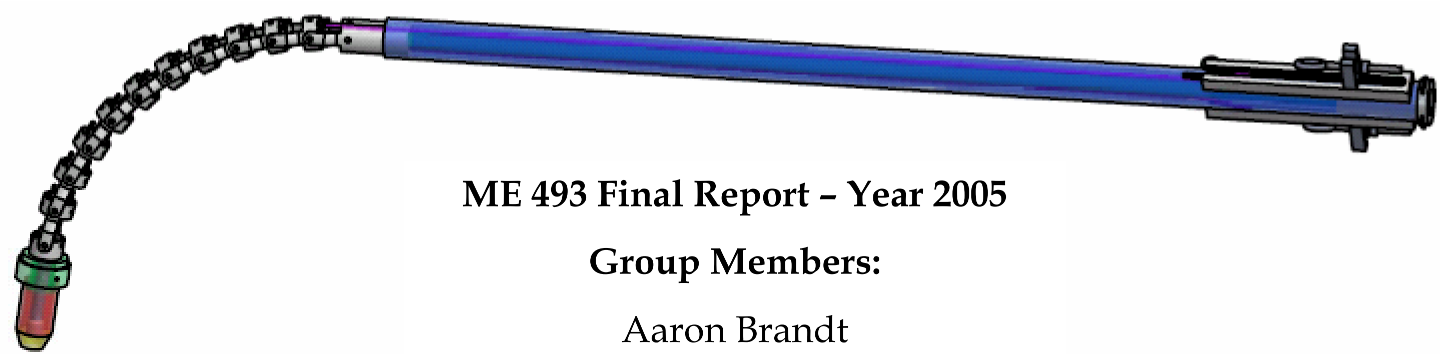
PORTLAND STATE UNIVERSITY

Maseeh College of Engineering and Computer Science

Mechanical Engineering Department



ME 493 Final Report – Year 2005

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1 · EXECUTIVE SUMMARY

Black liquor is a byproduct of the kraft paper pulping process; it is made up of chemicals, solids and water. A recovery boiler's main purpose is to provide heat in order to convert the chemicals in the black liquor back to reusable form. This is accomplished by spraying the black liquor through nozzles into the boiler. While the droplets are suspended, the water is evaporated, the solids are combusted, and the reusable chemicals fall to the bottom of the boiler where they are recovered. The excess heat from the process is used to create steam which is used for other processes or to produce power.

Mathematical models of the recovery boiler environment are utilized by the pulp and paper industry to increase the life of equipment, increase chemical recovery, and reduce atmospheric emissions. The most important factors in the model are the airflow and black liquor spray characteristics. Currently the spray characteristics in the model are developed analytically. The model's accuracy would be improved if the spray characteristics were developed from empirical data.

The project sponsor, Anthony Ross Company, would like an instrument that can provide data that accurately represents the spray characteristics. Anthony Ross Company currently provides infrared video cameras to kraft paper plants to image the inside of the boiler for maintenance purposes. This same camera combined with a proper optical system could be employed to provide high quality images of the black liquor spray for data collection purposes. By designing an optical assembly that can attach to Anthony Ross' infrared camera and provide clear images of the black liquor spray, accurate characterization would be possible.

The design team has developed an optical assembly that allows for adjustable viewing of the black liquor spray. The assembly can be used at first as an R&D tool to gather data. From the data, the current model could be improved and accurately reveal the effect of droplet size and spray pattern on chemical recovery efficiency. If significant improvements in efficiency can be made by using the system, the camera and optics assembly could become marketable.

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3 · INTRODUCTION & BACKGROUND INFORMATION

The kraft paper pulping process uses an aqueous solution of sodium hydroxide (NaOH) and sodium sulfide (Na_2S) to break down the binding agents in wood pulp. During the pulping process, most of the NaOH is consumed in the neutralization of wood acids, and some of the Na_2S is oxidized to sodium thiosulfate ($Na_2S_2O_3$). The spent pulping chemicals in combination with dissolved wood components and water make up what is referred to as the weak liquor byproduct of the pulping process. The weak liquor is fed into evaporators where most of the water is removed. The liquid is then referred to as black liquor.

Black liquor may contain as much as 85% solids. Most of the solids are carbon based and can be burned off. The recovery boiler is used for this purpose. Black liquor is sprayed through nozzles into the boiler. The water in the droplets evaporates quickly and combustion takes place. The generated heat from combustion is used to oxidize the inorganic sodium salts to reusable form and to create steam, which can be used to produce power. The reusable substance is referred to as smelt and falls out of the bottom of the boiler. If the droplets are too large as they enter the boiler, complete combustion will not occur and chemical recovery will be limited. If the droplets are too small, complete combustion takes place too early and the particles get entrained in the central airflow rather than falling out of the boiler; this can clog the exhaust system. Figure 1 illustrates the recovery process.

Anthony Ross Company produces mathematical models of the boiler environment. The models predict boiler behavior, which can assist in improving chemical recovery and reducing wear on the equipment. Two of the most important factors in the model are the airflow and black liquor spray characteristics. Anthony Ross would like to improve the model's accuracy through experimental determination of black liquor spray characteristics including droplet size and spray pattern.

To obtain these characteristics, high-speed infrared camera technology currently employed as a boiler inspection tool, will be modified to capture images of the black liquor spray. The current camera and lens system has limitations. The camera lens assembly is short and cannot extend into the boiler to meet the necessary distance. The lens assembly also does not have an adjustment for viewing angle, making it difficult to view the liquor spray from a limited number of access points.

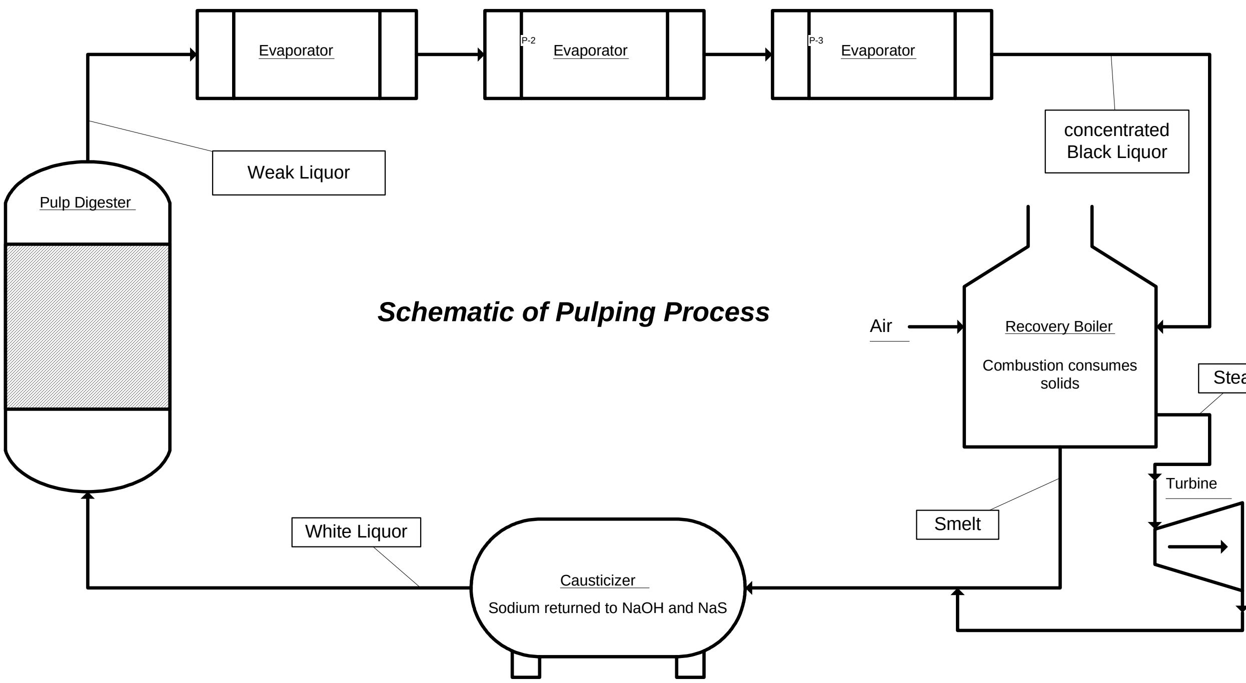


Figure 1: *Schematic representation of pulping and chemical recovery process*

4 · MISSION STATEMENT

Design an optical assembly that will attach to the infrared camera currently being distributed by Anthony Ross Company. The assembly will provide clear images of black liquor spray to the camera. Data gathered from the images will allow Anthony Ross' engineers to improve their mathematical model of the recovery boiler.

5 · PRODUCT DESIGN SPECIFICATIONS

Anthony Ross Company is the main customer for the optical assembly. The camera to be used is distributed by Anthony Ross Co. through a license agreement with Enertechnix. The design team has worked with Anthony Ross Co. to establish the following major design specifications:

A · The equipment will be safe to operate. It is possible that flame may escape the boiler through the air injection ports where the assembly will most likely be inserted. The operator must be protected from the escaping flame. The installation of the assembly onto the boiler must be simple and not require any actions that may pose a hazard to the operator.

B · The assembly must survive the boiler environment. The boiler can reach temperatures of 2,000°F and contains debris moving at high velocities. The assembly must withstand the environment for a minimum of 30 minutes without suffering damage or degradation to the image quality.

C · The viewing angle must be adjustable. The apparatus will have an adjustable viewing angle of 90º. This means that the assembly must be able to look straight ahead as well as down.

D · The camera must extend far enough into the boiler. Because of a recovery boiler's internal structure, the assembly must extend a minimum of 1 meter into the boiler to allow for multiple views of the spray.

E · The focal length and field of view must be adjustable. The versatility of the camera and assembly will be increased if the focal length and field of view are adjustable.

6 · TOP LEVEL DESIGN CONSIDERATIONS

The requirements listed above gave rise to conceptual solutions in four primary areas including optics, actuation, materials, and cooling. The requirement that the optics be able to look straight ahead as well as down created difficulties in designing optical components that could adapt to the actuation. The best solution found for this requirement was to use a fiber optic imaging bundle. The imaging bundle used is shown in Figure 2. Upon this decision, the rest of the assembly was designed accordingly.

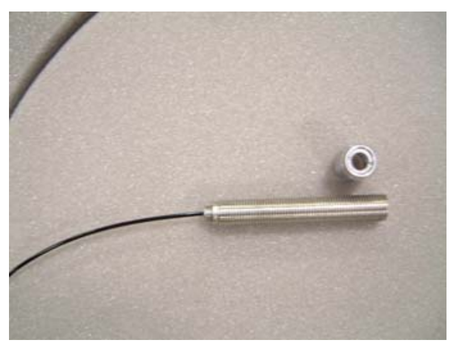


Figure 2: *Fiber optic imaging bundle*

For imaging, coherent bundles are necessary which maintain the order of the fibers (thousands) from one side to the other. The fibers in the bundle are often held in place with epoxy and housed in plastic sheathing which results in a relatively low maximum operating temperature. For this application, the fibers have to be held together mechanically and housed in high temperature sheathing. These types of fiber bundles are expensive and require that any sort of lens system be designed and attached to the bundle by qualified personnel for optimal performance. The components of a complete system include the optics at the tip of the bundle (distal end), the optics at the camera (proximal end), and the coherent bundle itself.

The assembly that houses the optical components must enter the boiler in the horizontal position and the distal optics actuated downward while inside. Two possible concepts were developed to accomplish this requirement. The design team researched existing actuation systems for endoscopes. A particular system is the shape memory alloy (SMA) actuator shown in figure 3-a. SMA actuators revert to a preheated shape when the material is heated to the proper temperature. The temperature range that SMA's operate within is too low for a boiler environment. However, the idea of achieving actuation by rotating multiple sections through a small angle inspired the bracket concept shown in Figure 3-b.

