Optimized Cutting Method for Transnuclear Used Nuclear Fuel Canisters

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1. Abstract

Current designs for a federal repository for used nuclear fuel within the United States requires all fuel be removed from its current canister into a standardized canister type. These standardized canisters within the federal repository will allow for reduced cost in maintenance, reduced space requirements, and increased security of the fuel. Existing canisters that are located throughout the United States at each nuclear plant were designed for short-term storage in-lieu of the Federal repository being built. As such, they range in sizes, sealing methods, and fuel type. While some canisters are bolted shut and allow for a quick transfer of fuel into the standardize canisters, other canisters are welded shut. Through the licensed way of opening these canisters, it would take approximately four hours to open each canister excluding any transition time and gas testing.

With the thousands of canisters that are welded shut, allowing a time commitment of four hours for each canister is not possible for the future federal repository. To be prepared for this, seven cutting methods have been evaluated for optimality in this application, including the current method. During the evaluation it was determined that rather than doing a traditional, nondestructive, opening procedure, the canisters could be opened at a faster rate through a more destructive method. This new method includes cutting below the lids of the canisters, requires a redesign of the gas testing mechanism, and is not a licensed or tested method. Both options for opening the welded canisters were evaluated for six cutting methods, though seven were available but not always applicable.

The comparison of the seven methods is only considered applicable under specific design parameters and include assumptions that require further evaluation. This report should be regarded as a starting point for the research that must be completed for optimization of opening the welded used nuclear fuel canisters within the United States.

2. Design Narrative

2.1. Used Nuclear Fuel Storage Crisis

The Yucca Mountain Nuclear Fuel Repository has been a hot button topic for the nuclear industry for nearly four decades. If built, the repository would become the final stop for all of the United States' (US) used nuclear fuel (UNF). Nuclear fuel is currently stored onsite at nuclear facilities around the US indefinitely, where the volume of UNF continues to increase and space is limited which increases the need for a federal repository. The Yucca Mountain repository would solve the issue of nuclear facilities having to store their UNF, increase the national safety of UNF, decreases overall cost of upkeep and maintenance, and allow a more uniformed storage system. Regardless of if the Yucca Mountain Nuclear Fuel Repository is ever to be built, there is a dire need for a centralized repository in the US. A map detailing the location of the UNF canisters in the US can be seen in Figure 1 ("NRC Maps Of Independent Spent Fuel Storage Installations (ISFSI)", n.d.).

This issue started in 1954 when Congress passed the Atomic Energy Act. Through this act, the Federal Government accepted responsibility for storing UNF accumulated from US energy companies. However, it was not until 1987 that Congress chose Yucca Mountain Nevada to become the repository for UNF. The Department of Energy (DOE) claimed that Yucca Mountain was the most optimal place for this repository due to its scientific and geological characteristics. The Yucca Mountain land is Federally owned, located in the desert of Nevada and isolated. The UNF would be stored well below 1,000 feet underground ("Eureka County, Nevada", n.d.). A section view of Yucca Mountain can be seen in Figure 2 ("Yucca Mountain All But Scrapped", n.d.)

Nevada has not accepted the Yucca Mountain project since its envision. After many years of protesting and political battles over the repository, it has mainly been untouched since the initial geographic testing. In 2002, President George W. Bush signed the Yucca Mountain Development Act (YMDA) which would jumpstart the project again. However, the project went years without progress due to more political issues, and when President Obama took office. The Obama administration shut down the project without any alternatives and claimed that the project was shut down due to the steep cost of the project ("Eureka County, Nevada", n.d.).

While any progress on the physical building of the Yucca Mountain Nuclear Fuel Repository has been frozen in time, the problem remains, as there is a need for a centralized repository in the US. A centralized repository would be much more cost effective for the nuclear companies that are running out of space for dry cask storage. Regardless of if Yucca Mountain is to be built or not, it will inevitably be necessary for Congress to determine the future of UNF in the US.

2.2.Project Background

In 2008, the DOE awarded a five-year, $2.5 billion contract concerning Yucca Mountain's management and operation to USA Repository Services. This corporation was supported by Shaw Environmental and Infrastructure Inc and AREVA Federal Services Inc. ("Yucca Mountain Contract Is Awarded" 2008). In January 2018 AREVA was rebranded into Orano and Framatome. ("About Orano" 2018) ("Our Organization Evolves", n.d.) Since Orano is focused on the nuclear materials side of what was AREVA, they specialize in the transportation and storage of nuclear material, UNF, and were awarded the Yucca Mountain contract responsibilities formally given to AREVA.

Since the rebranding, Orano, in conjunction with Waste Control Specialists (WCS), created a consolidated interim storage facility (CISF) company, Interim Storage Partners (ISP). ("Home", n.d.) In 2018, ISP's license application was accepted for detailed review by the Nuclear Regulatory Commission (NRC) for their CISF design for the existing WCS storage site in Andrews County, Texas. ISP's application proposed 40-year license with a potential total of 40,000 metric tons of UNF being stored at the CISF. ISP will rely on storage technologies that are already licensed and used throughout the US that were designed by Orano and NAC International. ("NRC Accepts License Application For Used Nuclear Fuel Consolidated Interim Storage Facility In West Texas" 2018) This CISF will be an above-ground processing and storage facility for nuclear waste being held at decommissioned nuclear power plants around the US. Currently, there are 13 decommissioned nuclear plants within the US where UNF is being stored and no power is being made. This facility was determined to be necessary with the delayed creation of the federal repository site originally due to be opened in 1998. However, it is planned to complement the future national repository, as designed by Orano, and will develop a repackaging facility that can be replicated for future canister re-storage purposes. ("Project Overview". n.d.)

There is a second CISF storage facility currently under review by the NRC that was proposed by Holtec International (HI). The potential facility, planned to be in New Mexico, is known as HI-STORE CIS. In February 2018, HI was given a preliminary schedule from the NRC predicting that their license will be active by July 2020. HI-STORE CIS is a subterranean design with an initial licensing capacity of 8,680 metric tons of UNF. The goal is to place all canister types, both vertical and horizontal, in a standard HI-STORM UMAX cavity system in order to ease the operations and aging management of UNF within the US and prepare for the permanent federal repository. HI reports that, "... HI-STORE CIS is the only ongoing licensing effort in the country that seeks to fulfill DOE's declared aspiration for a consolidated interim storage facility." This is in part due to their initiative to become a certified storage destination for all UNF throughout the US. HI further plans to use the underground thermal energy produced by the contained fuel at HI-STORE CIS to purify water for New Mexico while the fuel waits for the federal repository. ("HI-STORE CIS In Southeastern New Mexico Edges Closer To Regulatory Approval – Holtec International" 2018)

With two opportunities to transport and uniformly store UNF from different nuclear plants and storage facilities, Orano started a research project through the University of North Carolina at Charlotte (UNCC), and Industrial Solution Laboratory (ISL) to determine the optimal method for opening welded UNF canisters. This optimal method design could serve industry purposes for both Orano and Holtec International due to their similar goals requiring that all current canisters be opened, emptied, and disposed of.

2.3. Current Cutting Method Used

The current approved NRC cutting process is skiving. Skiving is performed non-destructively on the canisters and is further explained in sections 3.2.5. and 5.2.1.

2.4. Project Research Parameters

The research parameters associated with this project include seven major specifications.

- Identify the options for opening welded canisters in dry and wet environments.
- Contrast the options concerning: safety, operator dose, waste types, and volumes produced, cost, duration, and damage done to the canister.
- Propose ways to optimize operations, if possible.
- Contrast the differences in the performance of opening a canister at a nuclear reactor site versus at a facility dedicated to the handling of UNF (e.g., hot cell).
- Establish if the current method of gas sampling (e.g., for hydrogen) is required before the opening activity or can be improved.
- Establish the viability of performing as a remote/robotic operation with limited human interaction.
- Create models that depict at least one optimized canister opening method.

These specifications were established by the research sponsors, Orano. These parameters ensure that the team can focus on the shareholder's interests in order to achieve success.

2.5. Project Design Parameters

Design parameters for the project were determined after the research team began and started understanding how wide-ranging the scope of UNF storage can be. Among the many important considerations when handling UNF, a few parameters were set by the team when completing the design phase of their canister opening mechanism and determining the optimal cutting method. These specifications include:

- Cutting process will be completed at the federal repository

- Cutting process will be completed within a hot cell
- Assume heat transfer and radiation from the canister will be taken care of by the hot cell design
- Venting considerations will be designed with the hot cell
- The cutting process will occur in a dry environment
- The canister will remain vertical during the cutting process
- Assume the canister is already removed from its transfer cask
- Design to open Transnuclear 3-lid UNF canisters
- Assume canister dimensions and drawings will be provided at the time of opening
- Gas testing will be either done traditionally or designed to meet optimized cutting method specifications
- Nondestructive cut refers to the traditional method of opening welded UNF canisters by removing the weld material and lifting each lid individually allowing for the reuse of the canister if desired
- Destructive cut refers to a new method proposed by team for opening welded UNF canisters by cutting below the shield plug and lifting all three lids, and a portion of the canister walls, at the same time to expose the fuel basket

3. Cutting Methods

3.1. Proposed Options

Initially, the research generated several different cutting method options for opening welded UNF canisters. Options considered in the beginning were diamond wire, diamond saw, plasma, water jet, laser, skiving (and rotabroach). A process known as "cold cutting" using a device called a clamshell lathe was brought to the team's attention while researching diamond wire cutting from industry contacts. Diamond sawing was found to be too difficult to implement because sawing is primarily done on the vertical plane, but the canister orientation would require a horizontal planar cutting method. A rotabroach is used in combination with the traditional cutting method to gain access to the vent and siphon block, opening the silver dollar ports to allow for gas testing before venting the canisters.

The final list of the proposed options for opening the canisters are as follows:

- Clamshell
- Diamond Wire
- Laser
- Plasma
- Skiving
- Water Jet

3.2. History of Cutting Method Options

3.2.1. Clamshell

Initially, the clamshell cutting method was not considered. It was discovered when the team reached out to an industrial cutting company that did substantial work on remote diamond wire cutting. A phone conference was set up with Mirage Machines, where the team at Mirage quickly referred the team to their "cold cutting" device, later to be recognized as the clamshell lathe. This was recommended to the team because of how simple it was to set up and run in comparison with other methods originally discussed.

The primary function of a clamshell lathe is a mobile lathe that drops down over a cylinder and can be adjusted to various outside diameters (OD). It has two cutting blades that are opposite one another. The two-blade design allows for continuous cutting and finishing cuts to minimize jagged edges. The clamshell lathe can be programmed to cut a certain depth to prevent cutting into the basket of a canister and is a remote operation once it has been attached to the canister. Therefore, it can be used for underwater cutting as well. Clamshell lathes can cut on the horizontal plane and the vertical plane, thus having the ability to perform destructive and nondestructive cuts. This cutting method is very safe with minimal moving parts, minimal heat induced, and the cutting blades move at low revolutions per minute (RPM).

The clamshell cutting method can cover a range of diameters because it is adjustable through hydraulic mounting. The specific model considered for this project was the HD80, which can be seen in Figure 3 ("HD Clamshell" 2019). The HD80 would cover a range of ODs from 68 to 80 inches. There are additional machines to cover smaller canisters or larger ODs as well, up to 120”. The HD80 machine was quoted at approximately $110,000, which included a hydraulic mount, necessary for this application. The cost of replacement blades depends on the type of application the clamshell lathe is being used in. For a horizontal, destructive, cut, the blades would be commercial cutting blades and cost approximately $20 each (2 blades per canister = $40). For a vertical, nondestructive, cut, the blades would need to be high-speed steel (HSS) blades, which would cost approximately $150 each (2 blades per canister = $300). The HD80 weighs 1063 pounds (lb) and would require a crane of some sort (i.e., gantry crane) to lower the device onto the canister. More machine specifics can be seen in Figure 4 ("HD Clamshell" 2019).

The estimated cut time for the clamshell lathe again depends on its application. If it is cutting on the horizontal plane, it will require about 30 minutes (min) for setting up and 69.4 min to cut based on a cutting rate of 0.003”/revolution at 3 RPM. For the vertical cutting plane, it will take longer to cut. This is because cutting two lids which will require two set up times of 30 min each and a slower cutting time because it would be along the welds of the canister, taking an estimated 104 min at 0.002”/revolution at 3RPM. The estimated volume of debris created would be approximately 46 in^3 for both methods. ("HD Clamshell" 2019)

3.2.2. Diamond Wire

At the beginning of this project, the team had high confidence in the diamond wire cutting method. Diamond wire cutting is a robust and proven cutting method, except for use on nuclear canisters. During the initial phone conference with Mirage Machines, the team was looking at their remote diamond wire cutting device but were swayed away from the device since the size of the remote device would not allow for the size of a nuclear canister.

The diamond wire cutting device works by running a wire that is comprised of beads of diamonds around the object continuously. The wire requires a cutting lubricant, most often water, to be across some portion of the wire to prevent heat buildup and the wire from prematurely failing. For this application, the wire would be most optimal cutting in the horizontal plane, with water being applied as a lubricant.

If a diamond wire sawing device were to be used for cutting nuclear fuel canisters, many precautionary steps would need to be taken first. The first preparation would be an extensive water filtration system for the cooling water if it is to be reused, as well as a substantial sum of money and time. It would take an estimated 2-3 hours to complete this cut horizontally because halfway through the cut, the wire would need to be replaced because the stainless-steel canister would "gum up" the wire leaving it irreparable. To complete this cut, two wires would need to be running simultaneously to ensure thorough cutting of the canister. These wires cost approximately $2000 each, equating to a total cost of $8000 per canister (2 wires at a time, at $2000 each = $4000, with two replacements = $8000 total for wire cost). To cut the canister on the vertical plane, nondestructive method, with the diamond wire cutting device, it would be unsafe for this application. This is due to the minimum wire thickness is 0.425 in and the weld thickness on the canister is 0.250 in. This would be a significant safety hazard cutting into the lids of the canister.

3.2.3. Laser

The laser cutting option initially appeared to be a high-speed method that would be simple to automate, while only producing minimal waste. However, after further research and talking to industry representatives, this method proves to be problematic. While laser cutting is quite rapid, with an industry resource reporting a cutting rate of 0.1in/sec for our purposes; it also requires Computer-Aided Design (CAD) models for each canister to develop an automated design. In most industrial scenarios, CAD files for automating laser cutting would be available. However, this becomes an issue for our unique case since the current CAD files for each canister variant is not publicly available. This notably complicates laser automation use on UNF canisters. Additionally, most laser cutting operations currently used in industry deal with thin metal sheets and cut on a 2-dimensional (D) plane only. 3D laser cutting is practiced commercially as well, although it is uncommon.

One of the companies contacted for information and specifications on their laser cutting equipment was Laser Photonics. After talking with them, they recommended their 4kW Cobra series 3D robotic fiber cutting laser. Fiber laser cutters are generally stronger than their CO_2 counterparts and thus more appropriate for the team's purpose. An image of this product, as well as its specifications, can be seen in Figures 5 and 6 (*Cobra FLR Fiber Laser Robotic Cutting & Welding System*, n.d.). Even though this laser can be operated robotically in the 3D plane, it is limited in a few ways that are critical for our application. First, the arm must be fixed to a face such as a floor or ceiling. This limits the mobility of the laser itself to only the distance that the arm can reach. The maximum reach for the laser and robotic arm, when laying completely flat, is 80 inches, which is smaller than what would be necessary to maneuver around the canister itself and complete the necessary cut. Due to this limitation, the only way that the robotic arm would be able to cut completely around the diameter of the canister would be to fix the machine and develop a method to rotate the canister itself at a constant rate. Though not impossible, this adds to the level of infrastructure and initial cost needed to perform the operation. These factors were considered when completing the pairwise comparison.

3.2.4. Plasma

Plasma cutting is traditionally used in fabrication and scrapping operations to cut conductive metals such as steel, aluminum, brass, copper, and stainless steel. Plasma torches pass an electric arc through a high-speed gas to raise the temperature of that gas into a plasma state. By creating a circuit between the torch and the metal, the metal is cut, and the debris produced includes melted metal and fine sparks. Plasma torches can be used in sheet metal cutting, handheld operations, pipe beveling, and robotic processes. For this research, only pipe beveling, and robotic plasma torches were considered due to the radiation and scale of the cutting operation. The robotic application will also be beneficial in the hot-cell design to limit the required human interaction with the canisters and the plasma torch after exposure.

Pipe beveling can be completed using the same plasma torch that you would if you were completing a hand-held operation or a specialized torch. Pipe beveling operations are automated using an orbital system. Two systems found in the research include a band-type system or a saddle-type system. Both systems were found to reach sizes capable of completing the cut necessary for UNF canisters. Shown in Figure 7 is two systems manufactured by H&M Pipe Beveling Machine Company, Inc.

