metal drum itself may be rusted or damaged. In this case, just the inner liner could be removed intact, and placed in a new drum. End-effector designs developed in this project can be quickly adapted into the new project.

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Robotic Tooling for DOE Environmental Management

Annual Report

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Dr. Shih-Liang Wang

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ROBOTIC END-EFFECTORS FOR NON-DESTRUCTIVE OPENING OF WASTE DRUMS

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ABSTRACT

Mixed waste, much of which is stored in 55 gallon drums, consists of both radioactive and toxic waste. Tens of thousands of waste drums will have to be processed in waste treatment facilities. One of the promising processes is plasma hearth, a thermal process. Some toxic waste (lead and mercury) can not be effectively handled by this process, and therefore must be disposed of separately.

A nondestructive drum opening process is pursued in this research so that drums can be resealed after toxic waste has been retrieved for final disposition. The whole process requires four tasks. First, the bolt assembly that secures the drum's closure ring (c-ring) must be disengaged. Afterwards, the c-ring, which clamps the lid to the drum, must be removed. Then the lid itself must be dislodged. Finally the top of the inside plastic liner must be cut out and removed. Each task will require the design of one or more end-effectors, used with an industrial robot.

I. INTRODUCTION

The Department of Energy (DOE) has created nuclear weapons for defense for over forty years. During this time, hazardous and nuclear wastes have accumulated, and contamination of soils and groundwater have occurred, as environmental stewardship was not fully appreciated until recent times. Thousands of sites require clean up, and hundreds of facilities require decontamination and decommissioning.

Mixed Waste Operations deal with low level and transuranic mixed waste containing both hazardous and radioactive materials. Mixed waste occupies over two and a half million cubic feet at 49 DOE sites in 22 states across the country (Ward 1994). The reduction in waste volume or level of harmful constituents, or the complete transformation of the waste into an inert substance, is

preferred over the endless costs and risks of simply storing the waste.

The plasma hearth process is a promising thermal treatment. It is able to vitrify, or reduce to a glassy slag, a broad diversity of mixed wastes. The process does so by destroying the organic components and confining the inorganic components and radionuclides in a stable waste form. Importantly, extensive characterization of mixed wastes is not needed with this operation. However the process is unable to handle hazardous inorganics like mercury and lead. Still, the plasma hearth has the potential to significantly reduce the amount of mixed waste in storage.

Mixed waste is stored in a variety of containers: 30, 55, and 85 gallon drums, metal bins, and wooden boxes. Most of the volume, however, is contained in 55 gallon storage drums, and much of this is in the form of heterogeneous dry solids, as shown in figure 1.

This work focuses on the 55 gallon drums containing heterogeneous dry solids. The 55 gallon drums' weights vary from 100 to 600 pounds. They are not packed by weight but by their level of radioactivity, which does not exceed 300 mrem/hr (Ward 1996). The objective of this research is to use a robot to open waste drums non-destructively. Hazardous waste can be removed and then drums can be resealed for a final process - the plasma hearth.



Figure 1 Waste Drums in Storage