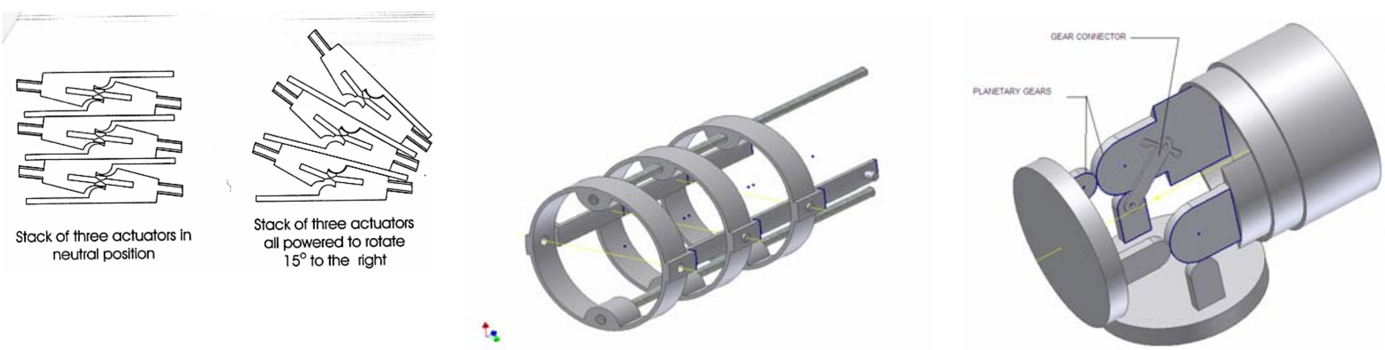


Figure 3: *Three conceptual methods of tip actuation*: *a) SMA actuator* [1] *b) bracket actuator c) planetary gear actuator*

The bracket design involves several pieces linked together that are allowed to rotate with respect to one another. The brackets would support a flexible sheathing for protection of the fiber bundle and to allow purge/cooling air to flow to the distal end. Cables run through the top and bottom of the brackets to allow actuation to be controlled from outside of the boiler. With this simple design, the bend radius can be increased or decreased by adding or removing brackets.

Figure 3-c shows a planetary gear based actuation concept. The figure shows the system in the horizontal and downward positions. The gear connector (shown in the downward position) would connect the two sections of the assembly which would be sheathed by a flexible material. The top arm of the gear connector would be attached to a cable that is tightened or loosened by the camera operator. The bottom arm of the bracket would be connected to a spring, which would be at its natural length in the

downward position. As the camera operator tightens a cable attached to the upper arm of the gear connecter, the end would move toward the horizontal position. The disk at the end (facing left) would have a hole big enough to allow the fiber bundle to pass through. This design is complex and would require high precision manufacturing. The bend radius would also be very small which would not adapt well to the fiber bundle or the sheathing.

The bracket concept was the most appealing option and the final design is shown in Figure 4. The design was simplified so it could be cut from standard tubing and connected together with rivets that are loose enough to allow rotation. The rotation is limited by the tabs at the end of the brackets in order to prevent binding.

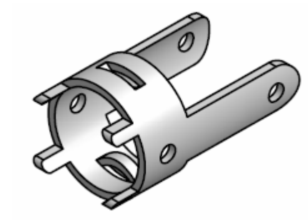


Figure 4: *Final design of actuation brackets*

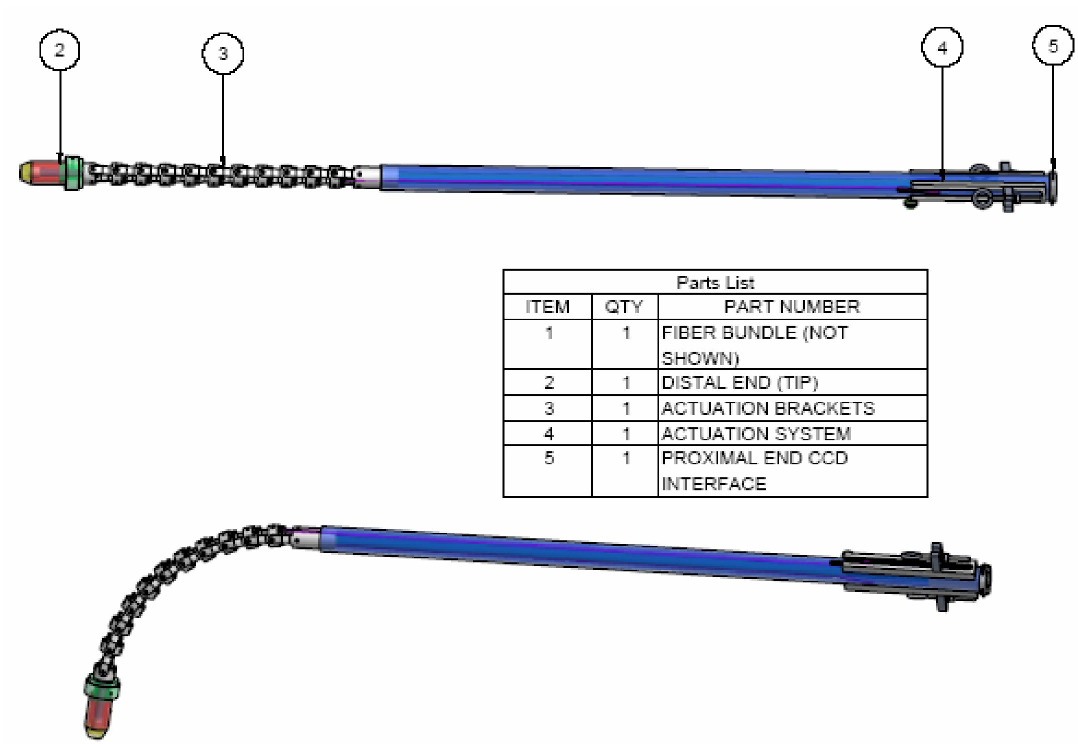
Material selection of the components was important due to the harsh boiler environment. The optical assembly is designed to enter through one of the boiler's tertiary air ports. The temperature range of the combustion air in this region is 260° F - 1000°F. The lens system currently being used for maintenance inspection is made of 304 stainless steel, which has proven to be effective. Other materials such as 316, 321 or Inconel stainless steel were looked at as possibilities, but the price and limited availability (especially for Inconel) was not justified.

Since all recovery boilers have compressed air systems, air is the best choice for cooling. Also, the cooling air will purge the tip and keep the optics free of debris. The plant systems can provide continuous compressed air at around 60 psi. A compressed air fitting can be threaded into the base of the assembly to attach to the compressed air system. A standard valve to turn off and on the airflow and an air filter to remove contaminants can be placed in line with the assembly attachment.

7 · FINAL DESIGN PRESENTATION

Overview

The optical assembly is designed to attach directly to the camera. A rigid tube extends from the camera into the boiler for approximately 4.5 ft, exceeding the1 meter requirement. A flexible portion then connects the rigid tube to the tip assembly which houses the distal optics. The flexible section can be actuated by the user in order to view different regions of the spray or the boiler. A NPT-threaded fitting in the rigid tube near the camera interface will allow connection to a compressed air system for cooling and purging the optical components. The majority of the assembly is designed to be made of 304 stainless steel, which performs well at high temperatures. The assembly can be split into five main sub-assemblies for ease of discussion. The separate sub-assemblies are indicated in Figure 5 except for the fiber bundle. They all will be explained in detail in the following sections.



Parts List		
ITEM	QTY	PART NUMBER
1	1	FIBER BUNDLE (NOT SHOWN)
2	1	DISTAL END (TIP)
3	1	ACTUATION BRACKETS
4	1	ACTUATION SYSTEM
5	1	PROXIMAL END CCD INTERFACE

Figure 5: *Complete design*

1 • Optical Fiber Imaging Bundle

The optical fiber bundle assembly is the key component that made meeting the actuation requirement possible. The original requirement was 90º of rotation. However, by using a fiber bundle it was easy to design the system for 90º of additional rotation. The final design allows for the distal optics to view up, down and any angle in-between (180º). This will enable users of the assembly to image different sections of the spray as well as other regions of the boiler.

The bundle assembly includes three main components: the distal optics, the fiber bundle, and the proximal optics. The distal optics gathers infrared light emitted from objects within the field of view and delivers it to the fiber bundle. The proximal optics then projects the light from the bundle onto the CCD of the camera. As explained earlier, a coherent fiber bundle is necessary for imaging so the light that enters the bundle at the distal end is at the same cross-sectional location at the proximal end.

The distal optics must withstand high temperatures since they will be approximately one meter within the boiler. This means that no epoxies can be used to hold the fibers or lenses in place. Epoxy is commonly used in less-expensive imaging bundles. By holding the fibers and lenses together mechanically rather than by epoxy, the operating temperature increases dramatically and can withstand 800ºF.

A 10 ft. image circle at a focal length of 15 ft. was desired as an initial configuration for the prototype. The maximum depth of focus (DOF) was also desired so clear images could be provided at distances other than the focal length. It was necessary that the distal optics be adjustable in the future in case more magnification or a smaller DOF is necessary to image the individual droplets. The magnification is increased by decreasing the image circle, thus projecting and enlarging a smaller image onto the CCD. The DOF is decreased by increasing the aperture size.

The non-standard configuration of the infrared camera used by Anthony Ross required the use of a custom proximal optics configuration. Most cameras use a standard system such a C-mount or CS-

Table 1: *Fiber Bundle Assembly Requirements*

Distal Optics	▪ 15 ft. focal length ▪ 10 ft. image circle at 10 ft. (37º angle of view) ▪ Depth of focus to be 0 ft. to 10 ft. ▪ Fibers and lenses mechanically fixed (for high temperature requirement) ▪ Ability to change in the future
Proximal Optics	▪ 19.5mm image circle (fills CCD) ▪ Focal length greater than 0.7 in.
Assembly	▪ Long enough so entire assembly is 80 in. from end to end ▪ High temperature ▪ Transmit short IR

mount which specifies the CCD size and distance from the camera face to the CCD. All of the requirements of the fiber bundle assembly are summarized in Table 1. Myriad Fiber Imaging Inc. was the only vendor found that could meet all of the requirements shown in the table. Because of the infrared requirement, special coated lenses must be used in the optical assemblies that allow for optimum infrared transmittance. For simplicity, both the proximal optics and distal optics are housed in a stainless steel barrel, threaded on the outside for the entire length. Figure 6 includes pictures of the distal optics barrel. The proximal barrel looks identical except that it has a slightly larger aperture.

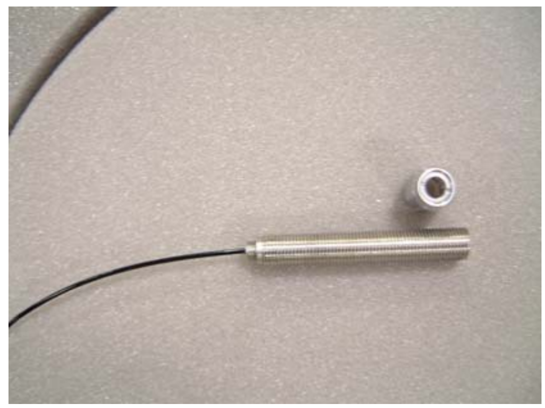


Figure 6: *Pictures of the distal optics barrel used in the prototype*

The number of fibers in a fiber bundle affects the digital image resolution. The resolution increases as the amount of fibers approaches the amount of photodiodes on the CCD that are exposed to light. Due to the high cost of fiber imaging bundles, a 30K fiber bundle was used for the prototype. Fiber bundles with up to 50K fibers are available [2]. A tradeoff between image size and resolution is present at the proximal end. For maximum image size, the image circle diameter must match the diagonal dimension of the CCD, thus overfilling it. Since there are fewer fibers in the bundle than there are photodiodes (77K) on the CCD, the light from one fiber is projected onto approximately two photodiodes. The resolution can therefore be improved by decreasing the size of the proximal image circle which sacrifices the image size. For the prototype, it was decided that the proximal image circle overfill the CCD. This can be adjusted later if necessary. Figure 7 indicates the proximal and distal optical configurations along with important dimensions.