Figure 7 (A) displays the band-type system that H&M offers. This system uses an adjustable chain and metal band that clasps around the pipe being cut. Figure 7 (B) displays the saddle-type system that H&M offers. This system uses an adjustable horse-shoe shape gear-teeth mechanism that clamps around the pipe. While both systems are shown cutting a horiztonal pipe in Figure 7, they can both be used in our horizontal canister operation. They reach sizes required for UNF canisters and can be automated, though the saddle-system is normally hand-turned by the user. These systems typically require around 1 hour for setup per canister.

In addition to the pipe beveling option, remote operations using robotics are available for a faster interchange between canisters and a more consistent cut. One robotic plasma cutting system found is through AGT Robotics. This machine is designed explicitly for gouge cutting metal with a plasma cutter. Shown in Figure 8 is the Gouge Master designed and sold by AGT Robotics. The Gouge Master system is proven to be capable of consistent cuts and is advertised through a case study cutting a horizontal rotating pipe located a short distance in front of it. This system is capable of cutting canisters in the vertical direction as long as it is appropriately positioned within the hot cell design.

The reason the Gouge Master from AGT Robotics was chosen as the robotic system for this research is due to the need to use a gouge plasma cut rather than a regular plasma cut. Gouge cutting is also possible with the two H&M pipe beveling systems and is key to the safety of the canister cut. Gouge cutting will prevent molten metal and sparks from entering the canister and damaging its contents. With this cutting method, all debris are directed away from the plasma torch and the canister being cut. The cutting method is estimated to take around 1.65 hours to cut the canister in the destructive method completely. This time will double for the non-destructive method. When the Gouge Master is used in the hot cell design, the total time is only the cut time as there will be no set up for aligning the plasma torch system onto the canister, like other cutting methods or the orbital systems.

3.2.5. Skiving

Skiving is the current cutting method that is licensed by the NRC and mentioned in opening operations throughout the nuclear industry. The skiving machine has two arms extending from the body of the machine. One arm has a blade attached and the second arm has a metal block to remove debris from the cut made by the blade. The blade is used to cut the welds, located around the outsides of the canisters, from the top of the canister going down. The blade is manually cranked down by the operators to cut the welds further. The manufacturer of the skiving machine, Tri Tool Inc., was contacted for specifics of the machine.

After speaking with Tri Tool Inc., it was discovered that the skiving machine was upgraded to simultaneously using two blades, instead of the one blade, one block system; this reduced the total cut time. The licensure and use for the updated skiving method in the nuclear industry are unknown. The new process is automated because it does not require an operator to crank down the blade. Skiving can be done underwater with precise specifications. The initial cost of this machine is $200,000. Cutting one canister requires 4 blades, each at the cost of $125 totaling to $500 per each canister. The average set-up time for the machine is 2-3 hours and the cut time is 1.7 hours. Skiving produces long ribbon-like debris. The failure rate for this method is low due to the low revolutions per minute of the blade.

3.2.6. Water Jet

When underwater cutting options were being considered, water jet cutting was thought to be an optimal method due to fast cutting rates and the ability to cut underwater. Water jet excels in the fact that the cutting is not in direct contact with the material and there is no additional heat induced to the canister. Chukar Waterjets Inc. was contacted to gain insight into the cutting method. Figure 9 displays the “Zip-Tide” outer diameter pipe cutter water jet designed by Chukar Waterjets ("UHP Abrasive Water Jet Cutting", n.d.). Water jetting is a destructive cutting process, and efforts to find a non-destructive method have been unsuccessful.

Chukar Waterjets was able to disclose information on the machine specifics on the Zip-Tide based on prior testing. The Zip-Tide is attached to the cutting surface through a belt-like fastening method. This belt-like fixture would be wrapped around the outside diameter of the canister to be cut and then be used as a guide for the water jet to wrap around the canister, allowing for continuous cutting. This would be an automated process once set up on the canister and lowered underwater. Chukar Waterjets estimated a total cut time of approximately 2.25 hours that includes a 30 min setup and installation process. The water jet operates at 55 thousand pounds per square inch (KPSI) (3800 bar). The estimated cost of this cutting device was quoted to be approximately $220,000. Other highlights of water jetting include a high level of reliability with minimal maintenance, as well as a broad cutting depth range. The Zip-Tide has currently only been evaluated during underwater cutting. This was a critical detail that was considered during the pairwise evaluation.

4. Canister Design

Canister storage/transport systems are those in which the used fuel is first placed in large stainless-steel canisters, sealed, and then transferred and loaded in either a metal or concrete storage cask using a transfer cask. Figure 10 shows this used nuclear fuel cycle.

4.1. Size Variation

During the fall of 2018, the team contacted Dr. John Scaglione from Oak Ridge National Laboratory (ORNL) for information regarding the welded UNF canisters. As a result, he sent a 2013 ENERGX report sponsored by the Department of Energy with specifications and details of canisters currently in the United States. Table 1 shows relevant dimensional information pulled from that report (Greene, Medford and Macy 2013). The team focused primarily on any 3-lid Transnuclear canister variants. Key dimensional ranges from the report above include:

- Overall Length: 163.50” - 198.50”
- Overall Cross-Section: 37.00” - 69.75”
- Wall Thickness: 0.5” - 0.75”

These dimensions played a critical role in determining cutting machine sizes.

4.2. Key Port Location, Size, and Use

The key port is a critical piece of the canister that weighed heavily when researching potential cutting methods. This is because the keyhole is necessary for the drainage of water and gas testing purposes. Therefore, if gas testing is performed as designed, only non-destructive cutting operations would be viable. If gas testing could be performed at an alternate location below the top shield plug to bypass the need to open the first lid to gain access to the key port, this would greatly increase total operation speed. This kind of gas testing would be used in combination with a destructive cutting method, saving both time and money.

4.3. Internal Components

Internal components within the canister assembly include the fuel rod basket, shield plugs, and inner and outer lids on either end of the fuel rod basket. The fuel rod basket is unique in that it also includes some critical internal features to be considered during the destructive cutting method. The fuel rod basket includes an inner tube which is fixed to one of the two vent holes in the key port itself. The key port, as discussed above, is crucial for gas testing and draining. This tube goes to the bottom of the canister so that it can drain water when the canister is pulled from the spent fuel pool.

4.4. Fuel Safety

For this report, the cutting methods chosen can be categorized as destructive or non-destructive. When performing a destructive cut, fuel safety becomes an important area of concern. This is because the destructive cutting process relies on cutting into the canister from the outer shell rather than through the lids on top. When cutting into the canister through the lids, the shield plug acts as a barrier between the lids and the fuel, keeping it safe from interference with the cutting tool. However, there is not a designed barrier between the cutting tool and the fuel itself if the operation is performed destructively. This means the cutting operation must be careful to ensure that the cutting tool removes only material from the outer shell without intruding on the fuel rod basket. If the cutting tool contacts the fuel rod basket, the cutting operation should immediately be halted. This should be done so that the tool does not cut through the fuel rod basket and into the fuel rods themselves, which poses serious safety concerns. Additionally, any debris created by the cutting method should be directed away from entering the fuel rod basket as these debris can cause damage to the fuel rod assemblies and the basket itself.

5. Gas Testing

5.1. Purpose

The purpose of gas testing the canisters that will be cut open will be to check for gases presented by damaged fuel cells, water left in the canister, and any possible hazardous gases before penetrating the canister and exposing the surrounding area or causing an accident during the cutting process. These canisters are filled with helium gas before being closed because helium is a noble gas and will not be reactive with the cutting processes though it could have reacted with any damaged fuel cells during storage. Gas testing is done before opening the canisters to determine how to vent the canister if it is required. It is essential that the gas testing results are accurate to ensure safety among workers, the public and not to overload the hot cell where the cutting will take place. The gases emitted throughout the cutting process will also be monitored within the hot cell to ensure the safety of the process.

5.2. Method

5.2.1. Current Method – Nondestructive

For Transnuclear 3-lid canisters, the current method for gas testing utilizes the key port where the vent and siphon block are located under the first lid. To gain access to the key port, the first lid must be removed and the cutting device must be detached from the canister. The rotabroach is then used to open the key port and expose the two “silver dollars” that shield the vent and siphon holes. The gas testing device will then be welded onto the vent and siphon block to gas test the canister.

5.2.2. New Proposed Method - Destructive

The team is proposing a new method of gas testing in order to complete a proposed destructive cut and bypass the current need to open the top of the canister to gain access to the key port. This new method of gas testing would call for the creation of a self-contained gas testing unit that could be mounted to the side of fuel canister. This side port gas testing method would need to be airtight to the side of the canister and remain airtight during the testing process in order to prevent any hazardous gas leaking into the surrounding area. The side port testing method would need to remain attached to the side of the canister for the duration of the cutting procedure to prevent accidents until venting requirements are determined.

6. Comparison of Cutting Methods

6.1. Pairwise Comparison

6.1.1. Theory of Pairwise Comparison

Traditionally, a decision matrix is used to analyze and determine the best decision under given constraints. A common issue in a decision matrix is comparing two significantly different populations with one another. Pairwise comparisons allow for considering the metrics that are different and uses the majority vote to rank the different metrics. Ranking includes the following voting options for how a metric is evaluated between two options: strongly favorable to option one, more favorable to option one, mildly favorable to option one, neutral for both options, strongly favorable to option two, more favorable to option two, mildly favorable to option two. The pairwise includes a statistical solution to evaluate random variables relatively to make the final decision. A sensitivity test can be done on a pairwise to ensure the biases from the votes of the team are removed. ("Paired Comparison Analysis: Working Out Relative Importances" 2019)

6.1.2. Comparison Criteria

6.1.2.1. All Potential Criteria Considered

Metrics are the variables that change between different cutting methods which affect the overall process. Initially, the team created a list of 27 metrics, shown in Table 2. After discussing the list, many metrics were removed or combined with other metrics to simplify the list. It was important that each metric was measured quantitatively or qualitatively to ensure the pairwise analysis would work. The discussion of why specific metrics were removed or accounted for can be seen in Table 2. This list was discussed compiled to ensure the correct engineering assumptions were made.

Time: The metrics under the Time attribute were combined to a single metric, Total Time, which included set up time and cut time only. There was not a need to evaluate the Time metrics individually because, ultimately, our scope was to decrease the overall process time. The Clean Up time metric was changed to be a separate attribute. Debris also became its own metric because it would condense the multiple number of metrics related to debris. The team felt Debris is a key attribute to be on its own.

Cost: The cost of Number of People needed for breakdown and setup was negligible due to the cutting machine assumed to be fixed. The machine would not require recurring personnel for the process. As mentioned before, The Cleanup cost was further broken down with a new attribute, Debris. Initial Machine Costs and Reoccurring Costs/Maintenance were both kept as individual metrics due to their importance in choosing an optimal cutting method and overall impact on the future use.

Ease of Operation: The attribute, Ease of Operation, was renamed to Flexibility to make the metrics quantitative. The Compatible with Current Facility layout metric was renamed to "Level of Infrastructure needed" under the Cost attribute to also ensure it was measured quantitatively. Cut Tolerance & Accuracy was removed because the cutting location tolerance did not need to be precise. After further evaluation the level of internal heat generated was removed due to the inability to calculate as students and the ability of the hot cell to handle heat and radiation. All cutting methods were Easily Adjusted Among Varying Canister Designs and therefore this metric was also removed. The Intricate/Delicate Settings metric was removed since the assumption that all operators of the canister opening procedures will be well versed in machining capabilities and all training required will be completed before the processes begin.

Safety: The Dosage Cost per person was removed due to the design being within a hot cell and being completely remotely operated. The Number of Interactions a person must have with the machine during the cut was removed due to the same number of people required in each cutting method and the operations being done remotely. The Debris clean up, Debris Type, and Amount of Debris metrics were simplified to two metrics: Debris Clean up and Debris Volume of Waste. The Debris Clean up metric includes Debris type to measure the metric relatively. Remote operation metric was moved under Flexibility criteria and added the cost of developing a Hot Cell. Sensitivity to Error in measurements was removed when it was determined that the destructive cut could be completed freely at any location under the shield plug. The Types of Machine Failure criteria was imperative to the study and included in the final comparison as it deals with the safety of the public and the success of the entire operation.

Bonus: The attribute, Bonus, was also renamed to Flexibility. The lubrication metric was included in the Debris attribute under the Debris Clean up metric. Underwater process was removed once the design parameters included cutting the canisters in a hot cell. All the cutting methods had to cut through the Welds on Top of the Lid. This metric was removed because if the cutting method was not able to cut the welds, the method would not be evaluated in the pairwise. Multi-Cut possibility metric was removed due to evaluating the two methods, destructive and non-destructive, separately further explained in Section 6.1.3. The last metric, Under the Lids, seemed to be repetitive with the Multi-Cut possibility metric and therefore removed.

6.1.2.2. Assumptions Made
Engineering assumptions were made throughout this project with the help of the project supporters, Orano. Due to their knowledge and experience in the field, the team was able to simplify the metrics list. The assumptions made throughout the Pairwise metrics decision are listed below:

1. Transition time and operation between canisters: The transition between canisters would be consistent and could be ignored from the total cut time. The mechanics behind moving and transferring canisters and fuel baskets would be designed by industry professionals.
2. Intricate settings necessary for personnel to know: It was assumed all personnel operating would be knowledgeable about the operation.
3. Level of internal heat generated and radiation emitted: Both could be ignored due to being within the hot cell and having remote operations.
4. Gas testing results and venting considerations: These parameters would be part of the hot cell design and NRC licensing and were not directly part of the optimized cutting process and could be omitted from the research

6.1.2.3. Final Criteria Used
After modifying several metrics and making engineering assumptions the new list of 7 metrics was created, shown in Table 3. The description of how each metric was evaluated quantitatively and relatively can also be seen in Table 3. Once the final metrics were created, they were ranked against each other to determine their weight on deciding the optimal cutting method. These values are shown in Table 4.

There was a heavy emphasis on Safety and Time by the team. Safety of the personnel and the machine was the top priority, which is why Possibility of Failure ranked first. Time was also emphasized because the scope of the project was to improve the current lengthy process, skiving. The last three criteria's, Hot cell and Remote Operation, Initial Equipment Cost and Reoccurring Cost and Maintenance are related to the cost of the process. This was ranked lower because the safety of the personnel is imperative.

6.1.3. Method Comparisons
The next step in the pairwise was comparing the cutting methods with the seven decided metrics. The cutting methods used in the pairwise are skiving, water jet, clamshell lathe, diamond wire, plasma, and laser cutting. The process to determine the best method was by taking each pair of cutting methods (i.e., skiving and water jet) and evaluating within a single metric (i.e., time). The cutting method that had the lowest time would be ranked higher giving that method more points. By pairing each method and comparing with each metric, the ranks for the cutting methods were determined.

The team evaluated non-destructive and destructive cutting methods in two different pairwise because the parameters were different. For example, Total Time for the destructive cut was much lower than Total Time for the non-destructive cut for all cutting methods. The seven metrics remained constant for both the non-destructive and destructive pairwise.

6.1.3.1. Nondestructive
The nondestructive pairwise only evaluated five out of the six methods: skiving, water jet, clamshell lathe, plasma, and laser cutting. Diamond wire was removed because this cutting

method can only be done destructively and cannot cut through welds. The data collected from the respective industry contact for the method can be seen in Table 5. Using this table, the cutting methods were evaluated.

Plasma won the non-destructive cutting method pairwise as shown in Table 6. Plasma won first place in the metric Initial Equipment Cost and tied with other methods in the metrics Reoccurring Cost and Maintenance, Clean Up, Volume of Waste and the Possibility of Failure. Plasma ranked poorly in the Hot Cell and Remote Operation metric due to requiring additional cost to develop method in these areas.

6.1.3.2. Destructive

The destructive pairwise only evaluated five out of the six methods as well: diamond wire, water jet, clamshell lathe, plasma, and laser cutting. Skiving was removed because the current skiving method cannot cut along the side of the canister. Skiving can only be done non-destructively further explained in section 6.1.3.4.2.1. The data collected from the respective industry contact for the method can be seen in Table 7. Using this table, the cutting methods were evaluated.

Plasma won the destructive cutting method pairwise as shown in Table 8. Plasma won first place in the metric Initial Equipment cost and tied with other methods in the metrics Reoccurring cost and Maintenance, Clean Up, Volume of Waste, the Possibility of Failure. Plasma ranked poorly in the Hot cell and Remote Operation metric due to requiring additional cost to develop method in these areas.