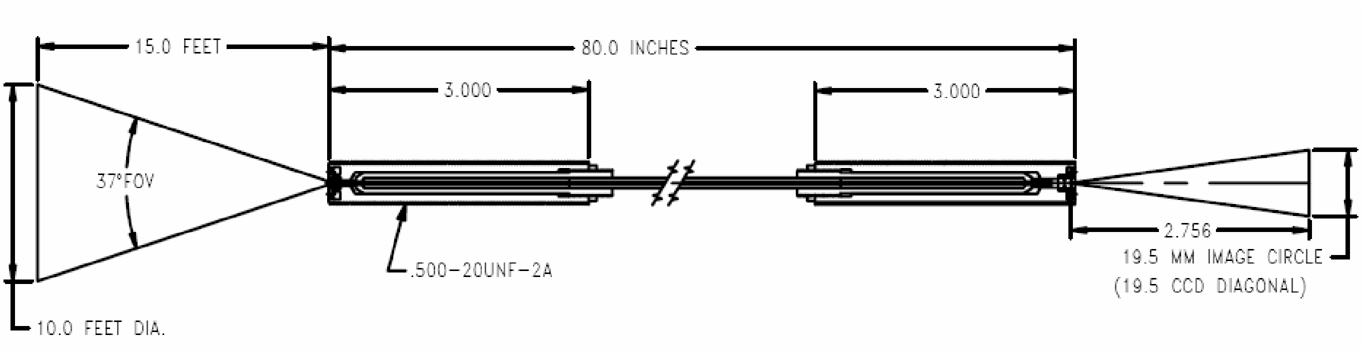


Figure 7: *Distal and proximal lens assemblies* [3]

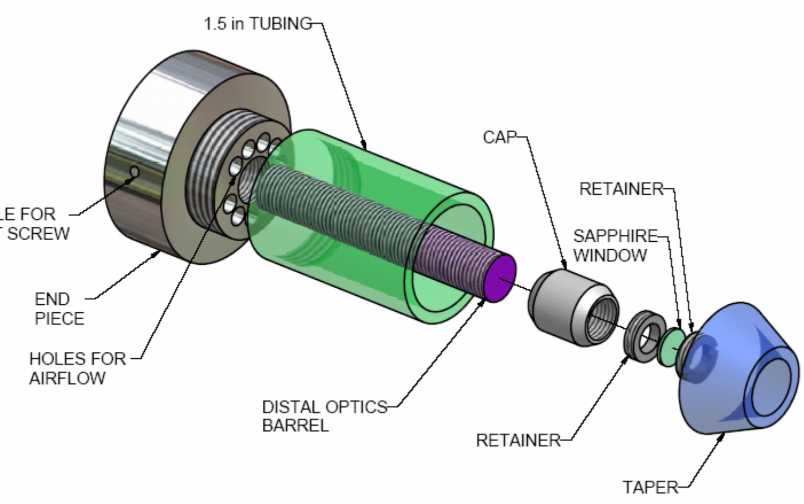
2 • Tip Assembly

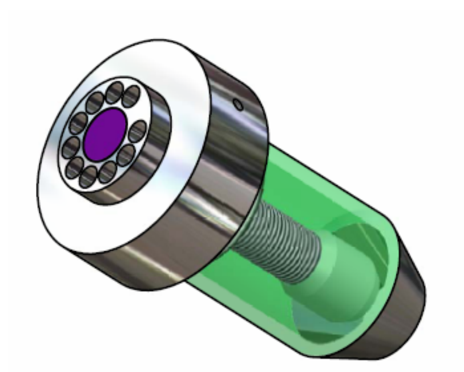
The tip assembly holds the distal optics barrel in place and protects it from the boiler environment. This piece extends further than any other component into the boiler and needs maximum protection. The end piece indicated in Figure 8 is threaded on the inside for attachment to the barrel. A set screw is used to hold the barrel in place so any vibration will not unthread it while in the boiler. There are holes all around the perimeter of this piece to allow the cooling/purge air to surround the barrel.

A cap was designed that threads onto the barrel and holds a sapphire window in front of the optics for protection from any debris that may overcome the purge air. Sapphire was used because of its durability, high operating temperature, and excellent infrared transmission. Contrary to common assumption, laboratory grade sapphire is rather inexpensive and is readily available. The sapphire window is held in place by two retainers that are threaded into the cap as shown in Figure 8. The retainer closest to the distal barrel also serves as a spacer between the optics and the window. This prevents debris on the window from being in focus on the image.

A taper was designed to be welded to a 1.5 in. piece of straight tubing and thread to the end piece. The purpose is to accelerate the cooling/purge air to maximize debris deflection and heat transfer. The opening diameter had to be large enough to prevent obstruction of the image but as small as possible to maximize the air velocity. The taper and straight tubing assembly was sized to accommodate a 45º angle of view (AOV). This AOV value was a conservative assumption to ensure there would be no image obstruction. Figure 9 illustrates how this assumed optical acceptance does not interfere with the taper. The actual AOV of the distal optics is 37º so there is some room for a wider angle optics configuration if desired later.

a)





b)

Figure 8: *Tip assembly: a) Exploded view b) Back view*

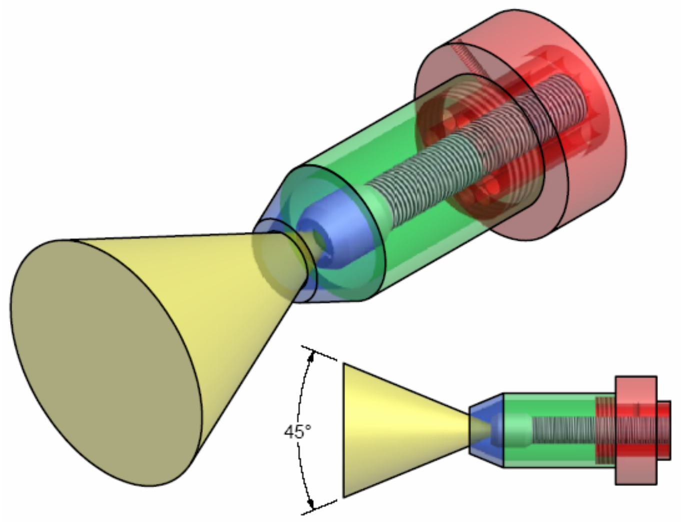


Figure 9: *Tip assembly showing the assumed 45° angle of view*

3 • Actuating Bracket Assembly

Three separate brackets were designed that make up the flexible portion of the assembly. All of them rotate about one another and are designed to be sheathed in a flexible, air-tight material. The distal bracket is designed to be welded to the end piece of the tip assembly while the proximal bracket is welded to the main tube. An assembly of eleven center brackets connects between the two end brackets, attaching the tip assembly to the main tube. The brackets are held together with loose pop rivets so they can rotate freely. Tabs were strategically placed to limit the amount of rotation in order to prevent binding. Figure 10 includes a model of each of the three brackets.

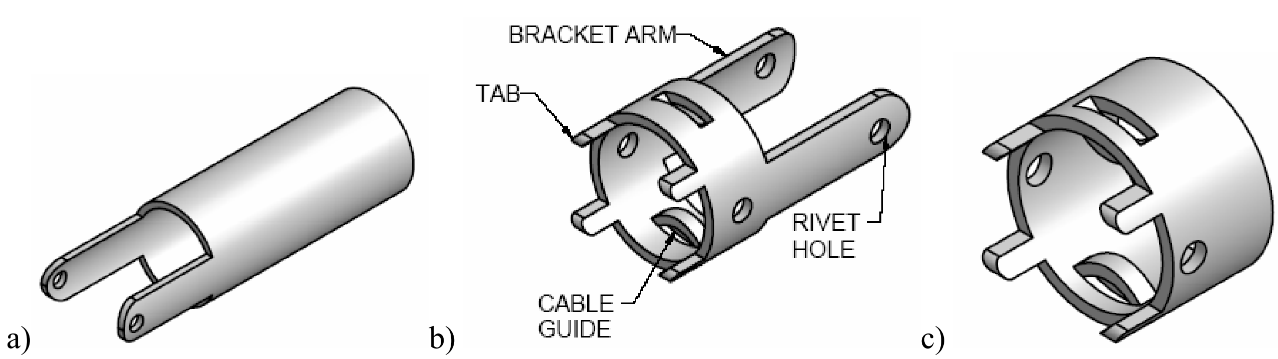


Figure 10: *Actuation Brackets: a) Proximal b) Center c) Distal*

Actuation is accomplished by passing a cable through cable guides formed into all of the center brackets and the distal bracket. The cable guides are shown in figure 10. By constraining a cable to the distal bracket's upper and lower cable guide, up and down actuation is accomplished by applying tension to the upper and lower cable respectively. This is illustrated in Figure 11.

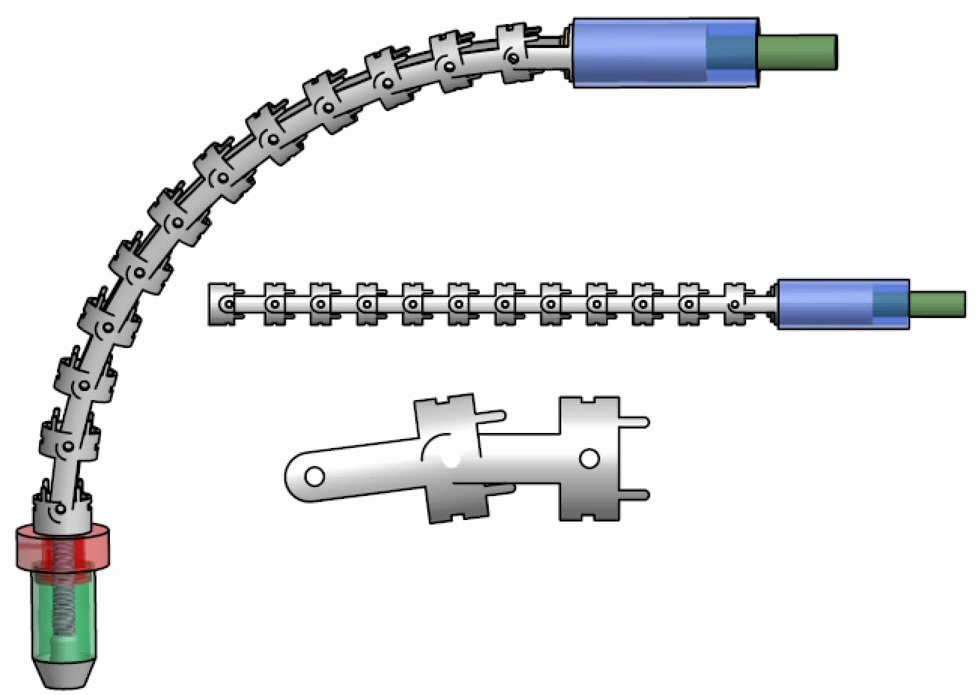


Figure 11: *Bracket assembly in the bent and straight positions*

The entire bracket assembly is sheathed with flexible braided stainless steel hose. The stainless steel hose is attached to the end piece with four tap screws. The other end is welded to a piece of tubing that tightly fits over the main tube (blue in Figure 11). The piece is held in place by four set screws. The stainless steel hose used for the prototype is shown in Figure 12.

Figure 12: *Stainless Steel Sheath Used for Prototype*

4 • Main Tube with Actuation Control

Tension is applied to the cables that actuate the brackets through two separate eye bolts on the top and bottom of the assembly. The cable is attached to the eye bolt and is run through stainless steel tubing that is welded to the proximal bracket. This is to ease the installation of the cables. The stainless steel tubing is bent to fit through slots that are cut in the main tube near the eye bolts. This is shown in Figure 13 (tubing is purple). Epoxy is used to seal the slot so no cooling air is leaked.

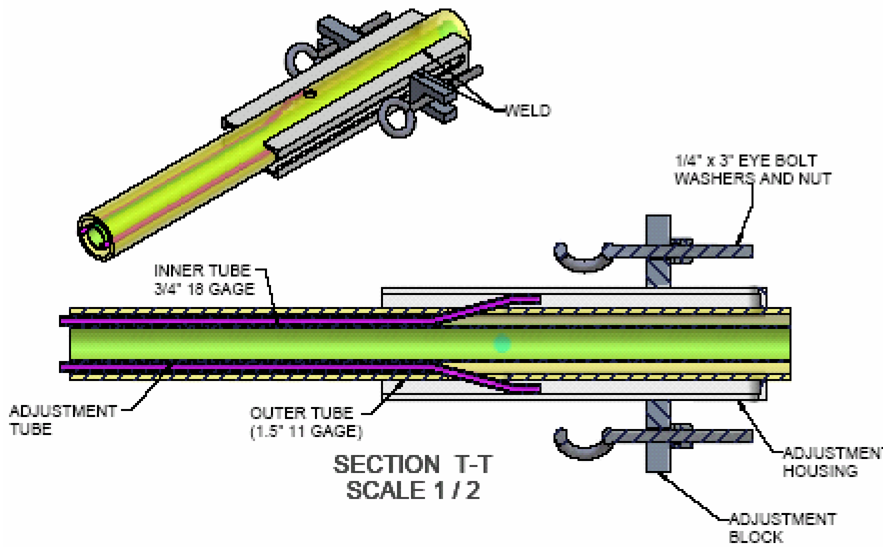


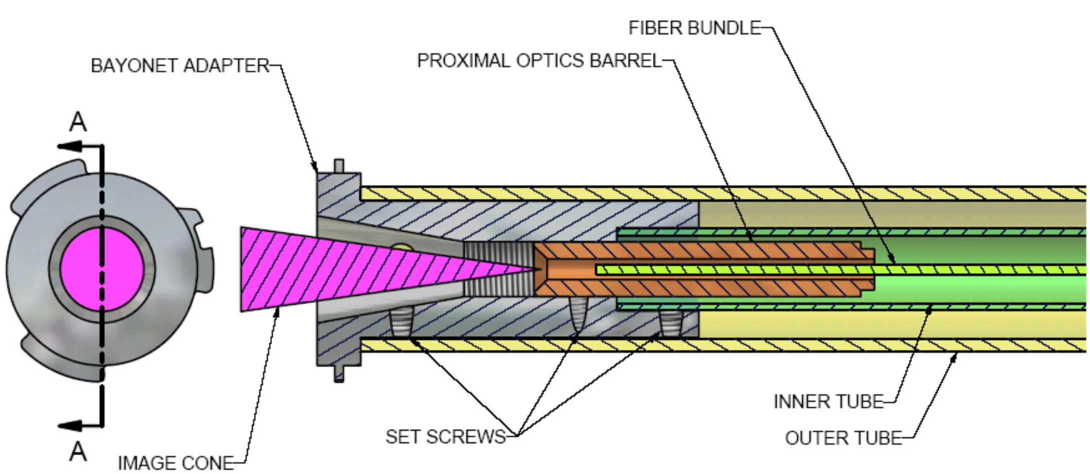
Figure 13: *Control assembly*

The eye bolts are held in place by slotted blocks. A nut is threaded over the eye bolt on the opposite side of the cable. By tightening the nut, the cable is tensioned and actuation of the brackets occurs. Tension should always be applied to both cables in order to prevent motion due to the strong air currents in the boiler

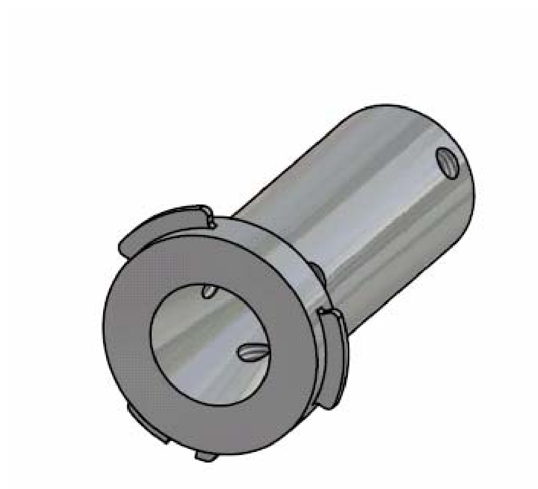
5 • Camera Interface

A bayonet adaptor was designed that attaches the assembly to the camera and houses the proximal optics barrel. The adaptor is designed so the barrel can be threaded to the appropriate location where the image is focused onto the CCD. It can then be locked in place by a set screw. It was ensured that the image being projected onto the CCD would not be obstructed in any way. This was accomplished by tapering the inside of the adapter. Figure 14 illustrates the image projection (pink cone) from the lens assembly. The dimensions of the cone were provided by the fiber bundle manufacturer upon the completion of their custom design.

The bayonet attachment is standard on all of the infrared cameras used and sold by Anthony Ross. The detailed design on the fitting was already done and integrated into the bayonet adaptor. The design allows for the fiber bundle to pass though an inner tube that supports the fiber bundle along the outer tube to the point where the actuation occurs. Figure 14 shows the complete assembly of all of the parts near the camera interface.



a)



b)

Figure 14: *Proximal end design a) Section view of the distal end b) Bayonet adaptor*

8 · EVALUATIONS

A prototype was built and the performance and ease of assembly was tested. The following sections go into detail on the testing and the results.

1 • Fiber Bundle

Both the proximal and distal adaptors are shown in Figure 15. During assembly it was found that the barrel has to be threaded into the adaptor before it gets inserted into the main tube. The barrels of the fiber bundle assembly fit precisely into both adaptors. The overall length of the assembly is one inch shorter than the fiber bundle. This worked as planned and the extra inch of fiber cable will prevent stressing the bundle when the tip is actuated.

Figure 15: *Fiber bundle adaptor at proximal end & distal end*

The first time the fiber bundle assembly was installed, the retainer on the distal optics barrel came off and several of the components fell out, including the lenses. Everything was recovered except for a spacer. The dimensions of the missing spacer were provided by the fiber bundle assembly manufacturer and it was machined at the Anthony Ross facility. The video quality was tested with a visible and infrared light camera and found to be acceptable. This was done the day before the due date of this report; no data or images were available to attach.

2 • Actuation system

The actuation system achieved 180° of actuation. Figure 16 shows the assembly with the stainless steel hose in place while "looking" down. The brackets actuate freely when the hose is not in place. When the hose is installed, a considerable amount of additional force was required to actuate the assembly. In an effort to decrease the actuation force, the cable was reinstalled on the outside of the brackets. The cable is secured to the end bracket at the tip and allowed to float between the brackets and the steel hose. The force needed to actuate the tip was reduced significantly by doing so. The eye bolts provide excellent control over the actuation angle, but it is slow, requiring 30 seconds to actuate 90°.

Figure 16: *Tip actuated 90*°.

3 • Air flow system

A standard NPT fitting was used to connect to a 50 psig compressed air system. The velocity of the air leaving the tip was sufficient in the straight as well as actuated positions to keep debris from entering. The airflow did not cause vibration issues in the tip when actuated 90°. Minor leaks were detected where the steel hose attaches to the main tube and at the actuation controls. The leaks at the controls where fixed with epoxy and the leak at the steel hose does not pose any problems.

4 • Environmental Testing

Environmental testing inside a boiler was not possible due to the optical issues with the fiber bundle assembly.

9 · FUTURE CONSIDERATIONS

Improvements could be made to the assembly in several areas. The actuation system could be improved if the cable was allowed to travel freely. To do so, the brackets need a smooth cable guide that will reduce friction. The flexible hose diameter could also be decreased; this would increase the flexibility of the hose and decrease the actuation force required. The bracket assembly would be easier to disassemble if the brackets were connected together with small bolts instead of rivets. If this was done, the tip could be threaded onto the barrel of the fiber bundle reducing both installation time and the risk of damage.

The fiber bundle diameter is very small, but the barrels are ½ in. The diameter of the barrels at the distal and proximal ends could be decreased. If the barrel diameters were decreased, the overall scale of the assembly could be decreased. The overall weight would be reduced, allowing for easier handling. Since the surface area would be reduced, less heat would be absorbed, reducing the cooling requirement.

10 · CONCLUSION

Prototyping the assembly has been very informative. The assembly has been partially tested and the overall design is sound. The assembly can be actuated 90° to look up or down, exceeding the actuation requirement. The force required to actuate the tip was greater than expected due to friction in the cable guides on the brackets, the problem was resolved by allowing the cable to float between the outside of the bracket and the steel hose. The actuation controls, although slow, allow precise angle adjustment of the tip. Airflow through the assembly was tested and found to be sufficient in blocking debris from entering the tip and providing supplemental cooling.

The optics at the distal and proximal ends of the fiber bundle can be changed in the future. At the proximal end, the optics can be changed to work with a different camera or to partially fill the CCD and provide better resolution. At the distal end, the magnification, depth of focus, and the field of view can be changed by replacing the lenses. This will have to be performed by the bundle manufacturer. The design is both versatile and durable. The imaging performance was acceptable. It could be improved with the use of a higher density bundle or by under-filling the CCD.

11 · REFERENCES

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12 · ACKNOWLEGMENTS

This project would not have been possible without the expertise and resources of Anthony Ross Company. A special thanks is given to Dan Higgins of Anthony Ross Company, for his dedication to moving the project forward. Thanks to Rich Hogle of Enertechnix, for the infrared camera support. Thanks to Jim McDonald of Myriad Fiber Inc. for the fiber bundle support. Thanks to Brent Benoit Machining for the part manufacturing on short notice.

13 · APPENDICES

APPENDIX A: Manufacturing Instructions

Overview

Drawings are shown below of the tip subassembly, the bracket subassembly, the end subassembly, and the full assembly. The full assembly describes the assembly of all of the three subassemblies. A list of manufactured parts is provided after each of the assembly drawings. The parts are referenced to an assembly and the material and method of manufacture is listed. For more detailed part information, refer to the drawings in Appendix G.

TIP ASSEMBLY

The tip is assembled according to Figure A-1. The 1.5 inch outer tube is threaded onto the end piece. The proximal bracket is then welded to the back side of the end piece, opposite the threaded end. The taper is welded to the 1.5 in. outer tube. Two retainers hold the sapphire window in place inside the cap piece. One retainer is threaded into the cap and the window is placed against the retainer while the second retainer is threaded into the cap locking the window in place. The fiber bundle is threaded through the end piece and the cap is threaded onto the distal optics barrel.