6.1.3.3. Modified Sensitivity Study

The pairwise analysis generally includes a sensitivity study. A sensitivity study removes the biases created while evaluating the metrics and methods, individually. The team evaluated the metrics as a group rather than individually because each individual was only an expert on their respective cutting method. Due to this reason, the sensitivity study was modified to fit the needs of the project and included determining the changes in parameters it would take to have the second-best cutting method move into the first-place position. This modified sensitivity study is described further in the section 6.1.4.1 where the Parameters Required for Success is discussed in detail.

6.1.4. Top Cutting Methods

The team set up two pairwise comparisons to determine the top two cutting methods. One pairwise as destructive and the other as a nondestructive cutting method with both using the same criteria categories. These are listed as Total Time, Initial Equipment Cost, Reoccurring Cost and Maintenance, Clean Up, Volume of Waste, Hot Cell, and Remote Operation. Plasma was the highest scoring cutting method for both nondestructive and destructive cutting processes. Clamshell was the second highest scoring cutting process for both destructive and nondestructive pairwise comparisons. The remaining four cutting process for both destructive and nondestructive pairwise comparisons were not consistent in order. The top two cutting method winners were plasma and clamshell. The difference in normalized percentages for non-destructive and destructive cuts between plasma and clamshell were 5.6% and 1.62%, respectively. Since clamshell and plasma were close in scores, they were both deemed the optimal cutting method options for the design parameters used and had operation procedures written for them.

6.1.4.1. Parameters Required for Success

Parameters required for success includes those parameters that could have been swayed depending on the voting body. These specific parameters had the power to change the top performing method from plasma cutting to the clamshell lathe if they were all changed together. These parameters are:

- Possibility of Failure
- Remote Operation Cost
- Total Time
- Initial Equipment Cost

While all four had to be altered to change the first and second place cutting processes, they were also the main categories where personal judgement was used to compare the cutting processes rather than strict factual data. Therefore, it is reasonable to assume that a different group of researchers could have come to the conclusion that our second-best method was actually the highest scoring method and that these four parameters were required for the success of a method to be chosen as the optimal method.

6.1.4.2. Winning Methods Compared to Current Technique

The current method of opening the UNF containers by Orano fuel is skiving. Skiving is the only cutting currently approved and licensed by the NRC. Skiving is a top mounted lathe that has two mounted blades that have a perpendicular force acting on them. This cutting process is considered nondestructive, and the canister can be reused. Skiving is a non-automated process and in turn needs to be manually attached by personal.

6.1.4.2.1. Clamshell

Clamshell and skiving are lathe machines and similar methods. The clamshell is the upgraded skiving method due to its dual use and remote operation. As mentioned previously, skiving uses two blades to cut the canister, the same as the clamshell lathe. The current skiving machine cannot be cut destructively, but clamshell can cut both, non-destructively and destructively. With the updated skiving method, the process is fully automated and no longer requires personnel to crank the blade down to cut through the welds. Clamshell is a fully remote process once the initial set up has been completed.

6.1.4.2.2. Plasma

The biggest difference between plasma and skiving is that plasma is a non-contact robot with a fully automated process. Skiving's automated process is more robust, not as flexible as the plasma cutting method, and is still in its early development stages. Another notable difference is that skiving uses blades to cut the canister where plasma uses heat energy and produces little to not debris when compared to skiving. Lastly, the plasma machine does not have to be set up on each canister which increases total time efficiency and lowers the requirement for each canister to be similar in size and true roundness.

7. Cutting Procedures

7.1. Procedure for Clamshell

7.1.1. Cutting Process

The following information was provided by Hydratight. This information contains the operating procedure for the HD (*Heavy Duty (HD) Clamshell Operating And Maintenance Manual* 2014) line of clamshell lathes. This section details the machine basics of the clamshell lathe device.

The Hydratight HD Series Clamshells manufactured at Hydratight's Red Wing facility, are portable pipe lathes designed to simultaneously sever and bevel in-line pipe, plus form machine cut any angle bevel as they cut. The frame is split for easy installation on in-line pipe. The tool bits automatically feed into the work piece with each rotation of the lathe to assure smooth precise finish.

Machining Function & Capacities

- Sever In-Line Pipe
- Sever and Bevel In-Line Pipe
- Sever and J-Bevel In-Line Pipe
- Sever and Double Bevel In-Line Pipe
- Socket Weld Removal
- Weld Overlay Removal (accessory required)
- Single Point Cutting and Facing (accessory required)
- I.D. Counter Bore (accessory required)

Drive Assembly

There are many different drive arrangements available for the HD Clamshells (see Figure 11). Straight back drives are standard and are available in pneumatic, hydraulic, or electric motors. The front drive reversible (FDR) mount allows for forward or rearward mounting positions and can be used with the hydraulic, electric or pneumatic motor. The Right Angle Adjustable (RAA) mount allows for angularly adjustable mounting positions and can be used with pneumatic or hydraulic motors.

Tooling

1/2 X 1 sever bits and 1 X 1 bevel or sever combination high speed steel bits are standard. Any angle of bevel or counter bore bit can be designed; Hydratight Corp. stocks all standard prep configurations for right and left hand severing and beveling. Specialty bits can be designed as required. Indexable tooling is also available on request.

7.1.1.1. Components

Housing

An aluminum split ring housing that is capable of being disassembled for installation on in-line piping. The housing has bearing mountings for the rotating cutting head, two mounts for the drive motor assembly, and locator pockets.

Cutting Head Assembly

Made from 4140 alloy steel, this split ring assembly will align with the split lines of the housing when the clamshell is separated into halves (quarters for HD 60 or larger). The cutting head assembly has gear teeth on the outside diameter of the cutting head and mounting locations for the slide assemblies. An internal bearing race allows the cutting head to rotate about the housing.

Drive Assembly

Mounted to the housing and arranged with a pinion gear on a shaft. The mounting bracket is designed to accept the reaction torque generated by the drive motor.

Bearings

The cutting head assembly runs on adjustable precision bearings that provide for axial and radial force reaction. The bearings are adjustable to compensate for normal wear.

Slide Assembly

The slide assembly is designed to hold the cutting tool (tool bit). The slide assembly has adjustable gibs and also contains a feed screw assembly, which is used to feed the tool bit into the work piece. The slide assemblies are bolted to the face of the clamshell assembly and can be moved in ½" increments.

Tripper Assembly

The tripper assembly is designed to hold the tripper pin. The tripper pin is used to turn the star wheel on the feed screw assembly, which "feeds" the tool bit into the work pieces. There are two different styles of tripper assemblies that may be provided with the clamshell, a sliding style and a flip style. The tripper assembly is bolted to the OD of the housing. There is 1, 3, or 4 different mounting locations (depending on the Clamshell size) that allow for more flexibility in machine mounting (see Figure 12).

Locator Pad Assembly

The HD clamshell uses adjustable locator assemblies with 1" of travel. Turning set screws located on the outside of the housing actuates the adjustable locators. Locator extensions are required to mount on smaller diameter pipe.

7.1.1.2. Gas Testing Process

7.1.1.2.1. Nondestructive

The gas testing procedure for the nondestructive cutting process will utilize the already established process licensed and approved by the NRC. This process is implemented after the removal of the first lid on the canister, and the clamshell lathe has been removed. The key port is used to gas test the canister once the silver dollar ports are removed through a rotabroach. Once the ports are removed, the gas testing process can begin and proceed normally.

7.1.1.2.2. Destructive

Please note that these are considerations and recommendations for a proposed gas testing process that has not been developed yet and will require additional research.

Before starting the clamshell cutting procedure, gas testing must be completed to ensure hazardous gases are not present. If they are present, specialized ventilation procedures must be considered and implemented. To complete the gas testing for a destructive cut, the portable gas testing unit must be attached to the canister. The location of the portable gas testing unit is determined based on the original canister design and their location of the shield plug. The most optimal location for the gas testing unit will be below the shield plug in order to avoid contact or interference with the destructive cutting device. A check of the portable gas testing unit is imperative before attaching. The portable gas testing unit must pass inspections for gas testing ability, airtight seal for the gas testing portion of the unit, and piercing capabilities intact. Once these are done, a proper check of the attachment device must be done. The device must be able to create an airtight seal between the portable gas testing unit and the canister to provide a safety net against a possible leak within the portable gas testing unit. Once the portable gas testing unit and the attachment device are in order, the device will need to be attached to the canister.

Careful positioning determined by the canister schematic and the location of the shield plug will begin the process. The portable gas testing unit will then need to be precisely attached to the canister in the predetermined position. Once the portable gas testing unit is correctly attached to the canister, the device will be double checked before proceeding. After a check, the portable gas testing unit can begin the process of piercing the canister to sample the gas present in the canister. Once the gas testing measurements are captured, determination of continuing to cut the canister or not and any ventilation requirements will be established.

7.1.1.3. Set-Up and Process Nondestructive

The nondestructive cutting process involves utilizing the flange facing cutting technique on the clamshell lathe to cut the welds between the canister wall and the lid. The nondestructive cutting process will take longer because two lids will need to be cut. This process will salvage the canister, and the original gas testing equipment will be used.

The following procedure was provided by Hydratight. This is the operating procedure for the HD (Heavy Duty) line of clamshell lathes (*Heavy Duty (HD) Clamshell Operating And Maintenance Manual* 2014). This section details the set up and process for nondestructively cutting the canister. Text denoted in (RED) are indicative of manual operations.

General safety precautions provided by Hydratight:

- **Do not rush the job!** – Read the instructions before operating the machine.
- If ever a problem develops where a question about safety or technical expertise is required, call (651) 388-8661, or (800) 283-1937 for technical support.
- Wear protective clothing including: safety glasses, gloves, hard hat, steel toe shoes, ear plugs (hearing protection), hair restraints, and coveralls.
- Keep loose clothing, long hair, or any other unsecured parts away from operating machines.
- Keep work site and machine clean. Use brush to remove chips. **<u>Do not</u>** use hand or air hoses to remove chips and swarf.
- Ensure adequate work space around the work piece before mounting the Clamshell.
- Support pipe for total machine weight. If severing pipe, support both sides of the cut.
- Take precautions to prevent the machine from falling or sliding due to locator failure (i.e. cribbing or rigging)
- Before connecting the power to the machine, be sure the following components are tightly secured:
    - Clamshell Split Line
    - Tool Blocks
    - Locator Pads

    - Feed Pin Bracket
    - Tool Bits
    - Motor and motor mounts
- **Keep Hands away from Clamshell when rotating!** Adjustments should only be made when the Clamshell is stopped and the power disconnected.
- **NEVER** move or work on the Clamshell without first disconnecting the power source and hoses from the Clamshell
- **ALWAYS** close control valves if a power failure occurs.
- Inspect hoses and wires associated with the particular power supply used for wear or damage that could result in failure during operation.

Machine Set Up

Pre-Installation Procedure

Note: Motor should be removed from the clamshell

Separating Clamshell Halves

1. Rotate gear by hand until both the gear and housing split lines are aligned. If the lock pin holes in the gear will not line-up with the holes in the housing, rotate gear 180 degrees for proper alignment.
2. Place the locking pins into the holes through the gear and housing to prevent gear rotation when the clamshell is split. Press the top button to allow pin to slip into the hole.
3. Loosen the 4 swing bolt flange nuts (8 on HD60 or larger) and swing the bolts out of the pockets in the housing. Loosen the 2 clamping bolts (4 on HD60 or larger) on the gear halves (quarters) and separate the clamshell halves (quarters) by pulling straight apart and then open. (see Figure 13)

<u>**CAUTION:**</u> ***DO NOT FORCE THE CLAMSHELL OPEN USING TOOLS***

4. Determine pipe OD and select proper locator extensions. If required, bolt the locator extensions to the locator pads (see Figure 14). The locator pads are adjusted by turning the set screws that are accessed from the outside of the housing with an Allen wrench. Back-up the locator pads as needed for proper clearance of pipe diameter.
5. Make sure the Slide Assemblies are positioned so they clear the work piece but are as close to the OD as possible (see Figure 15). The slides can be moved by removing the feed screw bracket and tool block and then removing the ¼-20 socket head cap screws.
6. Remove the lock pin. Push the handle of the tripper pin assembly in so the tripper pin is in the “engaged” position. If the tripper pin does not line up with the star wheel, reposition it. After the tripper pin height is set, check the tripper pin length (see Figure 16). The end of the tripper pin should be spaced .030” away from the cavity between 2 of the points of the star wheel. Lift the handle to disengage the tripper pin and reinsert the lock pin.

Installation on in-line Pipe

<u>**NOTE:**</u> ***The following are recommendations for handling the clamshell lathe. These recommendations are separate from Hydratight’s operating procedure.***

1. After the clamshell lathe has been properly checked over and secured to the crane/mounting device, the lathe can be raised overtop the canister. Raising the lathe over the canister must be completed very mindfully.
2. Once the lathe has been raised to the proper height to clear the top of the canister, positioning of the lathe will begin.
3. The center of the lathe must be in line with the center of the canister, after this is completed, the lathe can be lowered down around the canister. The lowering process must be done slowly to not disrupt the position of the clamshell lathe around the canister.
4. The lathe will be lowered onto the top of the canister in order for the cutting arms to sit flush with the top of the canister to gain access to the top weld.

Joining Clamshell Halves

1. Install the 2 halves (quarters for HD 60 or larger) of the clamshell around the pipe and tighten the housing bolts and the clamp bolts on the gear (see Figure 17).

Note: ***If Clamshell will not close, check locator pads for proper size and clearance. Adjust the locators if necessary.***

2. Lightly tighten two adjustable locator pads directly across from each other (locators 1 and 2 see Figure 18), just enough to secure the clamshell while trying to keep it centered on the work piece. Lightly tighten two more locator pads that are directly across from each other and close to 90 degrees away from the first set of locators (locators 3 and 4 see Figure 18). **DO NOT TIGHTEN** the locators down completely until the clamshell has been squared and to the pipe.

Squaring & Centering

1. Squaring: Place a Square on the back of the clamshell, directly in line with a locator, Hold the square against the housing and the work piece and square the machine to the work piece at four locations around the pipe (see Figure 18).
2. Centering: Using a 6" scale, measure the distance from the work piece to the clamshell ID at the four lightly tightened locator positions. Tighten the four locators so the 6-inch scale reads the same at all 4 positions. Pull out the locking pins so the clamshell gear can rotate.
3. Mount a dial indicator on the gear face with the tip resting on the work piece OD. Turn the gear so the indicator is positioned over one of the tightened locators (locator 1) and set the dial to zero. Slowly rotate the gear 180 degrees to another locator (locator 2) and take an indicator reading. If the reading is not zero, adjust the locators until the indicator reads one-half of the original reading. Reset the indicator dial to zero and repeat. If the clamshell cannot be centered, different locators are required.
4. Rotate the gear 90 degrees so the indicator is positioned over another locator (locator 3) and set the dial to zero. Slowly rotate the gear 180 degrees to another locator (locator 4) and take an indicator reading. If the reading is not zero, adjust the locators until the indicator reads one-half of the original reading. Reset the indicator dial to zero and repeat. The first two locators may need to be slightly loosened in order to zero the clamshell to the work piece.
5. Repeat steps 3 and 4 for all of the other locators. Most pipe is out of round, therefore a zero reading all the way around may not be possible.

Setting Tool Bits

1. Prior to installation of tool bits, determine which tool bits must be used for your specific machining operation.

<u>NOTE:</u> ***The Clamshell cuts in a clockwise direction, when viewed at its face. There are right hand and left hand bevel and sever bits, right hand bits bevel on the side which the clamshell is mounted, left hand bits bevel on the side opposite.***

2. Using the star wheel wrench, back the tool blocks away from the pipe, to allow enough room for the tool bits to pass completely through the work piece without running the tool blocks into the work piece. Disengage the feed pin.
3. Insert proper beveling and severing bit so that the tip touches the work piece OD. Hold the bit with one cap screw, snug but not tight.
4. Manually rotate the cutting head counter clockwise 1 revolution. This reverse action will push the tool bits away from any high spots in the pipe that could cause tool damage. After one complete revolution has been made tighten the cap screws on both tool blocks. Back the bevel bit 1/32" away from the work piece with the star wheel wrench (see Figure 19)

<u>NOTE:</u> ***Always cut with the sever bit leading the bevel bit by 1/32" in depth of cut***

Motor Installation

<u>**CAUTION:**</u> ***Both locking pins must be removed from the gear face before installing the motor, and all power must be turned off.***

1. Loosen the four motor mount clamp screws. Position the motor mount toward rear of the clamshell (see Figure 20).

<u>NOTE:</u> ***If the motor does not engage, check to make sure the two gears are properly aligned. Rotate the cutting head by hand if necessary to align gear teeth.***

2. Slide the motor mount under the motor mount clamps and slide the motor forward until the back of the motor mount is flush with the back of the clamshell housing. If the motor mount does not slide in all the way, rotate the cutter head to align the gear teeth. Tighten the motor mount cap screws.

Nondestructive Cut Machine Operation

<u>**CAUTION:**</u> ***To prevent damage to the tool bit, the work piece to be cut must be rigged properly to keep the tool bits from binding when the pipe is severed. Improperly rigged piping may result in personal injury.***

<u>**CAUTION:**</u> ***The operator should take a stance in relation to the cutting application that minimizes the risk of falling or ejected objects. Severing In-Line Pipe***

Flange Facing Single Point Attachment

The single point attachment comes with either a 6" or 10" long counter bore tube. The single point attachment can also be used for ID boring, OD beveling and flange face grooving.

1. Square and center the clamshell on the work piece. Disengage the tripper pin. Remove the cap from the tool blocks on both slide assemblies. Remove the feed screw assembly from one slide assembly. Bolt the swivel head attachment to the tool block with the slotted end of the bar pointing toward the slide assembly that has the feed screw assembly (see Figure 21).
2. Insert the facing bit into the bore bar. The cutting side of the bit should face the set screws in the bar (see Figure 7.1.1.3.9). Adjust the counter bore tube height and lock into place. Slide the single point attachment into position along the bar and tighten the 2 set screws to lock it in place. Tilt the counter bore tube to the desired angle and lock by tightening the 4 hex bolts on the single point attachment. Use the star wheel wrench and the hand wheel to position radially and axially the tool bit at the edge at the outer wall of the flange. Install the motor.
3. Start the machine. Engage the tripper pin to feed the tool bit radially. When the tool bit has traveled across the entire surface that needs to be faced, disengage the tripper pin and turn the hand wheel to lift the tool bit away from the surface. Stop the machine.
4. Use the star wheel wrench to radially position the tool bit at the flange OD. Turn the hand wheel to axially position the tool bit up to make another cut.
5. Repeat steps 3 and 4 until the flange face is flat.

Transitioning Between Lids

NOTE: ***The following are recommendations for handling the clamshell lathe. These recommendations are separate from Hydratight's operating procedure.***

1. Once the first lid's welds have been cut completely, the lathe will need to be detached from the canister so that the first lid can be removed. Removing the lid can be completed through previous methods including skiving.
2. After the first lid is removed, the canister must be gas tested. (See gas testing section)
3. If the canister passes the gas testing requirement, the clamshell lathe will need to be repositioned onto the canister.
4. After the canister is reattached, the lathe can be set up to begin cutting the second lid.

7.1.1.4. Set-Up and Process Destructive

The following procedure was provided by Hydratight. This is the operating procedure for the HD (Heavy Duty) line of clamshell lathes (*Heavy Duty (HD) Clamshell Operating And Maintenance Manual* 2014). This section details the set up and process for destructively cutting the canister. Text denoted in (RED) are indicative of manual operations that need to be developed into remote operations, and text in (BLUE) are indicative of coolant use.

General safety precautions provided by Hydratight:

- **Do not rush the job!** – Read the instructions before operating the machine.
- If ever a problem develops where a question about safety or technical expertise is required, call (651) 388-8661, or (800) 283-1937 for technical support.
- Wear protective clothing including: safety glasses, gloves, hard hat, steel toe shoes, ear plugs (hearing protection), hair restraints, and coveralls.
- Keep loose clothing, long hair, or any other unsecured parts away from operating machines.

- Keep work site and machine clean. Use brush to remove chips. **Do not** use hand or air hoses to remove chips and swarf.
- Ensure adequate work space around the work piece before mounting the Clamshell.
- Support pipe for total machine weight. If severing pipe, support both sides of the cut.
- Take precautions to prevent the machine from falling or sliding due to locator failure (i.e. cribbing or rigging)
- Before connecting the power to the machine, be sure the following components are tightly secured:
    - Clamshell Split Line
    - Tool Blocks
    - Locator Pads
    - Feed Pin Bracket
    - Tool Bits
    - Motor and motor mounts
- **Keep Hands away from Clamshell when rotating!** Adjustments should only be made when the Clamshell is stopped and the power disconnected.
- **NEVER** move or work on the Clamshell without first disconnecting the power source and hoses from the Clamshell
- **ALWAYS** close control valves if a power failure occurs.
- Inspect hoses and wires associated with the particular power supply used for wear or damage that could result in failure during operation.

Machine Set Up

Pre-Installation Procedure

Note: Motor should be removed from the clamshell

Separating Clamshell Halves

1. Rotate gear by hand until both the gear and housing split lines are aligned. If the lock pin holes in the gear will not line-up with the holes in the housing, rotate gear 180 degrees for proper alignment.
2. Place the locking pins into the holes through the gear and housing to prevent gear rotation when the clamshell is split. Press the top button to allow pin to slip into the hole.
3. Loosen the 4 swing bolt flange nuts (8 on HD60 or larger) and swing the bolts out of the pockets in the housing. Loosen the 2 clamping bolts (4 on HD60 or larger) on the gear halves (quarters) and separate the clamshell halves (quarters) by pulling straight apart and then open. (see Figure 13)

CAUTION: ***DO NOT FORCE THE CLAMSHELL OPEN USING TOOLS***

4. Determine pipe OD and select proper locator extensions. If required, bolt the locator extensions to the locator pads (see Figure 14). The locator pads are adjusted by turning the set screws that are accessed from the outside of the housing with an Allen wrench. Back-up the locator pads as needed for proper clearance of pipe diameter.

5. Make sure the Slide Assemblies are positioned so they clear the work piece but are as close to the OD as possible (see Figure 15). The slides can be moved by removing the feed screw bracket and tool block and then removing the ¼-20 socket head cap screws.
6. Remove the lock pin. Push the handle of the tripper pin assembly in so the tripper pin is in the "engaged" position. If the tripper pin does not line up with the star wheel, reposition it. After the tripper pin height is set, check the tripper pin length (see Figure 16). The end of the tripper pin should be spaced .030" away from the cavity between 2 of the points of the star wheel. Lift the handle to disengage the tripper pin and reinsert the lock pin.

Installation on in-line Pipe

<u>NOTE:</u> ***The following are recommendations for handling the clamshell lathe. These recommendations are separate from Hydratight's operating procedure.***

1. After the clamshell lathe has been properly checked over and secured to the crane/mounting device, the lathe can be raised overtop the canister. Raising the lathe over the canister must be completed very mindfully.
2. Once the lathe has been raised to the proper height to clear the top of the canister, positioning of the lathe will begin.
3. The center of the lathe must be in line with the center of the canister, after this is completed, the lathe can be lowered down around the canister. The lowering process must be done slowly to not disrupt the position of the clamshell lathe around the canister.
4. The lathe will be lowered to a specific distance from the bottom of the canister based on the location of the shield plug. The most optimal cut will be done below the shield plug.

<u>NOTE:</u> ***The location of the shield plug will be based on the canister design. Reference the canister drawing and dimensions for the proper location of attachment.***

Joining Clamshell Halves

1. Install the 2 halves (quarters for HD 60 or larger) of the clamshell around the pipe and tighten the housing bolts and the clamp bolts on the gear (see Figure 17).

Note: ***If Clamshell will not close, check locator pads for proper size and clearance. Adjust the locators if necessary.***

2. Lightly tighten two adjustable locator pads directly across from each other (locators 1 and 2 see Fig. 8), just enough to secure the clamshell while trying to keep it centered on the work piece. Lightly tighten two more locator pads that are directly across from each other and close to 90 degrees away from the first set of locators (locators 3 and 4 see Figure 18). **<u>DO NOT TIGHTEN</u>** the locators down completely until the clamshell has been squared and to the pipe.

Squaring & Centering

3. Squaring: Place a Square on the back of the clamshell, directly in line with a locator, Hold the square against the housing and the work piece and square the machine to the work piece at four locations around the pipe (see Figure 18).

4. Centering: Using a 6" scale, measure the distance from the work piece to the clamshell ID at the four lightly tightened locator positions. Tighten the four locators so the 6-inch scale reads the same at all 4 positions. Pull out the locking pins so the clamshell gear can rotate.
5. Mount a dial indicator on the gear face with the tip resting on the work piece OD. Turn the gear so the indicator is positioned over one of the tightened locators (locator 1) and set the dial to zero. Slowly rotate the gear 180 degrees to another locator (locator 2) and take an indicator reading. If the reading is not zero, adjust the locators until the indicator reads one-half of the original reading. Reset the indicator dial to zero and repeat. If the clamshell cannot be centered, different locators are required.
6. Rotate the gear 90 degrees so the indicator is positioned over another locator (locator 3) and set the dial to zero. Slowly rotate the gear 180 degrees to another locator (locator 4) and take an indicator reading. If the reading is not zero, adjust the locators until the indicator reads one-half of the original reading. Reset the indicator dial to zero and repeat. The first two locators may need to be slightly loosened in order to zero the clamshell to the work piece.
7. Repeat steps 3 and 4 for all of the other locators. Most pipe is out of round, therefore a zero reading all the way around may not be possible.

Setting Tool Bits

1. Prior to installation of tool bits, determine which tool bits must be used for your specific machining operation.

<u>**NOTE:**</u> ***The Clamshell cuts in a clockwise direction, when viewed at its face. There are right hand and left hand bevel and sever bits, right hand bits bevel on the side which the clamshell is mounted, left hand bits bevel on the side opposite.***

2. Using the star wheel wrench, back the tool blocks away from the pipe, to allow enough room for the tool bits to pass completely through the work piece without running the tool blocks into the work piece. Disengage the feed pin.
3. Insert proper beveling and severing bit so that the tip touches the work piece OD. Hold the bit with one cap screw, snug but not tight.
4. Manually rotate the cutting head counter clockwise 1 revolution. This reverse action will push the tool bits away from any high spots in the pipe that could cause tool damage. After one complete revolution has been made tighten the cap screws on both tool blocks. Back the bevel bit 1/32” away from the work piece with the star wheel wrench (see Figure 19)

<u>**NOTE:**</u> ***Always cut with the sever bit leading the bevel bit by 1/32” in depth of cut***

Motor Installation

<u>**CAUTION:**</u> ***Both locking pins must be removed from the gear face before installing the motor, and all power must be turned off.***

1. Loosen the four motor mount clamp screws. Position the motor mount toward rear of the clamshell (see Figure 20).

<u>NOTE:</u> ***If the motor does not engage, check to make sure the two gears are properly aligned. Rotate the cutting head by hand if necessary to align gear teeth.***

2. Slide the motor mount under the motor mount clamps and slide the motor forward until the back of the motor mount is flush with the back of the clamshell housing. If the motor mount does not slide in all the way, rotate the cutter head to align the gear teeth. Tighten the motor mount cap screws.

Machine Operation for Destructive Cut

The destructive cutting process involves cutting the canister from the side to access the fuel rods faster and more efficiently. This process is heavily reliant on the proposed side port gas testing method to be utilized because the original gas port will be bypassed. The destructive cut will use the severing process in the procedure to cut the canister walls and lift the upper section of the canister to access the fuel rods.

<u>CAUTION:</u> ***To prevent damage to the tool bit, the work piece to be cut must be rigged properly to keep the tool bits from binding when the pipe is severed. Improperly rigged piping may result in personal injury.***

<u>CAUTION:</u> ***The operator should take a stance in relation to the cutting application that minimizes the risk of falling or ejected objects. Severing In-Line Pipe***

Severing In-Line Pipe

1. Follow set-up procedures, replacing the bevel bit with another sever bit. Back up both bits (out approx. 1/32"). Attach the drive motor to the clamshell, disengage the tripper pin, and open the control valve slowly to check function and speed.

<u>NOTE:</u> *If the tool blocks do not move smoothly in the slides during the test rotation the adjustable gibs may need adjustment.*

<u>CAUTION:</u> ***The cutting operation is continuous until terminated by the operator. To stop the cutting feed during rotation, <u>LIFT THE TRIPPER HANDLE</u> and let the machine rotate a few times to clear the tool bit. Turn off the power to stop clamshell rotation. Letting the tool bit clear will prevent tool damage and gouging.***

2. Engage the tripper pin by pushing down on the tripper handle, after the machine has been started. Each Rotation will advance the tool bits approximately .003" with the tripper pin engaged. Use the tripper pin to advance the feed of the tool bits until both of the tool bits are cutting. If chatter or vibration occurs, reduce depth of cut. If the tool bits chip or become dull, replace them immediately with sharp bits.

<u>CAUTION:</u> ***Never try to re-sharpen the tool bits. They must be sent back to the factory for regrinding to maintain proper relief angles. Improperly ground tool bits can cause damage to the machine.***

3. Use Coolant during the cutting operation to reduce friction on the cutting edge.

<u>NOTE:</u> ***Coolant is recommended for cutting blades that are not high-speed steel (HSS) rated. If HSS is used, coolant is not necessary.***

4. Stop the machine when the severing is complete. Back out the tool blocks with the star wheel wrench to the full position.

In Figure 21 are the various sizes of severing tool bits compatible with the HD line of clamshell lathes.

7.1.1.5. Machine Maintenance

Cutting blades for the clamshell lathe range in size and shape depending on the application of the blade (flange cut, beveling, facing, etc.). The cutting blades for this application will need to be high-speed steel in order to avoid having to use coolant. Various cutting blades can be seen in Figure 22 (“Pipe Cold Cutting Machine" 2019).

Below is Hydratight’s maintenance handling procedure for the HD Clamshell line.

CAUTION: ***Disconnect the power source prior to cleaning or making adjustments to the machine.***

Adjusting Tapered Gibs on the Tool Block Slide

NOTE: ***Each tool block slide includes two tapered gibs, which may be adjusted for wear after heavy use. It must always fit exactly parallel to the slide for proper feed screw action.***

1. To adjust the gibs first remove the two socket head screws holding the star wheel and feed screw assembly into place on the back of the slide.
2. Pull out the tool block and feed screw assembly. Remove the feed screw assembly from the feed nut pocket on the tool block (usually this is a tight fit). Replace the tool block into the slide. Put a tool bit into the tool block and tighten it down. **Always adjust the gibs with a tool bit installed.** A detailed view of the cutting arm can be seen in Figure 23 (“Pipe Cold Cutting Machine" 2019)
3. Slide the tool block up and down by hand in the slide, adjust the side set screws until a snug fit is achieved with no sideways slop, yet not binding.
4. Remove the tool block, replace the feed screw assembly and tool block. Secure the feed screw assembly with two socket head screws. Using the STAR WHEEL WRENCH, move the tool block up and down the slide to check for a proper fit **(moving easily yet snug).**

Adjusting the Bearings

1. Place the fully assembled clamshell onto a flat surface, gear side up. Remove the locking pins so the gear can rotate on the housing. Remove the four pipe plugs from the access holes.
2. Remove the gear shield from the clamshell. Remove the outer locking set screws and loosen the eccentric set screws.
3. Starting at the split line, rotate the gear until the access holes are directly over the top of the first two bearings. One of the bearings is an inner bearing and the other is an outer bearing. Insert an Allen wrench thru the access hole into the top of the inner bearing; turn it clockwise until it is tight against the inner gear wall. Tighten the eccentric screw to lock it in place. Insert the Allen wrench into the top of the outer bearing; turn it counter-clockwise until it is tight against the outer gear wall. Do not turn too hard or the screw on

top of the bearing will unscrew and loosen up. Tighten the eccentric screw. Repeat this procedure for the bearings under the opposite side access holes.

4. Rotate the gear so the access holes are directly over the next two bearings. Repeat step 3.
5. Repeat step 4 until all the bearings are tight against the gear walls.
6. Slowly run the machine. Looking thru the access holes, verify that all the bearings are turning. Retighten all the bearings that are not turning. Tighten all of the set screws to lock the eccentric screws. Install the pipe plugs into the access holes and reinstall the gear shield. Insert the locking pins.

7.1.1.6. Potential for System Failure

Failure modes included for the clamshell lathe include:

- Dropping of the machine
- Power failure to the machine
- Hydraulic hose line failure
- Tool bit failure
- Tripper assembly failure
- Gear clamp failure
- Locator pad assembly failure
- Bearing failure
- Cutting arm failure
- Flange cutting attachment failure
- Miscellaneous bolts, gears, screws, etc.

Hydratight's recommendation for any failure associated with the clamshell lathe:

"We recommend that in the event of failure or of general maintenance, the Clamshell is returned to Hydratight DL Ricci., where our experience Service Technicians and Engineers can carry out the necessary repairs."