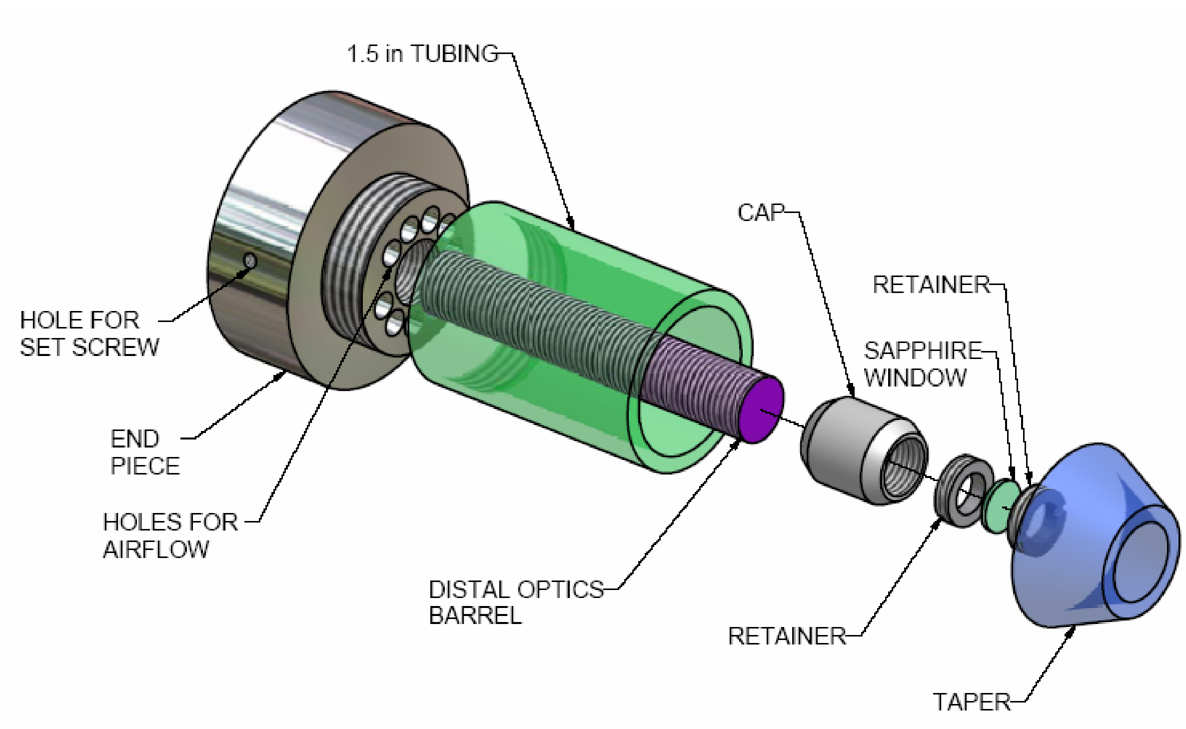


Figure A-1: *Tip Assembly*

ACTUATING BRACKET ASSEMBLY

The arms of the brackets need to be bent by approximately 15° to allow attachment to the next bracket. The proximal bracket is welded inside the 1 ½ in tubing as shown in Figure A-2. Use eleven center brackets riveted together to attach the proximal and distal brackets.

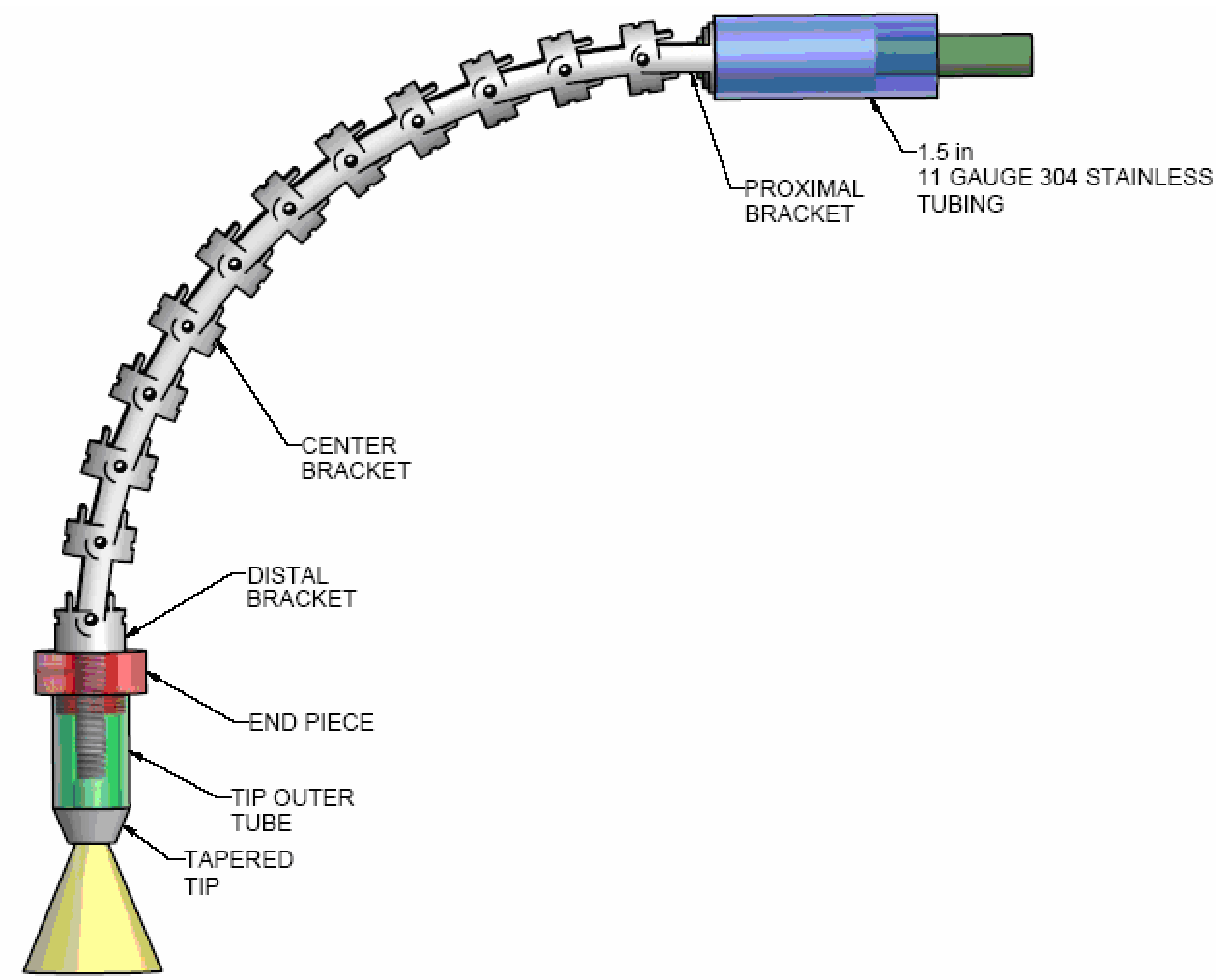


Figure A-2: *Actuating Bracket Assembly*

ADJUSTMENT ASSEMBLY

The adjustment housing is welded over the holes on the outer tube (see 1.5 in. outer tube drawing in appendix G). The adjustment blocks are welded onto the adjustment housing. The adjustment tube is bent at the proper angle and inserted into the 1 ½ in. tube. The adjustment tubes are spot welded at the adjustment housing end to hold them in place. The cables are fed though the adjustment tubes and swaged fittings are used to attach the cables to the eye bolts that sit in the adjustment block. The inner tube is inserted last and simply fits down inside the 1 ½ in. tube as shown.

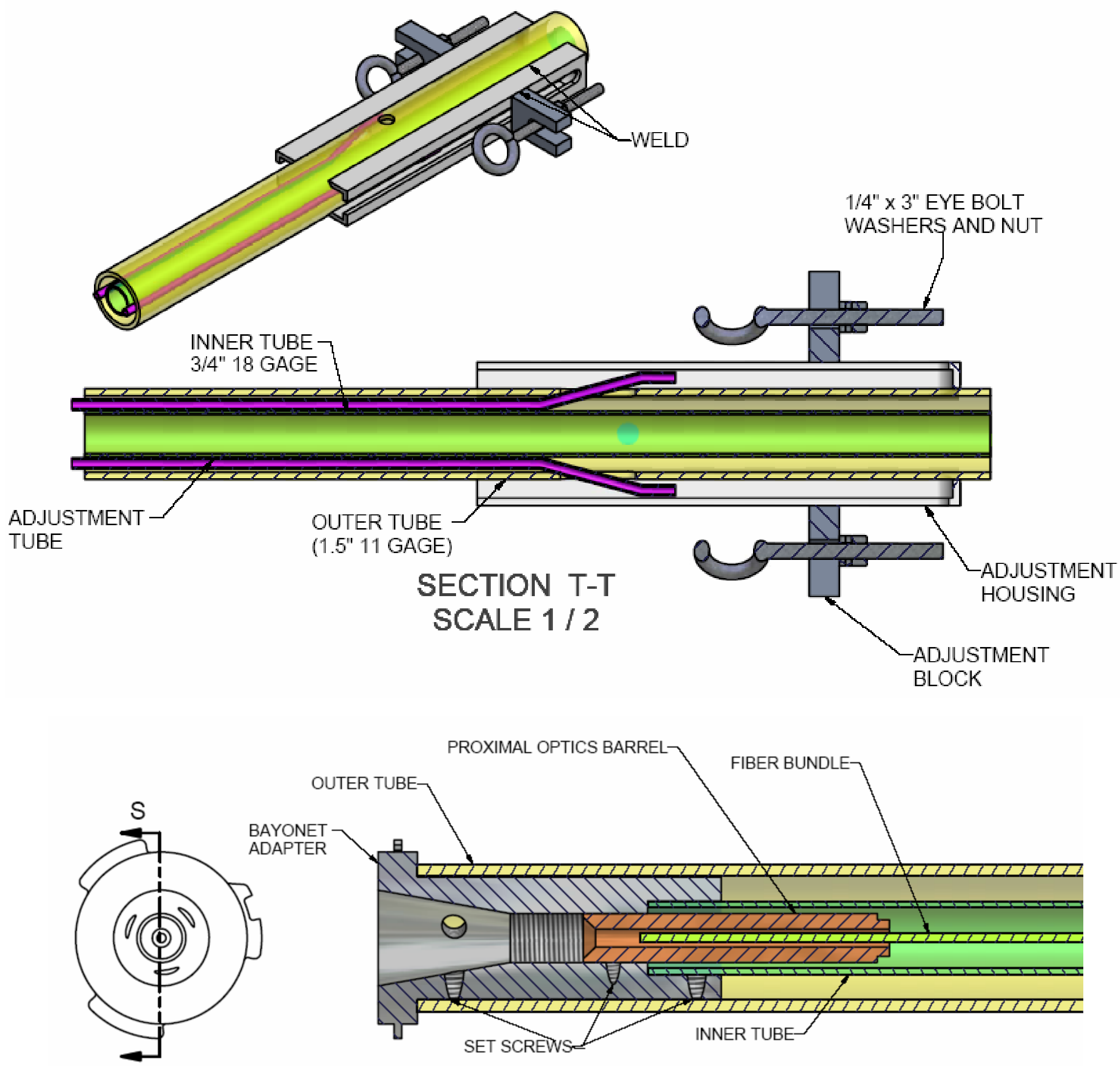


Figure A-3: *Adjustment Assembly*

COMPLETE ASSEMBLY

The full assembly drawing in Figure A-4 shows the locations of the subassemblies in reference to one another. The top figure is the complete assembly while the detailed views of the subassemblies are below. The braided steel hose is not shown in the assembly but it is important to note that the braided steel hose fits over the 1 ½ inch tubing prior to welding the proximal bracket in place.