7.1.2. Debris

7.1.2.1. Debris Type

From the clamshell lathe cutting method, there are two main types of debris to be expected: metal shavings, and coolant waste if coolant is used. For this application, the cutting lubricant will not be used. Figure 24 ("GBC Pipe Cold Cutting And Bevelling Machines Supercutter", n.d.) depicts a clamshell lathe cutting a pipe similar in size to a fuel canister. The metal shavings created are long, stringy chips that are not typically broken apart.

The cutting blades will be considered waste once they are used on the canister. After cutting a canister, the two (2) cutting blades will need to be replaced to keep cutting times consistent. Other types of waste include any parts that may need to be replaced on the clamshell lathe.

7.1.2.2. Debris Disposal

The metal shaving debris, cutting blades and used parts will all be considered low-level nuclear waste and will be disposed of properly at one of the four agreement state facilities. The cleaning and removal of the low-level nuclear waste from cutting these canisters will be done per NRC regulations based on the classification of the waste. The NRC provides the classification of the waste in 10 C.F.R. § 61.55 ("NRC: 10 CFR 61.55 Waste Classification." 2017). There are three different classes of low-level nuclear waste (A, B or C), where A is the least radioactive and C is the most radioactive. In Table 7, the classification details of A through C can be viewed. Once the waste is classified, the waste will be gathered from the hot cell and appropriately packaged to be shipped to one of the four low-level waste facilities in either Barnwell, South Carolina, Richland, Washington, Clive, Utah or Andrews County, Texas. Clive, Utah only accepts class A low-level nuclear waste. The transportation of nuclear waste is outlined in the following flow chart, Figure 25 ("Low-Level Radioactive Waste Disposal" 2019)

7.2. Procedures for Plasma

7.2.1. Cutting Process

The cutting process for plasma is centered around using the GougeMaster, manufactured, sold, and installed by AGT Robotics. The following procedures are based on a general proposal of purchase and use provided by AGT Robotics for the sole use of this report. Any further inquiry with AGT Robotics for the design of a hot-cell centered around using the GougeMaster could result in additional costs and change in general design reported here.

The overall cutting process using the GougeMaster is completed by an automated process with a plasma cutter programmed before loading the canister into place. The GougeMaster is originally designed as a portable cutting solution for pressure vessel, Oil and Gas manufacturing shop.

Machining Function and Capacities

- Nozzle Hole Cutting (Saddle Joints) – Radial and Tangential
- Circular Seam Gouging (Manual Override)
- Longitudinal Seam Gouging (Playback)
- Shell End Straight Cut (Optional Contact AGT)
- Shell End Bevel Gut (Optional Contact AGT)
- Potential for Welding and Other Tasks (Optional Contact AGT)

For this application, the GougeMaster will be used in a circular seam gouging capacity. It can perform both destructive and nondestructive cutting depending on how the hot cell is set up. Reported benefits of the GougeMaster specifically, that are relevant for our application, include; quick setup time, reduced post cut cleaning time, reliability in the equipment and technology with a proven track record, portability, unlimited outside diameter capability, high quality gouging, low fume with an argon-hydrogen gas mixture, low noise, and carbon arc gouging capabilities.

7.2.1.1. Components

Platform

A stiff structure that is portable and integrated protection for the robot, handling with crane or forklift. Shown in Figure 26 is AGT Robotic's platform.

Robot

6 axis robot that controls the plasma torch and gouging apparatus. Shown in Figure 27 and Figure 28 is AGT Robotic's robot components

Plasma Power Source

ESAB ESP-150 with PT-26SL torch. Shown in Figure 29 and Figure 30 is AGT Robotic's plasma power source component

Overall Dimensions

53 inches in diameter, 94 inches in height, and 72 inches wide.

Working Point

Between 48 and 84 inches from the ground

Total Weight

Approximately 2000 lbs

Input power supply

575VAC/60Hz/3Ph or 480VAC/60Hz/3PH

Air/Gas Supply

Requires a compressed air for shield gas at minimum 80 psi, dry and non-lubricated. 65% Argon and 35% Hydrogen at minimum 80 psi.

Part Cutting Dimensions

Outside diameter and length is unlimited and is determined by the work position and moving of the component being cut. There is a maximum 10 foot 6 inch longitudinal cutting and gouging for the machine if the robot and component are stationary. For circular seem diameters there is a minimum dimension of 6 foot but the maximum is unlimited.

7.2.1.2. Gas Testing Process

Before starting the plasma cutting procedure, gas testing must be completed to ensure hazardous gases are not present. If they are present, specialized ventilation procedures must be considered and implemented. To complete the gas testing for a destructive cut, the portable gas testing unit must be attached to the canister. The location of the portable gas testing unit is determined based on the original canister design and their location of the shield plug. The most optimal location for the gas testing unit will be below the shield plug in order to avoid contact or interference with the destructive cutting device. A check of the portable gas testing unit is imperative before attaching. The portable gas testing unit must pass inspections for gas testing ability, airtight seal for the gas testing portion of the unit, and piercing capabilities intact. Once these are done, a proper check of the attachment device must be done. The device must be able to create an airtight seal between the portable gas testing unit and the canister to provide a safety net against a possible leak within the portable gas testing unit. Once the portable gas testing unit and the attachment device are in order, the device will need to be attached to the canister.

Careful positioning determined by the canister schematic and the location of the shield plug will begin the process. The portable gas testing unit will then need to be precisely attached to the canister in the predetermined position. Once the portable gas testing unit is correctly attached to the canister, the device will be double checked before proceeding. After a check, the portable gas testing unit can begin the process of piercing the canister to sample the gas present in the canister. Once the gas testing measurements are captured, determination of continuing to cut the canister or not and any ventilation requirements will be established.

7.2.1.2.1. Nondestructive

Gas testing for nondestructive cutting when utilizing the plasma cutting method is a straightforward process. Once the plasma cutting device removes the welds around the top lid of the canister, and the top lid is removed, the operators will have access to the key port hole on the secondary lid. This key port can be removed through the traditional rotabroach method, a new method designed through the welded device unit, or through plasma cutting since it is a non-contact, precision, cutting technique. Once the key port is removed, gas testing can be completed through the traditional method already licensed and approved by the NRC.

7.2.1.2.2. Destructive

Please note that these are considerations and recommendations for a proposed gas testing process that has not been developed yet and will require additional research.

Gas testing through the destructive method is designed so that there is a quicker overall process and gaining access through the key port is not necessary. While the team has not designed this new gas testing method, it has been described that a similar method is used on the lids of single-lid canister designs. The team proposes that the system could be applied to the side of a two-lid canister and be just as successful which is what is required for the gas testing of the destructive cutting method. This desired system is a portable gas testing mechanism attached to the outside of the canister as previously described. A benefit of using the plasma cutting technique is that it can also be used in some fashion to open the testing port before completing the canister opening procedure. Since it is versatile in application and can cut theoretically any shape, there would not be a need for a second cutting device to open the gas testing port for this method. However, there would be a requirement based on what gases have the potential for being within the canisters to prevent any sparks or side effects from the gas used in the plasma cutting. The team discovered this consideration but not further researched or designed due to time constraints of the project.

7.2.1.3. Set-Up and Process Nondestructive

The nondestructive cutting process requires that the plasma cutting device be located above the canister and be able to angle in such a way that the gouging technique can be utilized. The plasma cutter will be required to gouge out the weld metal between the lid and the side walls of the canister. This method will take approximately 3.3 hours of cut time to completely open the canister and gain access to the shield plug. Listed below is the order of events that must take place for this cutting method.

- The first lid weld will be gouged, and the lid will be removed.
- The gas testing procedure will be completed through the vent port as designed with the rotabroach opening method for the keyhole.
- Any required venting or drying procedure that is necessary due to the gas testing results.
- The second lid weld will be gouged, and the lid will be removed.

After these steps are completed, the shield plug and fuel can be removed from the canister as designed. This technique and the professional procedure is similar to how the skiving and NRC licensed procedures are written and completed. The primary difference is that there is now not a set-up procedure for the skiving device as we are using a plasma torch and there are special considerations to watch for as the gouging process takes place. This solution allows for virtually no set-up since the torch, using the GougeMaster, does not need to touch or clamp onto each canister to complete its task. Merely load the instruction parameters and have a remote operation technician complete the actual gouging of welds and the set-up process is complete. The following instructions and facts about the GougeMaster can be found in the general instructions and purchase proposal provided by AGT Robotics (GougeMaster Proposal, 2019).

For circular seams, like weld removal, there is no programming required, according to the AGT Robotics information sheet on the GougeMaster. To ensure alignment with the canister, the GougeMaster is set up parallel with the vessel's longitudinal axis and roughly centered around the canister and then fully aligned through the robotic procedure. This set up is done through crane or forklift. However, if the equipment is rail mounted within the hot cell, it will start at its designated center point on the rail system every time.

For the start of the set-up, the plasma torch will need to be brought to a designated starting point of the weld. This is completed with a nylon stand-off pin, and the position is recorded. There will also be points approximately every 30 inches marked and recorded to ensure that the plasma torch stays on track. From this point, the gouging process can be initiated.

To start the rotation to cut circular seams, like the weld on the lid of the canisters, it is instructed that the operator rotates the workpiece, the canister, at a proper travel speed which is not integrated into the robotic plasma system. For this application, either the canister or the plasma torch can be rotated depending on the design of the hot cell. The travel speed should be consistent between canisters as the material and depth of cut is also staying consistent.

After rotation is started, the arc ignition can take place. This operation requires visibility of the arc approximately 12 to 24 inches behind the plasma torch. This is important to consider when designing remote operation and visibility of operation throughout the hot cell. Since there will be a designated starting point of the plasma torch location either from the rail system or the crane location, there should also be visibility access designed into the hot cell for the arc initiation procedure.

7.2.1.4. Set-Up and Process Destructive

The destructive cutting process requires that the plasma cutting device be located next to the canister and be able to angle in such a way that the gouging technique can be utilized. The plasma cutter will be required to gouge out the side walls of the canister. This method will take approximately 1.65 hours of cut time to open the canister and gain access to the fuel completely. Listed below is the order of events that must take place for this cutting method.

- The gas testing procedure will be completed through the side of the canister utilizing either the plasma torch or a secondary cutting device to open a gas testing port.
- Any required venting or drying procedure that is necessary due to the gas testing results.
- The upper portion of the canister and top lid will be secured to prevent any sliding or moving during cutting.
- A ring around the canister located below the shield plug will be gouged out.
- All three lids, along with a portion of the outside wall of the canister, will be removed through crane operation.

After these steps are completed, the fuel can be removed from the canister as designed. This technique has yet to be licensed through the NRC and has not yet been fully designed or tested due to the time limitations of the study. This procedure is to serve as a basis for future research into the actual design of the plan. This solution allows for virtually no set-up since the torch, using the GougeMaster, does not need to touch or clamp onto each canister to complete its task. Merely load the instruction parameters and have a remote operation technician complete the actual gouging of welds and the set-up process is complete. The following instructions and facts about the GougeMaster can be found in the general instructions and purchase proposal provided by AGT Robotics (GougeMaster Proposal, 2019).

For circular seams, including cutting the side of the canister, there is no programming required, according to the AGT Robotics information sheet on the GougeMaster. To ensure alignment with the canister, the GougeMaster is set up parallel with the vessel's longitudinal axis and roughly centered around the canister and then fully aligned through the robotic procedure. This set up is done through crane or forklift. However, if the equipment is rail mounted within the hot cell, it will start at its designated center point on the rail system every time.

For the start of the set-up, the plasma torch will need to be brought to a designated starting point on the side of the canister. This is completed with a nylon stand-off pin, and the position is recorded. There will also be points approximately every 30 inches marked and recorded to ensure that the plasma torch stays on track to complete a cut evenly around the entire circumference. From this point, the gouging process can be initiated.

To start the rotation to cut circular seams it is instructed that the operator rotates the workpiece, the canister, at a proper travel speed which is not integrated into the robotic plasma system. For our application, either the canister or the plasma torch can be rotated depending on the design of the hot cell. The travel speed should be consistent between canisters as the material and depth of cut is also staying consistent.

After rotation is started, the arc ignition can take place. This operation requires visibility of the arc approximately 12 to 24 inches behind the plasma torch. This is important to consider when designing remote operation and visibility of operation throughout the hot cell. Since there will be a designated starting point of the plasma torch location either from the rail system or the crane location, there should also be visibility access designed into the hot cell for the arc initiation procedure.

7.2.1.5. Machine Maintenance

Like all plasma technologies, there are specific components within plasma cutting technology that must be inspected and exchanged due to wear on the part. These parts are relatively small and very rarely must be replaced. For plasma torch systems there are a total of six consumables, one being the gases used which comes from a consistent source and therefore will not be further discussed in this section. The other five consumables can all be found in the torch tip for the machine and will allow for easy machine maintenance. These five consumables are the following:

- Electrode
- Nozzle
- Retaining Cap

- Shield
- Swirl Ring

Images in the following descriptions, and the descriptions themselves, of these consumables and machine maintenance, were found through Hypertherm. ("Powermax And <125 Amps MAX Plasma Systems: Powermax Consumable Education", n.d.) These consumables have general wear rates. However, if the plasma torch is not used appropriately, then the consumables will have a faster wear rate and could cause issues with the gouging process.

Electrode

The electrode's primary purpose is to provide power to the plasma arc. This item contains the arc attachment point which is where the majority of the deterioration occurs. This deterioration causes small pits which is what should be looked for when evaluating the torch for maintenance. It is recommended to change the electrode when the pits measure around 1 mm and should be inspected when the cutting process must be slowed down or is having trouble penetrating the material. Additional things to look for that could be from a worn electrode include green arc coloration, excessive dross appearance, arc misfire, or a difficult time starting the arc.

Nozzle

The nozzle should be replaced with the electrode, and vice versa, even if it appears that one may not need to be replaced. The nozzle focuses the arc and can be considered the most commonly replaced consumable. Typically wear on the part is shown by the hole in the nozzle widening due to the heat of the arc. If the operator notices the width of the cut increasing and the cut speed slowing down, it could be due to the nozzle wearing down. To protect the nozzle, it is suggested not to have a low gas flow as it can lead to immediate nozzle damage by causing the pilot arc to attach to the inside of the nozzle orifice.

It is shown in Figure 31 the wear rate of the electrode and the nozzle. The electrode and nozzle pairing are shown in the red box can cause a torch to blow out.

Retaining Cap

This consumable is used to hold the swirl ring, electrode, and nozzle together and in place. Additionally, it is designed to cool the consumables. While it does not have any visible effect on the arc when it wears out, it can be evaluated by looking at the threads. The retaining cap can typically last through a few electrode and nozzle replacements, but dirt within the threads can cause a premature replacement. For this application specifically, the retaining cap could melt due to the long-term heat exposure and will, therefore, have faster replacement times. Shown in Figure 32 is a new and a damaged retaining cap.

Shield

This component protects the other components from splatter while also assisting in cooling them. It gets changed regularly and shows issues through clogged vent holes and damage to the central orifice. Dross can form at the tip. If it can be removed through general cleaning, then the shield can be used again as long as the orifice is fine. Shown in Figure 33 is a clean and damaged shield.

Swirl Ring

The swirl ring controls the swirl action of the plasma gas flow around the electrode and centers the arc around the electrode and through the nozzle. It can constrict the arc for faster cut speeds and thicker cut capabilities. Though the general torch area is quite warm, this consumable is typically made of plastic and can typically last through 50 electrode and nozzle exchanges. A damaged swirl ring can cause the cut quality to decrease. Damage to the swirl rings include things such as cracks, deformations, and clogged holes. If any of these items are found, the swirl ring should be replaced immediately. Shown in Figure 34 are examples of damaged swirl rings.

7.2.1.6. Potential for System Failure

System failures for plasma cutting procedures generally only have to do with the consumables and the torch tip. These failures can be caused by using the wrong gas flow or arc settings as well as not replacing consumables when they need to be replaced. For the most part, plasma cutting failures found in the research to not pose a danger for the fuel or the hot cell as they are not catastrophic but more of failure to cut and require full replacement of the torch. Even with the low danger during failure, there is also a low possibility of these failures occurring. Overall plasma is a safe and reliable cutting method for this application.

7.2.2. Debris

7.2.2.1. Debris Type

Debris created through plasma cutting includes molten canister material, sparks from the arc and metal meeting, and fumes that are generated by the cutting procedure. The debris will mostly stay connected to the canister as molten material. Fume generation debris is typically around or less than 10 microns and can collect as dust within the hot cell. Since this application is cutting open stainless steel, it should also be considered that some debris can contain things such as manganese, chromium, cadmium, lead, nickel, and other hazardous substances which can all be found in the fume effecting air quality.