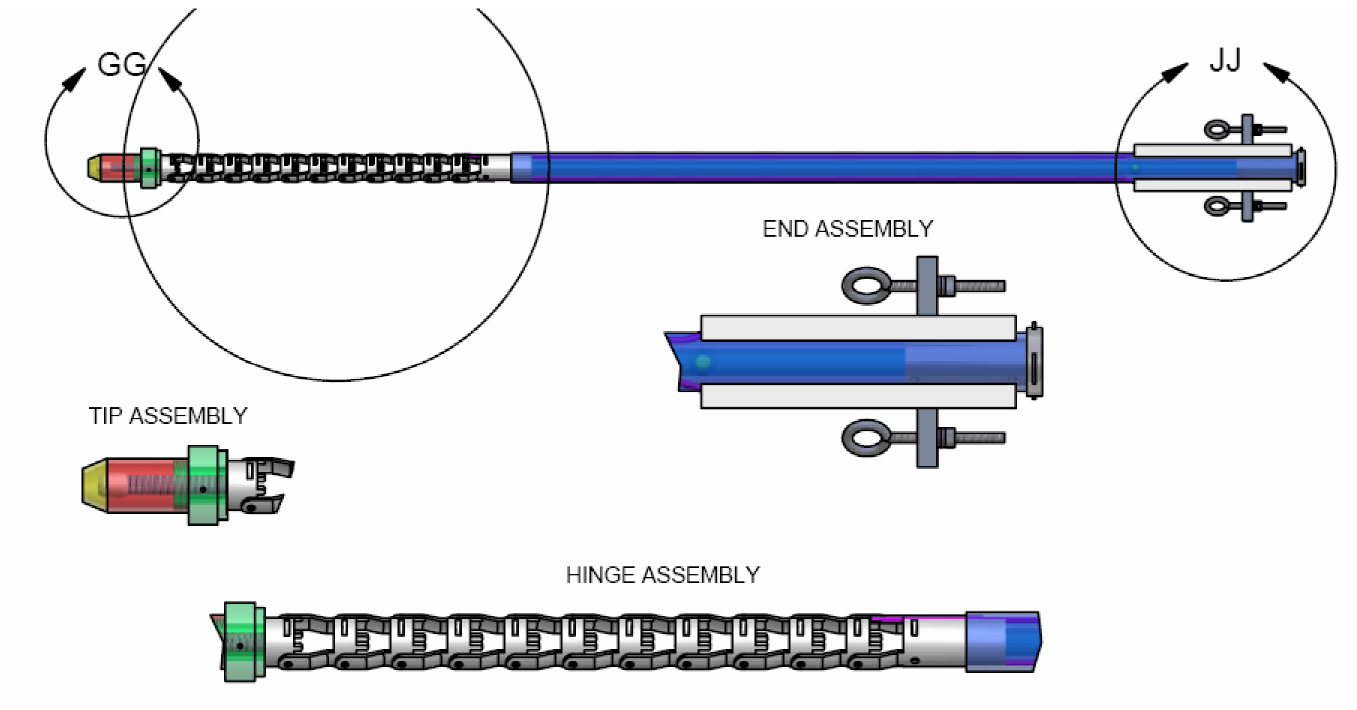
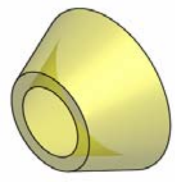
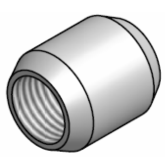
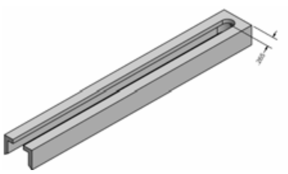
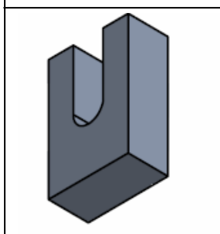
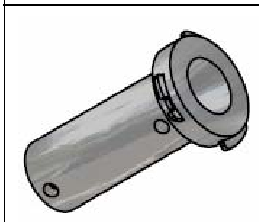
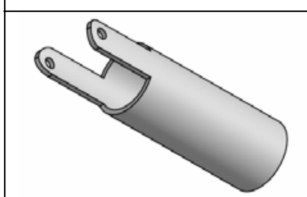


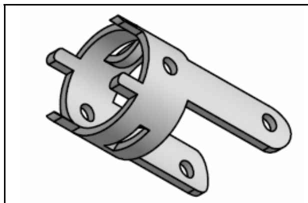
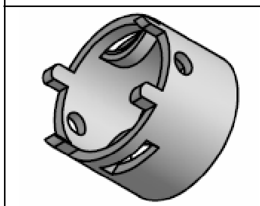
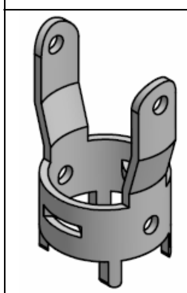
Figure A-4: *Complete Assembly*

Table A-1 shows the designed parts, how they are manufactured and the material they are made from. Standard off the shelf items such as tubing and bolts are not shown.

Table A-1: *Parts Description*

	***Tapered Tip*** – Machined from 304 stainless steel. **Location:** Tip assembly **Description:** This part is welded onto the tip outer tube shown next.
	***Tip Outer Tube*** – Manufactured from 1 ½ in, 11 gauge, 304 stainless tubing. **Location:** Tip assembly **Description:** This part is threaded onto the end piece.
	***Barrel Cap*** **–** Machined from 304 stainless steel. **Location:** Tip assembly **Description:** This part is threaded onto the distal barrel of the fiber bundle.
	***Retainer*** – Machined from 304 stainless steel **Location:** Tip assembly **Description:** This part holds the window in place inside the barrel cap.

	***End Piece*** **–** Machined from 304 stainless steel **Location:** Tip assembly **Description:** This part is threaded onto the tip outer tube and the distal end bracket is welded to the opposite side.
	***Adjustment Housing*** **–** Machined from 304 stainless steel **Location:** Tip adjustment **Description:** This part is welded to the main tube at the proximal end of the assembly.
	***Adjustment Block*** **–** Machined from 304 stainless steel **Location:** Tip adjustment **Description:** This part is welded to the adjustment housing.
	***Bayonet Adaptor*** **–** Machined from 304 stainless steel **Location:** Proximal end **Description:** This part is slip fitted into the main tube at the camera (proximal) end.
	***Proximal Bracket*** **–** Laser cut from 1.5 in, 11 gauge, 304 stainless steel tubing **Location:** Actuation Brackets. **Description:** This bracket fits into the main tube at the end opposite the camera.

	***Center Bracket*** – Laser cut from 1.5 in, 11 gauge, 304 stainless steel tubing **Location:** Actuation Brackets **Description:** This bracket is riveted to the proximal bracket and the next center bracket.
	***Distal Bracket*** – Laser cut from 1.5 in, 11 gauge, 304 stainless steel tubing **Location:** Actuation Brackets **Description:** The distal bracket is welded to the end piece and riveted to the last center bracket.
	***Bracket Arm Bending*** – Laser cut from 1.5 in, 11 gauge, 304 stainless steel tubing **Location:** Actuation Brackets **Description:** The center and distal bracket arms get 2 bends at 25°.
	***Bracket Bending Tool*** – Machined from steel. **Description:** The bracket is slid over the left hand side of the tool. The slits for the cable guide is aligned with the top portion and bent into place with a hammer and chisel. The bracket is then rotated and slid off the tool.

APPENDIX B: *Bill of Materials*

BILL OF MATERIALS

Category: Tubing

Item	*Gage*	*Length*
1.5 inch tubing	11	5 ft
1.25 inch tubing	11	3 ft
0.75 inch tubing	21	5 ft
3/16 inch tubing	22	4 ft

Category: Hardware

Item	*Description*	*Quantity*
Rivets	3/32 in aluminum	1 box
Cable	7 x 19 strand class, 3/32 in	10 ft
Tap screws		3
set screws		5
eye bolts	1/4 in x 4 in long	2
JB Weld	fix air leaks	2
Braided steel hose	2 in ID, 5 in OD, 24 in long	1
NPT fitting		1
Air Hose		20 ft

Category: Custom Parts

Item	*Description*	*Quantity*
Fiber Bundle	80" long, 30k fibers, 37 deg FOV,	1
Bayonet adaptor	machined to specs	1
Tip cone	very tip of assem.	1
Threaded tip connector	machined to specs	1
First Bracket	first bracket in actuation assem.	1
Center Brackets	brackets in between first and end	11
End Bracket	last bracket	1
Actuation guide	mount for eyebolts	2

APPENDIX C: *Operations Manual*

Safety:

- Proper clothing should be worn that covers the legs and arms.
- Do not touch the assembly as it comes out of the boiler; it will be hot.
- Two people are required to operate the camera and assembly.
- Always follow safety rules set forth by the boiler facilities management.

Operation:

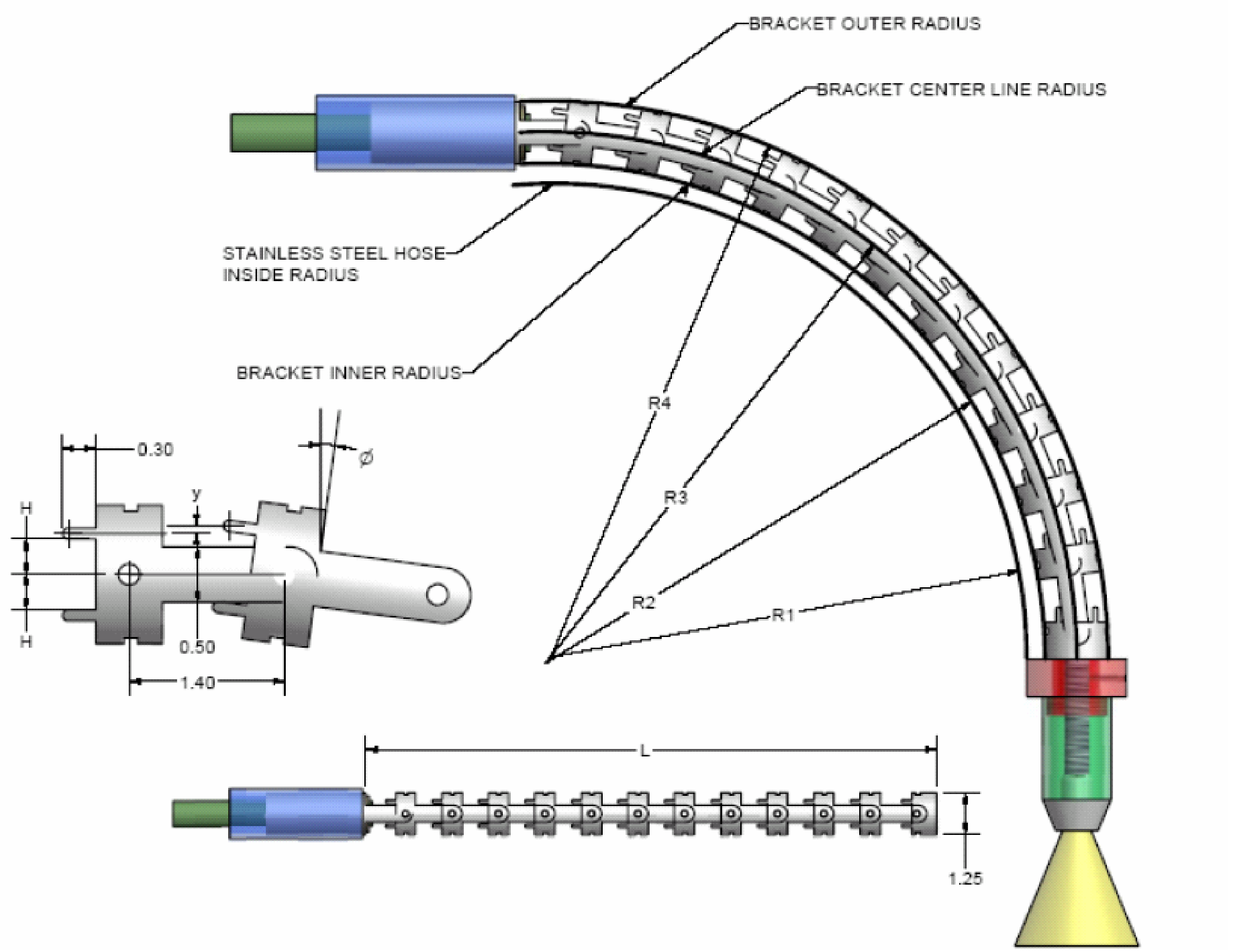
- Connect air hose to the assembly.
- Ensure that air is flowing through the assembly.
- Straighten the assembly to enter the boiler.
  - Using the ratcheting wrench, loosen or tighten the eye bolts until the tip is parallel with the rest of the assembly
- Insert the assembly into the boiler though the tertiary air port.
- To look down, tighten the bottom eyebolt and then loosen the top eye bolt until assembly is at desired angle.
- To look up, do the opposite.
- A thermocouple is installed near the fiber bundle at the tip. Remove assembly when temperature reaches 500°F to prevent damage to the fiber bundle.
- After capturing desired footage, straighten lens assembly back to parallel and remove from the boiler. Be sure not to touch the lens assembly as it will be extremely hot.
- Allow lens system to cool (could take an hour or more).
- Remove the fiber bundle and store in safe place.
- Clean the assembly using solvents where necessary.