7.2.2.2. Debris Disposal

Fumes and dust created by the plasma cutting process should be filtered out through a specialized ventilation system throughout the entirety of the cutting process. Without this filtration and dust collection, the fume and smoke can affect cut quality and visibility of the cutting process within the hot cell room. These fumes and smoke can also be detrimental to quality assurance and raise concern to the environment since the contaminants, and potentially hazardous waste is not disposed of properly.

The debris created and captured through the vent system should also be considered radioactive waste, as will all of the torch consumables and should be disposed of as such waste. The cleaning and removal of the low-level nuclear waste from cutting these canisters will be done per NRC regulations based on the classification of the waste. The NRC provides the classification of the waste in 10 C.F.R. § 61.55 ("NRC: 10 CFR 61.55 Waste Classification." 2017). There are three different classes of low-level nuclear waste (A, B or C), where A is the least radioactive and C is the most radioactive. In Table 7, the classification details of A through C can be viewed. Once the waste is classified, the waste will be gathered from the hot cell and appropriately packaged to be shipped to one of the four low-level waste facilities in either Barnwell, South Carolina, Richland, Washington, Clive, Utah or Andrews County, Texas. Clive, Utah only accepts class A low-level nuclear waste. The transportation of nuclear waste is outlined in the following flow chart, Figure 25 (“Low-Level Radioactive Waste Disposal" 2019)

8. Hot Cell Design

8.1. Reason for Hot Cell

Due to the nature of the canister contents, and the design of being at an off-site location, it was determined that the most straightforward method would be to cut the canisters within a hot cell. This will limit the infrastructure required and remove some of the concerns to be evaluated in the cutting process. The hot cell design will advance the ability to have remote operation while still allowing for human interaction when necessary. In addition, working with a company to specifically design a hot cell with the cutting process will allow for more freedom with infrastructure choices. This hot cell will also allow for the potential ability to transfer the entire system from one site to another if ever required.

8.2. Hot Cell Requirements

The hot cell will be required to hold the canister safely while also having the ability to operate the cutting process and potentially the set-up process remotely. The hot cell will need to be able to handle the debris accumulated during either cutting process, and handle the debris properly. Video surveillance within the hot cell during operation will also be imperative to success, to spot any problems remotely and maintain an eye on the canister during the cutting process. An emergency shut down and proactive solution to any malfunctions, issues are catastrophic failure must be established prior to any testing. The hot cell must also have a system for lifting and holding the upper half of the canister after a successful destructive cut, in order to safely gain access to the fuel. An automized way of repackaging the fuel into the new canisters must also be established within the hot cell.

8.3. Previous Hot Cell Designs for UNF Canisters

The Electric Power Research Institute (EPRI) previously designed a hot cell for opening bolted used nuclear fuel canisters and transferring the fuel into a permanent canister. Shown in Figure 34 is EPRI’s conceptional hot cell design of a dry transfer system which consisted of a 2 level concrete and steel structure paired with a preparation area. The canisters in this design were placed side-by-side for the procedure, and the fuel was lifted into the second level and then placed into the second canister. The entirety of this system was remotely operated and consisted of transportable components.

EPRI’s DTS consisted of three main areas, preparation, lower access, and transfer confinement. General operating functions of the DTS were moving the casks, removing the shield plug and lids, transferring the fuel, replacing the shield plug and lids, and decontaminating each cask. EPRI estimated the cost of building the complete DTS to be between $1.5M-$6.7M. EPRI’s DTS is a solid launch pad for designing the hot cell for opening Transnuclear used nuclear fuel canisters.

8.4. Proposed Hot Cell Design

The proposed hot cell design differs slightly between the two cutting methods of clamshell and plasma. Specifications for a plasma designed hot cell includes a looping rail or track system to place the plasma cutting tool in any orientation around the container. The assist gases for the plasma will need a holding space or chamber that can be accessed throughout the entire operation. Specifications for the clamshell lathe are a secondary crane to hoist the clamshell to the proper cutting location and height. Additional research is needed to develop automated and remote capability. These processes include fastening to the canister, removal from the canister, blade changes and maintenance. Current cutting procedure in sections (7.1.1.3 - 7.1.1.5) are completed manually and in need of an automated system to be used in the hot cell.

Regarding similarities between both designs will use the same gas testing used by the NRC the key port sampling method and the need for video surveillance of the entire cell operation and remote capabilities. The two hot cell designs are similar to the proposed design by EPRI in the above section (8.3). A dry transfer system made of a 2-level concrete and rebar supported structure with designated preparation area. The canisters in this design are placed side-by-side for the procedure, and the fuel was lifted into the second level and then placed into the second canister. The entirety of this system was remotely operated and consisted of transportable components. The 3 main areas consist of preparation, lower access, and transfer confinement.

9. Topics for Additional Research

A few topics were identified by the group as necessary for the full evaluation of the optimization of this application but were outside of the scope due to time constraints and resource availability of the project. These topics are listed below:

- Design of a gas testing method for the side of UNF canisters
- Conversion of manual clamshell operations into remote processes
- Specific hot cell requirements and design of the hot cell
- Venting capabilities of hot cells
- Mechanics of transferring fuel within the hot cell
- Closed circuit video surveillance capable of withstanding the radiation, heat, and other factors specific to this application
- Complete remote capabilities of current hot cell designs
- Mechanics of removing UNF canisters from their transfer casks within the hot cell
- Ability of remote debris clean up within hot cells
- Remote operation of inspection of and exchanging machine consumables for both plasma and clamshell operations
- Design of revolving Gouge Master or UNF canister within hot cell
- Gas testing procedures and continuous gas monitoring
- Emergency shut down systems for both plasma and clamshell
- Emergency safety considerations if there is a machine failure or fuel damage during the cutting operation
- Ability to disregard lubrication during clamshell cutting operations for this application
- Expected radiation and heat output of canisters
- Ability of chosen method to be completed on all canisters available outside of Transnuclear 3-lid design
- Transportability of chosen method and hot cell design

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11.Appendices

11.1. Appendix I: Figures

Figure 1: Map Detailing the UNT Storage Locations Across the US

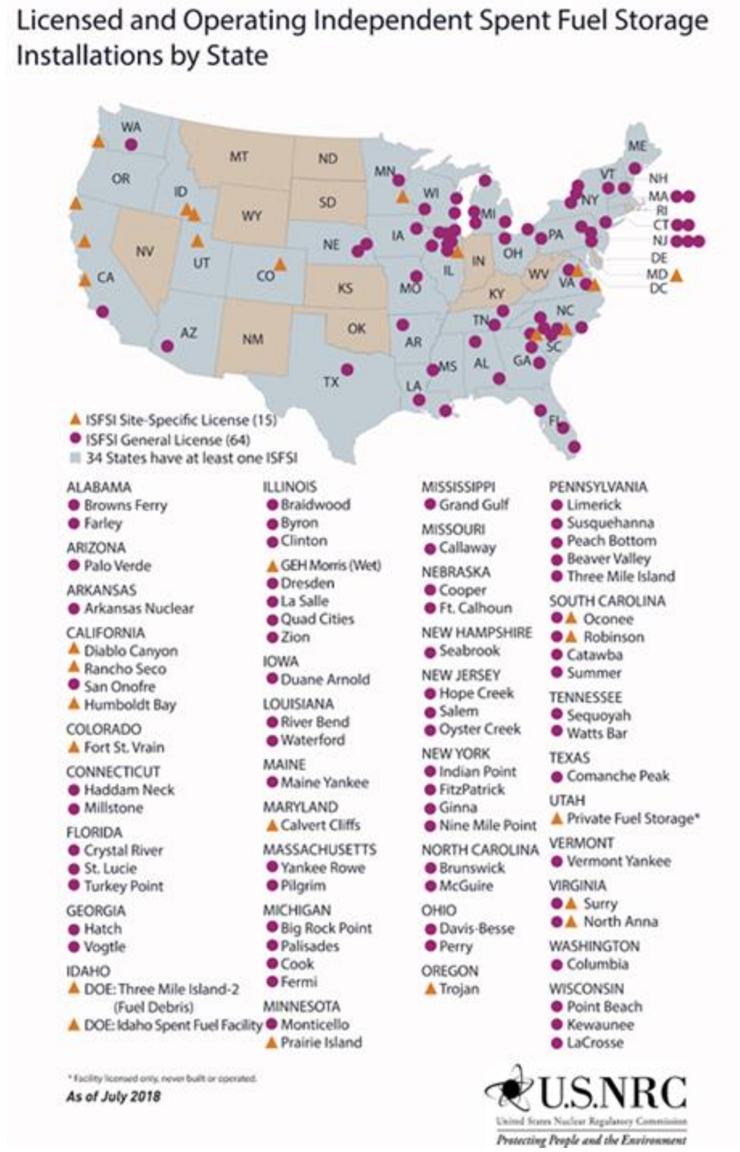


Figure 2: Section View of the Geography of the Yucca Mountain Repository

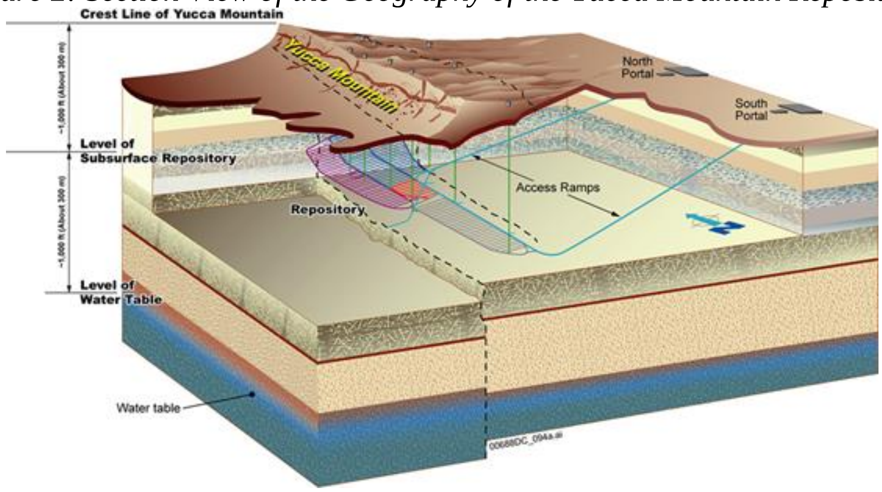
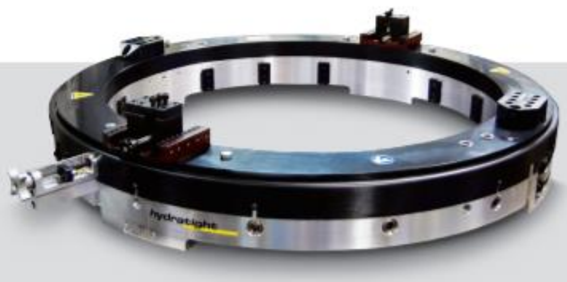


Figure 3: Hydratight HD Clamshell Product Introduction

hydratight

HD Clamshells



The robust design of the Hydratight portable HD or Heavy Duty Clamshell series makes them ideal for large diameter heavy wall pipe applications. Each of the machines within the HD series have a height of 6.25" (158.8 mm) and a width of 4.69" (119.1 mm) or 4.81" (122.2 mm). The mass created from these dimensions increases rigidity and helps maintain accuracy during use. These portable split frame machines are capable of pipe cutting, beveling, facing, ID boring and OD turning on a wide range of wall thicknesses.

Features:

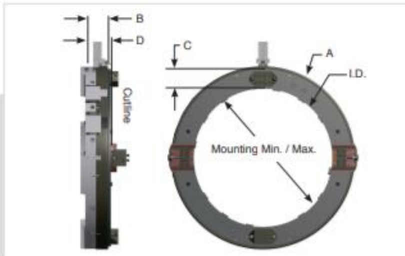
- 16 Standard models cover a range of 20" (508 mm) to 86" (2,184.4 mm) OD
- Pneumatic and hydraulic drive options provide increased versatility
- Fully adjustable heavy duty bearing design provides greater serviceability
- Stepped and keyed gear clamps equipped with a through bolt provide a positive fit at each assembly joint
- Several different drive options are available to best position the motor for a specific machining application
- HD series clamshells accept a wide range of accessories to increase performance and expand capabilities

Adjustable bearing design

Large diameter

Figure 4: Hydratight HD Clamshell Specification Sheet

hydratight



HD Clamshells

HD Clamshell Specs:

	HD32–HD57	HD60–HD86
B	6.25" (158.8 mm)	
C	4.689" (119.1 mm)	4.813" (122.2 mm)
D	8.5" (215.9 mm)	8.25" (209.6 mm)

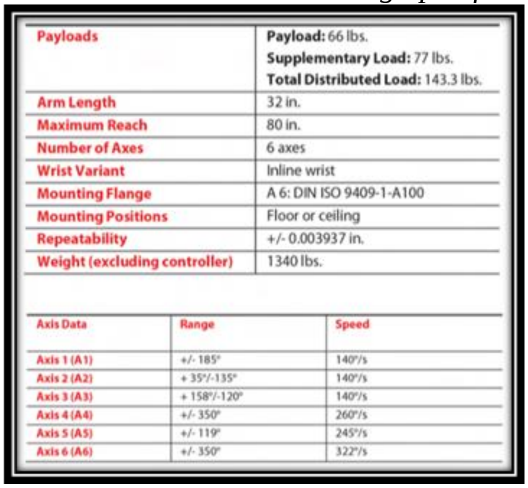
* "D" dimension (or cutline) may change with different tooling. Contact consultant for specifics.

Model	Part Number	Unit of Measure	Mounting Min Max	Machine ID	A	Machine Weight	B	C	D *
HD32	F0103D0320AA	Std. - in.	20–32	33	42.375	469 lbs	6.25	4.689	8.5
		Metric - mm	508.0–812.8	838.2	1,076.3	212.92 kg	158.8	119.1	215.9
HD36	F0103D0360AA	Std. - in.	24–36	37	46.375	509 lbs	6.25	4.689	8.5
		Metric - mm	609.6–914.4	939.8	1,177.9	231.08 kg	158.8	119.1	215.9
HD39	F0103D0390AA	Std. - in.	27–39	40	49.375	538 lbs	6.25	4.689	8.5
		Metric - mm	609.6–914.4	1,016.0	1,254.1	244.25 kg	158.8	119.1	215.9
HD43	F0103D0430AA	Std. - in.	31–43	44	53.375	595 lbs	6.25	4.689	8.5
		Metric - mm	787.4–1,092.2	1,117.6	1,355.7	270.13 kg	158.8	119.1	215.9
HD45	F0103D0450AA	Std. - in.	33–45	46	55.375	614 lbs	6.25	4.689	8.5
		Metric - mm	838.2–1,143	1,168.4	1,406.5	278.75 kg	158.8	119.1	215.9
HD48	F0103D0480AA	Std. - in.	36–48	49	58.375	643 lbs	6.25	4.689	8.5
		Metric - mm	914.4–1,219.2	1,244.6	1,482.7	291.92 kg	158.8	119.1	215.9
HD50	F0103D0500AA	Std. - in.	38–50	51	60.375	663 lbs	6.25	4.689	8.5
		Metric - mm	965.2–1,270	1,295.4	1,533.5	301 kg	158.8	119.1	215.9
HD53	F0103D0530AA	Std. - in.	41–53	54	63.375	692 lbs	6.25	4.689	8.5
		Metric - mm	1,041.4–1,346.2	1,371.6	1,609.7	314.16 kg	158.8	119.1	215.9
HD54	F0103D0540AA	Std. - in.	42–54	55	64.375	702 lbs	6.25	4.689	8.5
		Metric - mm	1,041.4–1,371.6	1,397.0	1,635.1	318.78 kg	158.8	119.1	215.9
HD55	F0103D0550AA	Std. - in.	43–55	56	65.375	716 lbs	6.25	4.689	8.5
		Metric - mm	1,092.2–1,397	1,422.4	1,660.5	325.06 kg	158.8	119.1	215.9
HD57	F0103D0570AA	Std. - in.	45–57	58	67.375	735 lbs	6.25	4.689	8.5
		Metric - mm	1,092.2–1,397	1,473.2	1711.3	333.69 kg	158.8	119.1	215.9
HD60	F0103D0600AA	Std. - in.	48–60	61	70.625	831 lbs	6.25	4.813	8.25
		Metric - mm	1,219.2–1,524	1,549.4	1,793.9	377.27 kg	158.8	122.2	209.6
HD66	F0103D0660AA	Std. - in.	54–66	67	76.625	891 lbs	6.25	4.813	8.25
		Metric - mm	1,371.6–1,676.4	1,701.8	1,946.3	404.51 kg	158.8	122.2	209.6
HD72	F0103D0720AA	Std. - in.	60–72	73	82.625	952 lbs	6.25	4.813	8.25
		Metric - mm	1,524–1,828.8	1,854.2	2,098.7	432.21 kg	158.8	122.2	209.6
HD80	F0103D0800AA	Std. - in.	68–80	81	90.625	1063 lbs	6.25	4.813	8.25
		Metric - mm	1,727.2–2,032	2,057.4	2,301.9	482.60 kg	158.8	122.2	209.6
HD86	F0103D0860AA	Std. - in.	74–86	87	96.625	1115 lbs	6.25	4.813	8.25
		Metric - mm	1,879.6–2,184.4	2,209.8	2,454.3	506.21 kg	158.8	122.2	209.6

Further details can be obtained from your local Hydratight representative or via the website **hydratight.com**.