APPENDIX D: *Calculations*

Bracket Analysis

PURPOSE:
This worksheet is used to calculate the number of brackets, the angle of actuation of each bracket, the overall length of the brackets in the assembly, and the distance from the centerline of the arm to the tab.

SCHEMATIC: Three drawings are shown below. One drawing shows the bend radii of the brackets and the braided steel hose. The second drawing shows the angle that the brackets rotate through when being actuated and the placement of the tabs relative to the centerline of the bracket arm. The third drawing is the length of the bracket assembly. A fixed number of brackets are shown, but any number of brackets could be included to change the angle of actuation or the length or the bend radius. The smallest bend radius is the limiting radius.



REQUIRED: Input: minimum bend radius.

FIND: Output: Number of brackets, overall length of brackets, angle of actuation per bracket, the bend radii R1-R4 and the distance H shown in the figure above.

CONSTANTS:

outer diameter of the bracket	$d := 1.25\text{in}$
thickness of the bracket arm	$a := 0.50\text{in}$
length of the tabs on the brackets	$t := 0.30\text{in}$
distance from hole to hole as shown above	$c := 1.40\text{in}$
angle of actuation	$\theta := \frac{\pi}{2}\text{rad}$
outer diameter of steel hose	$D := 5\text{in}$

INPUTS:

Minimum bend radius of steel hose $R_1 := 11\text{in}$

CALCULATIONS:

The minimum bend radius is related to the minimum overall length by

$L_{min} := \theta \cdot R_1$ $\quad L_{min} = 17.3\ \text{in}$

Minimum number of brackets required to achieve minimum length.

$B_{min} := \frac{L_{min}}{c}$ $\quad B_{min} = 12$

The angle of actuation of each bracket is

$\phi := \frac{\theta}{B_{min}}$ $\quad \phi = 7.3\ \text{deg}$

The bend radii R2-R4 are calculated as follows.

$R_3 := B_{min} \cdot c + \frac{D}{2} + \frac{d}{2}$ $\quad R_3 = 20.4\ \text{in}$

$R_2 := R_3 - \frac{d}{2}$ $\quad R_2 = 19.8\ \text{in}$

$R_4 := R_3 + \frac{d}{2}$ $\quad R_4 = 21\ \text{in}$

The distance H as shown in the figure above gives the location of the tabs in relation to the center line of the bracket arms.

$y := t \cdot \cos(\phi)$ $\qquad y = 0.298 \text{ in}$

$H := a + y$ $\qquad H = 0.8 \text{ in}$

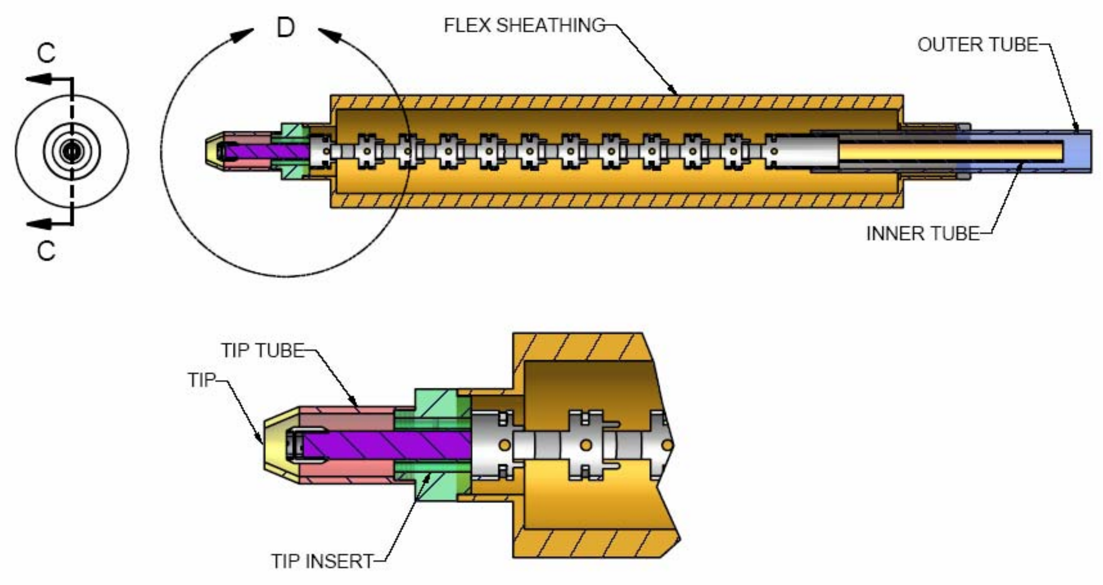
Air Flow Analysis

PURPOSE:

This worksheet is used to evaluate the air flow available at the tip, determine flow resistance characteristics and determine the cooling effects on the fiber optic assembly.

SCHEMATIC:

The drawings below show relationships of the parts and locations of the resistance calculations in the system.



REQUIRED:

Total system resistance to air flow and corresponding mass flow rates in the system with provided pressure range

FIND:

Individual air flow resistance of each component, maximum cooling rate possible, Reynolds number for flow, maximum flow rate possible through system.

CONSTANTS:

Airflow Available:	35CFM to 50 CFM
Inlet Air Temperature:	100ºF
Maximum outlet air temperature:	500 ºF
Cp Air (@ 370 ºF Ave. Temp.):	0.243 BTU/Lbm*ºR
ρair (@ 370 ºF Ave. Temp.):	0.051 Lbm/Ft^3

ASSUMPTIONS:

1. No air is lost through the adjustment tubes or fiber-optic interface.
2. Air introduced into the system is at 100 ºF with low relative humidity
3. Low velocity airflow modeling techniques are valid (relatively accurate) at extreme velocities.

CALCULATIONS:

The following calculations are based on airflow methodology and the work of Professor Gordon Ellison in relation to heat transfer and electronics cooling. To determine the heat transfer and dissipation characteristics of the system mass flowrate for the air must be calculated for the initial estimation purposes.

Mass flowrate = available airflow * density of the air mass* unit correction factor

Mass flowrate = (35CFM to 50 CFM) * (0.051 Lbm/Ft^3) * (1 min./60 sec.)

Mass flowrate =0.0298 to 0.0425 Lbm/s

Maximum heat transfer capability of the air in the system with all other properties constant is:

Q = mass flowrate * Cp air * Temperature change of the air

Q = (0.0298 to 0.0425 Lbm/s) * (0.243 BTU/Lbm*ºR) * (500 ºF- 100ºF)

Q = 2.897 to 4.131 BTU/s = 3056 to 4358 Watts

This is a generalized over estimation of the thermal dissipation properties of the system. The following calculations will refine the values above to closer model air resistance, flow and heat transfer characteristics within the system. First approximation of the velocity in the pipe can be calculated using the Bernoulli equation. Relating pressure drop and velocity in the system:

$\Delta P = (V_2^2 - V_1^2)\rho/(2G_c)$

$V=[(\Delta P*2*G_c)/ \rho]^{1/2}$

$V = [(50\ psi*2*32.2ft/s^2*144si/sf)/0.053Lbm/ft^3]^{1/2}$

V = 2958 ft/s

This allows us to calculate the Reynolds number for the airflow in the system:

$Re = \rho VD/\mu$

$Re = (0.053lbm/ft^3)(2958ft/s)(0.081\ ft)/(5.24e\text{-}7lb*s/ft^2)$

$Re = 2.4 \times 10^7$

Flow is high in the turbulent range and will cause a significant amount of noise in the system. This noise will be eclipsed by the surrounding noise of the boiler.

Using a relative roughness of 0.0015 for commercial steel pipe, the friction factor can be found to be approximately 0.0125. Calculating the flow area of the tube assembly is the first step in further evaluation of the system.

Flow area of the outer tube = 1.2469 in^2
Outer area of adjustment tube = 0.028 in^2
Outer area of inner tube = 0.442 in^2
Flow area = (1.2469 in^2)-2*(0.028 in^2)-(0.442 in^2)
Flow area (tube section) = 0.7489 in^2 = 0.0052 ft^2
Flow area of hinged section = $0.75*\pi(2.5in)^2/(4)$ = 3.68 in^2 = 0.0256 ft^2
Flow area of tip insert = $10*\pi(13/64)^2/4$ = 0.324 in^2 = 0.00225 ft^2
Flow area of tip tube = $\pi(1.125^2/4-0.500^2/4)$ = 0.798 in^2 =0.0055ft^2
Flow area of tip = $\pi(0.6)^2/4$ = 0.283 in^2 = 0.00196 ft^2
Flow area of inlet air stream = $\pi(3/8)^2/4$ = 0.295in^2 = 0.000767 ft^2

By adapting the air-stream resistances of the housing in the manner used by Professor Ellison a better estimation of flow through the system can be obtained. R is a resistance to airflow in inches H_2O/CFM^2. The units are unique in their purpose but valid in this context. Air flow resistance in a single stream can be added in series to combine for a total airflow resistance in the system. The following resistance formulas will be used to calculate the air-stream velocity and flow in the system:

Expansion Resistance:

$$R = 1.29*10^{-3}[1/A_1(1-A_1/A_2)]^2$$

where A_1 is the smaller Area and A_2 is the larger.

Sharp Turn Resistance:

$$R = 1.81*10^{-3}/A^2$$

Contraction Resistance:

$R = 0.5*10^{-3}[1-(A_2/A_1)]^{3/4}$

Linear Resistance:

$R = 5.18nL*10^{-4}/A^2$

Where A_2 is the smaller area and A_1 is the larger.

These formulas were adapted from <u>Electronics Cooling</u> By Gordon Ellison ©2005 (Electronic Version) on pages 62-65.

All areas are in inches^2 to keep dimensional constants correct.

$R_{hose\ inlet} = R_{exp} + R_{turn}$

$R_{hose\ inlet} = 1.29*10^{-3}[1/A_1(1-A_1/A_2)]^2 + 1.81*10^{-3}/A^2$

$A_1 = 0.295\ in^2$

$A = A_2 = 0.7489\ in^2$

$R_{hose\ inlet} = 0.00867$ inches H_2O/CFM^2

Linear hose resistance:

$R_{hose} = 5.18nL*10^{-4}/A^2$

Where:

$n = 1$

L = hose length = 50”

$A = 0.7489\ in^2$

$R_{hose} = 0.0462$ inches H_2O/CFM^2

Hinged tube resistance:

$R_{tube} = 5.18nL*10^{4}/A^2$

Where:

$n = 1$

$L = 17”$

$A = 3.68\ in^2$

$R_{tube} = 0.00564$ inches H_2O/CFM^2

The resistance found within the tip assembly can be calculated in one block.

$R_{tip} = R_{cont} + R_{tube} + R_{exp} + R_{tube} + R_{cont}$

$R_{tip} = 0.5*10^{-3}[1-(A_{21}/A_{11})]^{3/4} + 5.18nL*10^{-4}/A^2 + 1.29*10^{-3}[1/A_{13}(1-A_{13}/A_{23})]^2$

$+5.18nL*10^{-4}/A^2+0.5*10^{-3}[1-(A_{25}/A_{15})]^{3/4}$

Where:

$A_{21} = 0.324\ in^2$

$A_{11} = 3.68\ in^2$

$A = 3.68\ in^2$

$n=1$

$L = 0.75$ in

$A_{13} = 3.68\ in^2$

$A_{23} = 0.798\ in^2$

$A = 0.798\ in^2$

$n = 1$

$L = 1.688$ in

$A_{15} = 0.798\ in^2$

$A_{25} = 0.283\ in^2$

$R_{tip} = (0.000467 +0.0000287+0.00124+0.00137+0.00036)$ inches H_2O/CFM^2

$R_{tip} = 0.00347$ inches H_2O/CFM^2

The total resistance in the system can now be calculated:

$\Sigma R = R_{hose\ inlet} + R_{hose} + R_{tube} + R_{tip}$

$\Sigma R = (0.00867 + 0.0462 +0.00564 + 0.00347)$ inches H_2O/CFM^2

$\Sigma R = 0.06398$ inches H_2O/CFM^2

The resistance can now be related to the flow and pressure difference by:

$P_{sys} = \Sigma R * G_{sys}^2$

The pressure difference range is 35 to 50 psi. The units used for the equation above are inches H_2O. The pressures used will be 967 to 1382 inH_2O
The system flow will be:

$G_{sys} = (\Sigma R / P_{sys})^{1/2}$

G_{sys} = 122 to 147 CFM

These flow rates are above the available; the system flow is not currently limited by the pressure in the tube system.