HT_TL_103_1016_US

Figure 5: The Cobra Laser Cutting Specifications



Payloads	**Payload:** 66 lbs. **Supplementary Load:** 77 lbs. **Total Distributed Load:** 143.3 lbs.
Arm Length	32 in.
Maximum Reach	80 in.
Number of Axes	6 axes
Wrist Variant	Inline wrist
Mounting Flange	A 6: DIN ISO 9409-1-A100
Mounting Positions	Floor or ceiling
Repeatability	+/- 0.003937 in.
Weight (excluding controller)	1340 lbs.

Axis Data	Range	Speed
Axis 1 (A1)	+/- 185°	140°/s
Axis 2 (A2)	+ 35°/-135°	140°/s
Axis 3 (A3)	+ 158°/-120°	140°/s
Axis 4 (A4)	+/- 350°	260°/s
Axis 5 (A5)	+/- 119°	245°/s
Axis 6 (A6)	+/- 350°	322°/s

Figure 6: The Cobra Laser Cutter

Figure 7: H&M Pipe Beveling Options (A) The Band-Type System (B) The Saddle-Type System

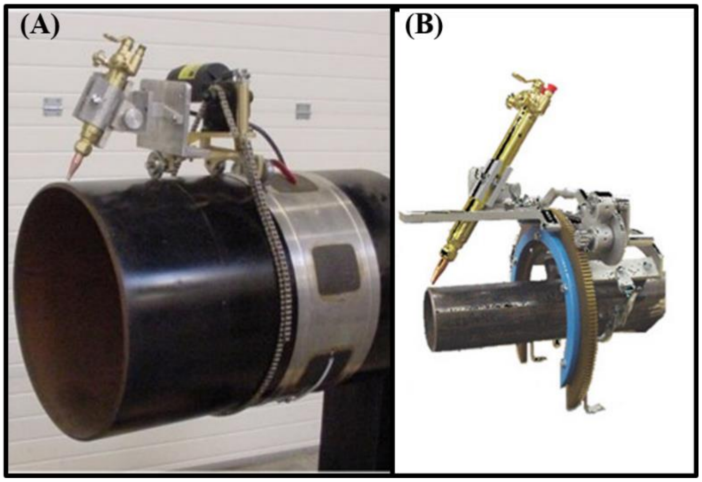


Figure 8: AGT Robotics Gouge Master

Figure 9: Chukar Waterjets Zip-Tied Outer Diameter Pipe Cutter

Figure 10: UNF Storage Cycle

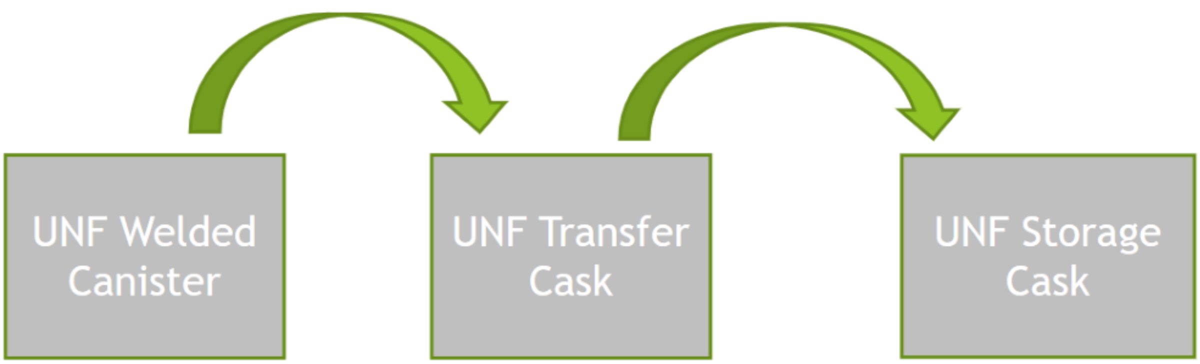


Figure 11: Various Drive Arrangements for Clamshell Lathe

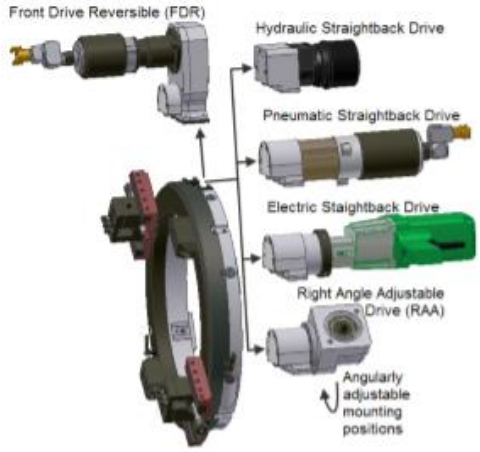


Figure 12: Tripper on the Clamshell Lathe

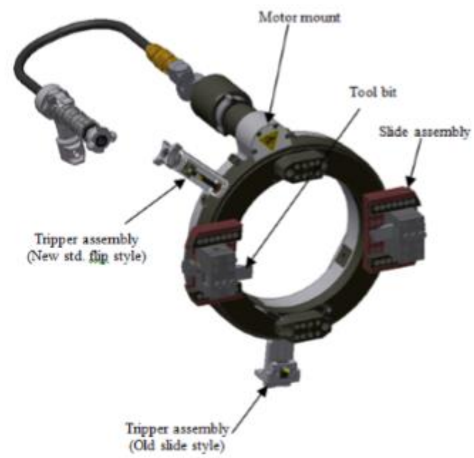


Figure 13: Clamping Mechanism for Clamshell Lathe

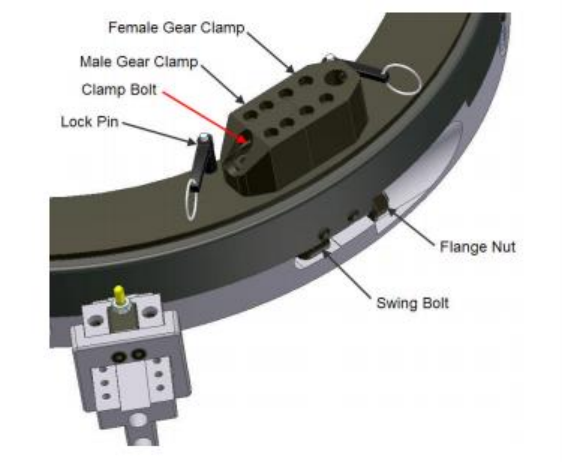


Figure 14: Locator Pads for Clamshell Lathe

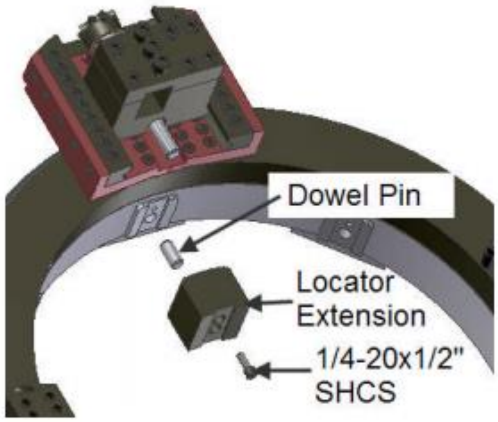


Figure 15: Slide Assembly for Clamshell Lathe

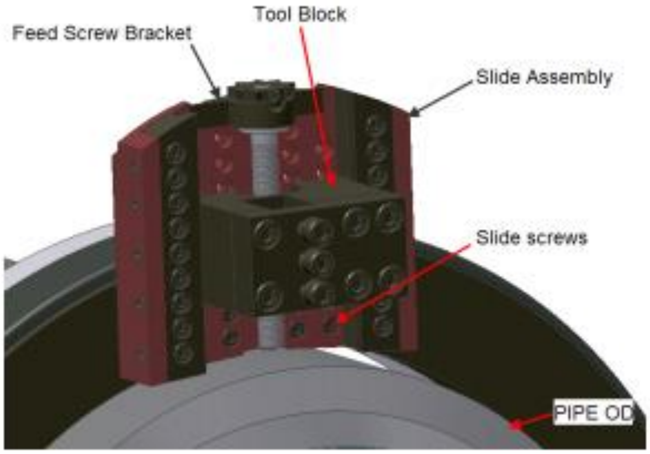


Figure 16: Tripper Pin for Clamshell Lathe

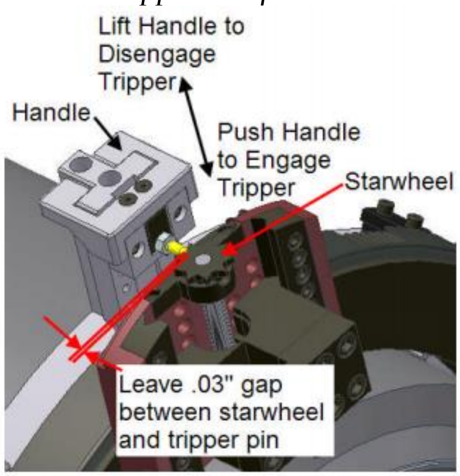


Figure 17: Clamshell Lathe Attaching to the Proposed Canister

Figure 18: Locators for the Clamshell Lathe

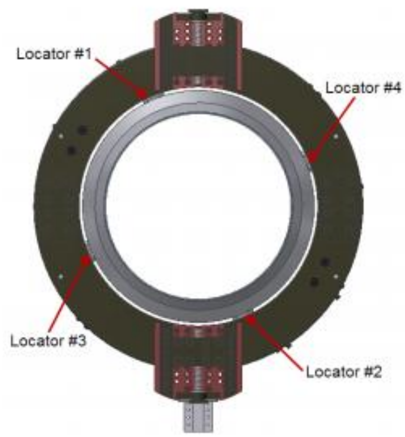


Figure 19: Cutting Arm Depth for Clamshell Machine

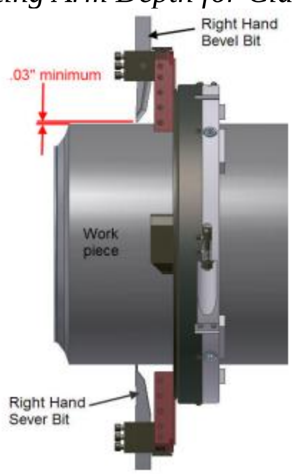


Figure 20: Motor Mount Clamp for Clamshell Lathe

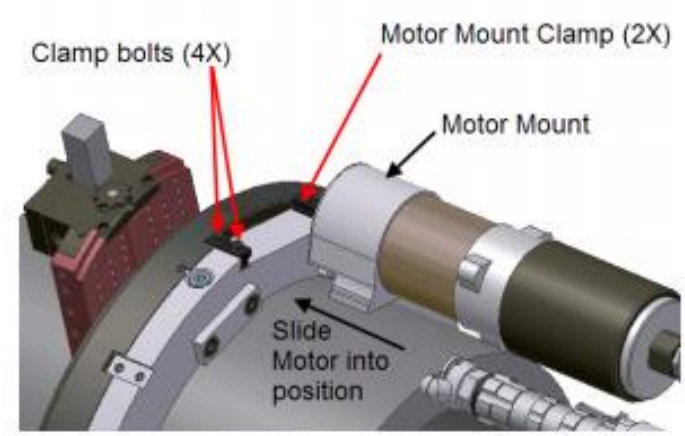


Figure 21: Flange Facing Tool Bit Clamshell Lathe

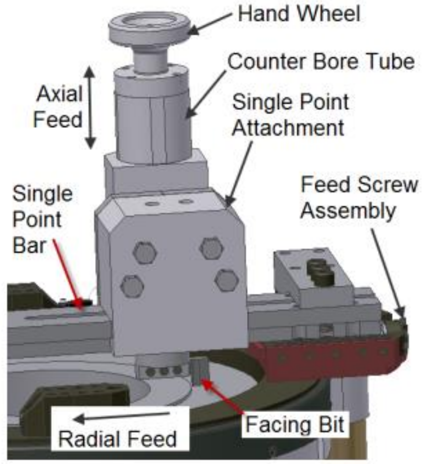


Figure 21: Severing Tool Bits for the Cutting Arm of the Clamshell Lathe

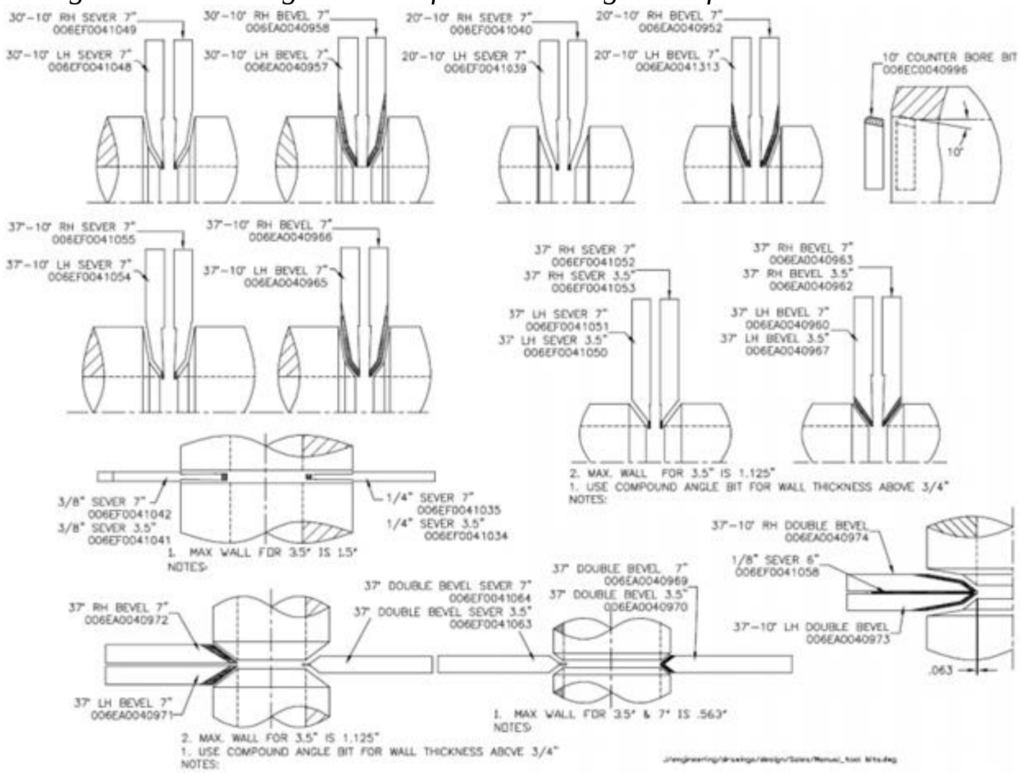


Figure 22: Various Types of Cutting Blades Available for the Clamshell Lathe

Figure 23: The Cutting Arm and Blade for the Clamshell Lathe

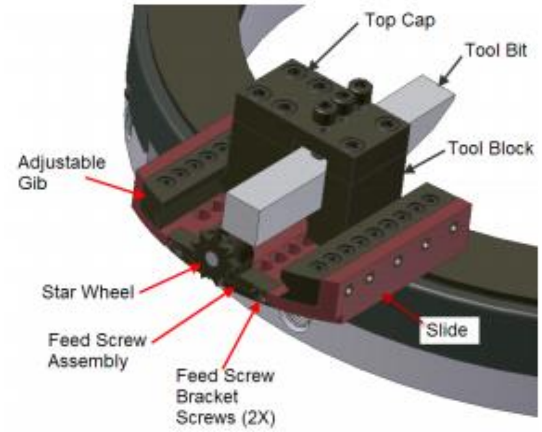


Figure 24: The Metal Shavings Created by a Severing Cut on a Clamshell Lathe

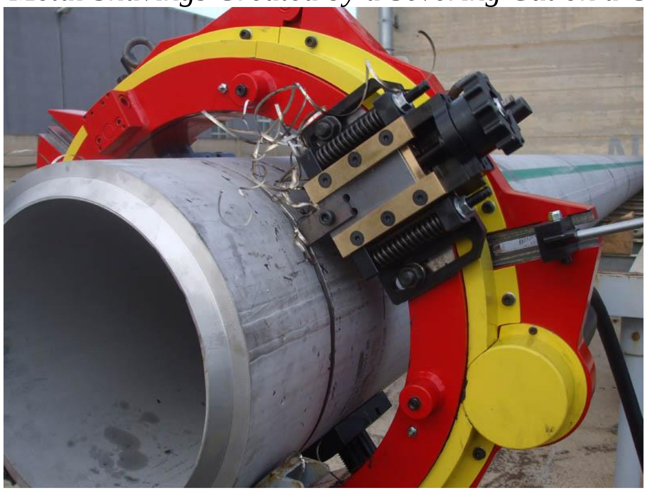


Figure 25: Transportation Flow Chart of Low-Level Nuclear Waste

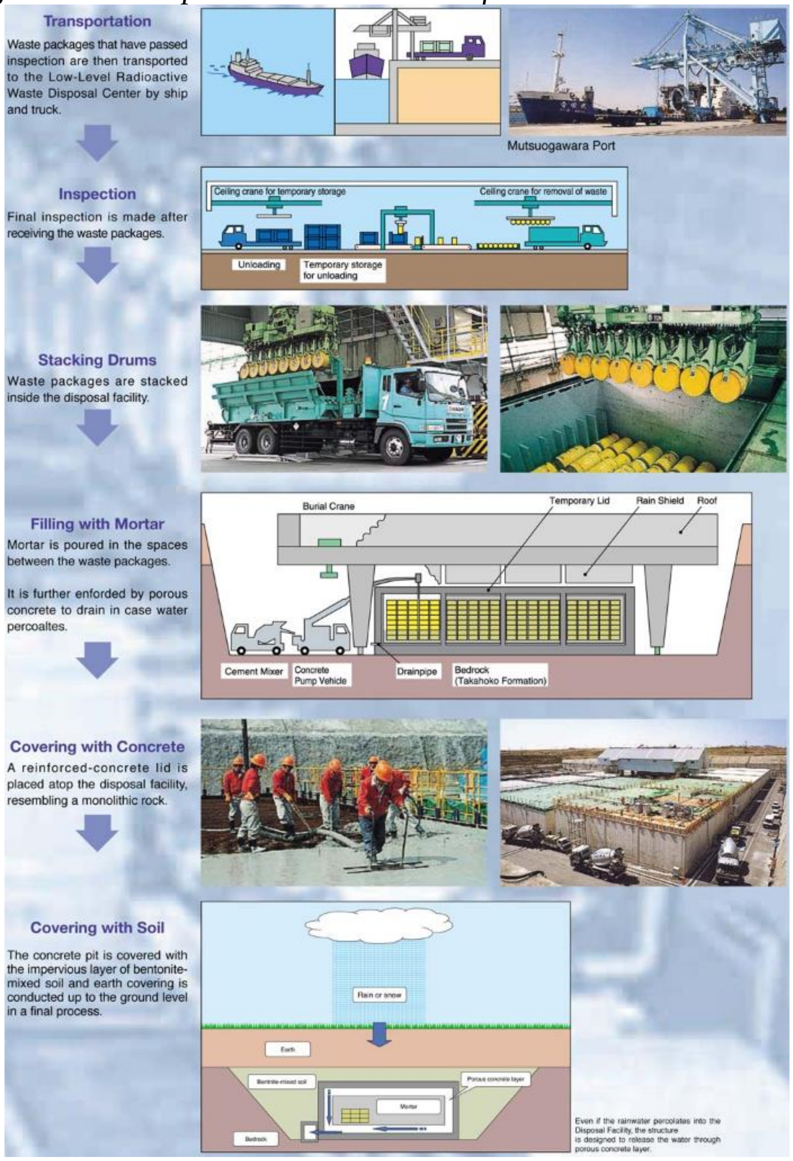


Figure 26: Plasma Platform Design from AGT Robotics

Figure 27: Plasma Robot Component from AGT Robotics

Figure 28: Plasma Robot Component from AGT Robotics

Figure 29: Power Source Component for Plasma System from AGT Robotics

Figure 30: Power Source Component for Plasma System from AGT Robotics

Figure 31: Nozzle and Electrode Consumables for Plasma Systems

Figure 32: Retaining Cap Consumables for Plasma Systems

Figure 33: Shield Consumable for Plasma Systems

Figure 34: Swirl Ring Consumables for Plasma Systems

Figure 35: EPRI DTS Hot Cell Design

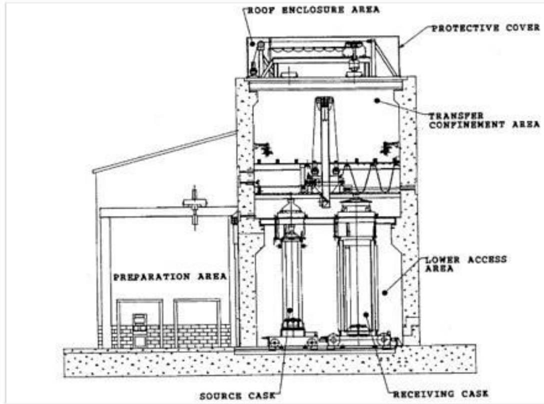


Figure 2-1
Cross-Section of the EPRI Conceptual Design for a Dry Transfer System

11.2. Appendix II: Tables

Table 1: Canister Specifications

Vendor	Variation	Overall Length (in)	Overall Cross-Section (in)	Wall Thickness (in)
EnergySolutions	W21M-LD	192.3	66	0.625
EnergySolutions	W21M-LS	192.3	66	0.625
EnergySolutions	W21M-SD	182.3	66	0.625
EnergySolutions	W21M-SS	182.3	66	0.625
EnergySolutions	W21T-LL	192.3	66	0.625
EnergySolutions	W21T-LS	192.3	64.75	0.625
EnergySolutions	W21T-SL	182.3	66	0.625
EnergySolutions	W21T-SS	182.3	66	0.625
EnergySolutions	W74M	192.25	66	0.625
EnergySolutions	W74T	192.25	66	0.625
Holtec Inc.	MPC-24	190.31	68.5	0.5
Holtec Inc.	MPC-24E / 24EF	190.31	68.5	0.5
Holtec Inc.	MPC-32 / 32F	190.31	68.5	0.5
Holtec Inc.	MPC-68/ 68F / 68FF / 68M	190.31	68.5	0.5
Holtec Inc.	MPC-37	181	75.5	0.5
Holtec Inc.	MPC-89	190	75.5	0.5
NAC Int.	DPC / Yankee-MPC	122.5	70.64	0.625
NAC Int.	CY-MPC, 24 Assy	151.75	70.64	0.625
NAC Int.	CY-MPC, 26 Assy	151.75	70.64	0.625
NAC Int.	Class 1	175.1	67.1	0.625
NAC Int.	Class 2	184.2	67.1	0.625
NAC Int.	Class 3	191.8	67.1	0.625
NAC Int.	Class 4	185.6	67.1	0.625

NAC Int.	Class 5	190.4	67.1	0.625
NAC Int.	Transportable Storage Container (PWR)	184.8	69.7	0.5
NAC Int.	Transportable Storage Container (BWR)	191.8	71	0.5
Transnuclear	NUHOMS 24PS	186.29	67.19	0.625
Transnuclear	NUHOMS 24PL	186.29	67.19	0.625
Transnuclear	NUHOMS 24PHBS	186.17	67.19	0.625
Transnuclear	NUHOMS 24BHBL	186.17	67.19	0.625
Transnuclear	NUHOMS 24PTH-S	186.55	67.19	0.5
Transnuclear	NUHOMS 24PTH-L	192.55	67.19	0.5
Transnuclear	NUHOMS 24PTH-LC	186.55	67.19	0.5
Transnuclear	NUHOMS 24PT2S	186.5	67.19	0.625
Transnuclear	NUHOMS 24PT2L	186.5	67.19	0.625
Transnuclear	NUHOMS 32PT-S100	186.5	67.19	0.5
Transnuclear	NUHOMS 32PT-S125	186.5	67.19	0.5
Transnuclear	NUHOMS 32PT-L100	192.55	67.19	0.5
Transnuclear	NUHOMS 32PT-L125	192.55	67.19	0.5
Transnuclear	NUHOMS 32PTH / PTH Type 1	193	69.75	0.5
Transnuclear	NUHOMS 32PTH1-S	185.75	69.75	0.5
Transnuclear	NUHOMS 32PTH1-M	193	69.75	0.5
Transnuclear	NUHOMS 32PTH1-L	198.5	69.75	0.5
Transnuclear	NUHOMS 32PTH2	198.5	69.75	0.625
Transnuclear	NUHOMS 37PTH-S	182	69.75	0.5
Transnuclear	NUHOMS 37PTH-M	189.25	69.75	0.5
Transnuclear	NUHOMS FO-DSC	186.2	67.19	0.625
Transnuclear	NUHOMS FC-DSC	186.2	67.19	0.625
Transnuclear	NUHOMS FF-DSC	186.2	67.19	0.625

Transnuclear	NUHOMS 24PT1	186.5	67.19	0.625
Transnuclear	NUHOMS 24PT4	196.3	67.2	0.53
Transnuclear	NUHOMS 52B	196	67.19	0.625
Transnuclear	NUHOMS 61BT	195.92	67.25	0.5
Transnuclear	NUHOMS 61BTH	196	67	0.5
Transnuclear	NUHOMS 69BTH	196	69.75	0.5
Transnuclear	NUHOMS 12T	163.5	67.2	0.625
Transnuclear	NUHOMS 07P	179	37	0.5

Table 2: Original 27 metrics

Attributes	**Metrics**
Time	Time needed to analyze the inside of canisters (IE precut measurements)
Time	Machine setup time & transition time between canisters
Time	Clean up time
Time	Cutting time
Cost	Number of people needed to complete the cut
Cost	Initial machine cost
Cost	Number of people for breakdown and setup
Cost	Cleanup Cost
Cost	Recurring cost/maintenance
Ease of Operation	Intricate/delicate settings necessary for personnel to know about
Ease of Operation	Compatible with current facility layout
Ease of Operation	Cut Tolerance & accuracy / thickness
Ease of Operation	Level of internal heat generated
Ease of Operation	Easily adjusted among varying canister designs
Safety	Dosage cost per person
Safety	Types of machine failure (Percent failure)

Safety	Number of times a person must interact with the machine during each cut
Safety	Debris clean up
Safety	Debris type
Safety	Amount of Debris
Safety	Remote operation capabilities
Safety	Sensitivity to error in measurements
Bonus	Does the process need lubricant to operate?
Bonus	Can the process be done underwater?
Bonus	Can the process be done through the welds on top of the lid?
Bonus	Multi-cut possibilities (underlid and through weld)
Bonus	Under the lids

Table 3: Final metrics used with evaluation comments

Attribute	Metrics	Comments
Time	Total Time	Time taken for the entire period including set up time and cut time.
Cost	Initial Equipment Cost	The cost of buying a machine from a contractor or developing the machine. Needs to be 60-90 in capable.
Cost	Reoccurring cost and Maintenance	This includes any cost of replacement blades/wires/parts that need to be fixed after the initial cost.
Debris	Clean Up	Complexity of clean-up. Will the debris allow for a simple/minimal clean up (melted solid material vacuum process, etc. vs requiring a special process like water filtration, air particulate filtration, etc.)
Debris	Volume of Waste	The estimated volume of debris to be cleaned up from the surrounding area after cutting process is complete is minimal. Do not include melted material/slag as debris.

Cost	Hot cell and Remote Operation	Feasibility of remote operation for cutting method (CNC or other) Is the technology already available * has a hot cell been designed before for the method, is it an industry-wide solution or does it need to be developed, what is that associated cost
Safety	Possibility of Failure	The possible machine failures do not include catastrophic results and/or a high percentage of machine tool failure during use cases similar to this task. (How does machine fail*how often the failure occurs)

Table 4: Final metrics ranked and normalized

Metrics	Rank	Normalized
Possibility of Failure	1	20.63%
Total Time	2	18.25%
Clean Up	3	17.86%
Volume of Waste	4	13.89%
Hot cell and Remote Operation	5	12.70%
Initial Equipment Cost	6	9.92%
Reoccurring cost and Maintenance	7	6.75%

Table 5: Non-Destructive evaluation data

Metric	Plasma	Clamshell	Diamond Wire	Laser	Water Jet
Total Time (hours)	3.3	1.5	2.5	1.15	2.25
Initial Equipment Cost	$8,000	$95,000	$175,000	$480,000	$220,000
Reoccurring Cost and Maintenance	$12	$40	$8,000	$12	$10
Clean up	Melted Material/Little Clean up requires air filter	Metal chips	Water and metal shavings	Almost none, possibly an air filter	Water

Volume of waste	Essentially none	As much as there moved area	Water used + amount of area removed	Essentially none	Water used
Hot Cell and Remote Operation	$100,000	Included	Included	Requires developing and exponentiall y increases price	Remote operation price is included but this method is not feasible in a hot cell
Possibility of Failure (Severity*Occurrence) (1-5 low-high)	Nozzle burn up if done improperly but very slim chance of damage (1*2)	Chip hang or blade failure but very low damage (1*1)	Wire explosion if not exchanged at appropriate timing. Catastrophic to surrounding areas (3*1)	Nozzle burn up if done improperly but very slim chance of damage (1*2)	Catastrophic damage when water jet cuts through canister and hits dry fuel (5*5)

Table 6: Non-destructive ranks and respective normalized percentages

Cutting Methods	Rank	Normalized
Plasma	1	37.73 %
Clamshell Lathe	2	32.13%
Laser Cutting	3	30.14%
Skiving	4	31.77%
Water Jet	5	19.86%

Table 7: Destructive evaluation data

Metrics	Plasma	Clamshell	Diamond Wire	Laser	Water Jet
Total Time (hours)	1.6	1.5	2.5	1.15	2.25
Initial Equipment Cost	$8,000	$95,000	$175,000	$480,000	$220,000

Reoccurring Cost and Maintenance	$12	$40	$8,000	$12	$10
Clean up	Melted Material/ Little Clean up requires air filter	Metal chips	Water and metal shavings	Almost none, possibly an air filter	Water
Volume of waste	Essentiall y none	As much as there moved area	Water used + amount of area removed	Essentially none	Water used
Hot Cell and Remote **Operation**	$100,000	Included	Included	Requires developing and exponentially increases price	Remote operation price is included but this method is not feasible in a hot cell
Possibility of Failure (Severity*Occur rence) (1-5 low-high)	Nozzle burn up if done improper ly but very slim chance of damage (1*2)	Chip hang or blade failure but very low damage (1*1)	Wire explosion if not exchanged at appropriate timing. Catastrophic to surrounding areas (3*1)	Nozzle burn up if done improperly but very slim chance of damage (1*2)	Catastrophi c damage when water jet cuts through canister and hits dry fuel (5*5)

Table 8: Destructive ranks and respective normalized percentages

Cutting Methods	**Rank**	**Normalized**
Plasma	1	50.81%
Clamshell	2	49.19%
Laser Cutting	3	46.17%
Water Jet	4	29.23%
Diamond Wire	5	25.06%

Table 9: Detailing A through C nuclear waste classification

Radionuclide	**Class A (Curies/m³)**	**Class B (Ci/m³)**	**Class C (Ci/m³)**
Total of all nuclides with less than 5-year half-life	700	No limit	No limit
Tritium (^{3}H)	40	No limit	No limit
Cobalt-60 (^{60}Co)	700	No limit	No limit
Nickel-63 (^{63}Ni)	3.5	70	700
Ni-63 in activated metal	35	700	7000
Strontium-90 (^{90}Sr)	0.04	150	7000
Cesium-137(^{137}Cs]]	1	44	4600
Carbon-14(^{14}C)	0.8		8
C-14 in activated metal	8		80
Nickel-59 (^{59}Ni) in activated metal	22		220
Niobium-94 (^{94}Nb) in activated metal	0.02		0.2
Technetium-99 (^{99}Tc)	0.3		3
Iodine-129 (^{129}I)	0.008		0.08
Alpha emitting transuranic nuclides with a half-life greater than 5 years	10 nCi/g		100 nCi/g
Plutonium-241 (^{241}Pu)	350 nCi/g		3500 nCi/g
Curium-242 (^{242}Cm)	2000 nCi/g		20000 nCi/g

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