RESULTS:

Final flow approximations:

Mass flow rate = 0.0298 to 0.0425 Lbm/s

Re = 2.4×10^7

$\Sigma R = 0.06398$ inches H_2O/CFM^2

G_{sys} = 122 to 147 CFM

Q = 2.897 to 4.131 BTU/s = 3056 to 4358 Watts

Maximum Velocity of 2958 ft/s

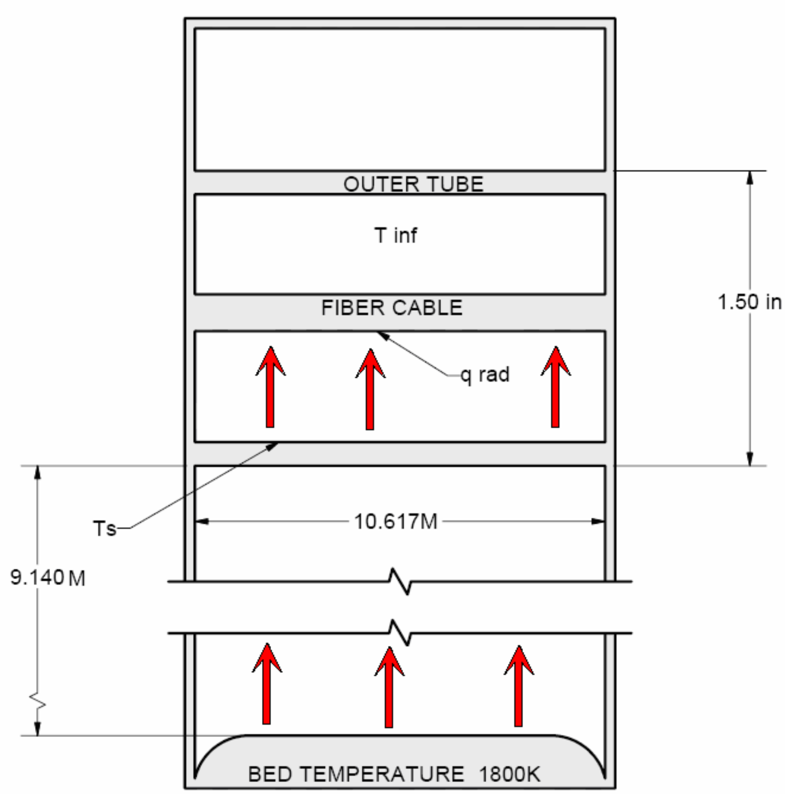
Given a pressure difference of 35 to 50 psi.

The preceding analysis shows that the system is not currently limited by the flow and will therefore perform at the optimum levels. The maximum values shown above are theoretical in nature and do not take into account variances in the input or output conditions. This steady state analysis also does not consider the effects of changing densities due to temperature in the system. These factors are considered negligible for this exercise.

Heat Transfer Analysis

PURPOSE:
This worksheet is used to calculate the heat transfer from the boiler to the surface of the fiber optics and verify that the assembly can remain in the boiler for approximately thirty minutes

SCHEMATIC:
The drawing below shows the bed of the boiler as being a body radiating heat onto our assembly. Also within the assembly the outer tube in radiating heat towards the fiber optic cable. There is air flowing into the tube to keep the fiber optic cable cool.



CONSTANTS:

$T_{bed} = 1800K$

$T_{inf,\ air} = 900K$

$h = 25 \frac{W}{m^2 * K}$

$\sigma = 5.67 * 10^{-8}$

$\varepsilon_T = .23$

$\varepsilon_o = .23$

Emissivity of solid stainless steel

$H = 9.144m$

$L = .6096m$

$w = 10.617m$

$C_{p,\ bundle} = 750 \frac{KJ}{Kg * K}$

$r_{outer} = .0381m$

$r_{inner} = .036m$

ASSUMPTIONS:

1. No losses in system.
2. The fiber bundle is located in the center of the housing.
3. After rising to 898K the surface temperature of the housing is constant.
4. The environment inside boiler is static. (No temperature fluctuation.)
5. Cooling airflow is at a constant temperature and pressure.

REQUIRED:

Determine the time that the fiber optic cable can be in the boiler before its temperature reaches 644 K.

CALCULATIONS:

First step of this solution is to determine the surface temperature of the outer tubing of the assembly by looking at the radiation from the bed.

$$q_{rad} = \varepsilon_T \sigma T^4 = 136850 \ \frac{W}{m^2}$$

By multiplying this by the area of the bed, the total power emitted by the bed can be found.

$$Q_{rad} = 136850 * \pi * \frac{1}{2} w^2 = 12115KW$$

By multiplying this power by 30 minutes we get the energy transmitted to the assembly.

$$12115KW * 1800\sec = 21.8GJ$$

To determine the percentage of power transmitted to the assembly, the difference in the volume of the boiler and the volume of the projected hemisphere from the bed is calculated.

$$V_{sphere} = \frac{4}{3} * \pi * 9.144^3 = 3202m^3 \qquad V_{boiler} = \pi * 5.3085^2 * 9.144 = 809.5m^3$$

$$\frac{V_{boiler}}{V_{sphere}} = .253 \qquad 21.8 * .253 = 5.5GJ$$

This is the amount of energy emitted in to the boiler. Compare the amount of energy in the boiler to the amount of energy absorbed by our assembly by comparing the projected area of the bed vs. the projected area of the assembly.

$$Ap_{assembly} = .0508 * .6096 = .031m^2 \qquad Ap_{bed} = \pi * 5.0385^2 = 79.75m^2$$

$$\frac{Ap_{assembly}}{AP_{bed}} = .00039 \qquad 5.5GJ * .00039 = 2.15MJ$$

By dividing this energy by the specific heat and the mass, the change in temperature over the 30 minutes is determined.

$$\frac{2.15}{477 * 11.33} = 398K$$

This is assuming no heat is being removed from convection. Adding this value to the temperature of the air in the tertiary air port of 500K, a constant surface temperature of 898K can be used as a conservative assumption. Using this constant surface temperature; the temperature change of the fiber optic cable due to radiation from the outer tube and convection to the air flow, energy transfer is calculated:

$$Q_{total} = Q_{rad} - Q_{conv} \qquad Q_{rad} = \sigma * T^4 * \varepsilon_T * \varepsilon_O * A = 270W$$

$$Q_{conv} = h * A * (Ts - T_{\inf}) = 166\text{W} \qquad Q_{total} = 104W$$

Therefore assembly time in boiler is determined to be:

$$t = \frac{644 * .45 * 750}{104} = 34.8 \min$$

CONCLUSION:

Through this conservative analysis it can be seen that the assembly should survive the boiler environment for 34.8 minutes before the surface of the fiber optic cable reaches the critical temperature of 644K.

APPENDIX E: *Product Design Specifications*

DOCUMENT PURPOSE

The purpose of this document is to:

- Clearly outline customer requirements and define methods to verify them.
- Provide a project plan.

MISSION STATEMENT

Design an optical assembly that will attach to the infrared camera currently being distributed by Anthony Ross Company. The assembly will provide clear images of black liquor droplets to the camera and allow Anthony Ross' engineers to improve their mathematical model of the recovery boiler.

CUSTOMER IDENTIFICATION

The following outline indicates our main customers along with their most important design criteria.

Anthony Ross:

- Performance
- Quality and reliability
- Testing
- Legal
- Product life

Boiler Personnel/Technicians:

- Safety
- Maintainability
- Performance
- Size
- Weight
- Installation
- Ergonomics
- Quality and reliability
- Applicable codes

PROJECT PLAN

The project fell behind by April, but recovered in May. The prototype was built by June, but testing time was reduced. The setback was due to the fiber bundle, which had to be custom designed for a difficult application. The time allotted for testing went from two weeks to three days. The assembly performance was tested and verified within those three days and the requirements were met.

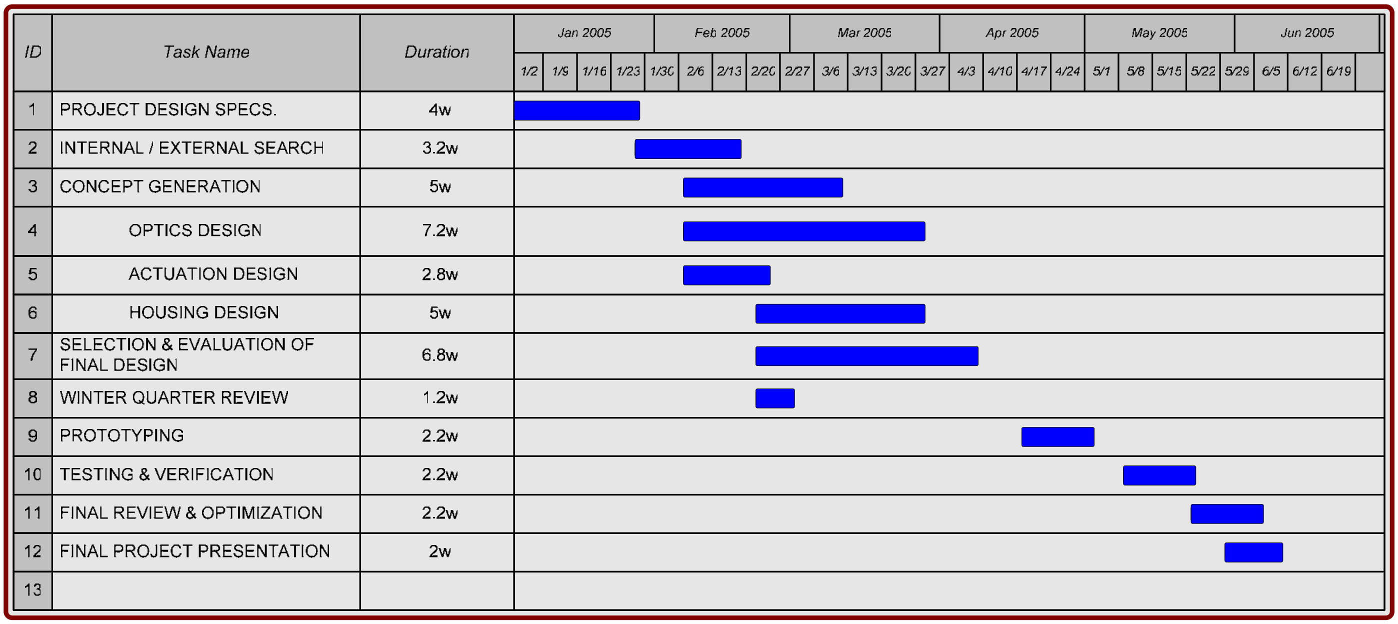


Figure E-1: *Project Timeline*

PRODUCT DESIGN SPECIFICATIONS

<u>**Environment**</u>

Primary Customers: Recovery boiler personnel, Anthony Ross

Customer requirement:

- Assembly will be able to withstand environment up to 2000°F for 30 minutes.
- Assembly will be able to handle an environment that contains harsh chemicals, fast moving debris.
- Assembly must fit through tertiary air port above the liquor guns (63 mm diameter).
- Assembly must extend at least 1 meter into the boiler.

Engineering Targets:

- Assembly will be capable of withstanding the recovery boiler environment for a period of 30 minutes minimum.

- The Assembly must handle the boiler environment without loss of resolution or equipment integrity.

Safety

Primary Customers: Recovery boiler personnel, Anthony Ross

Customer requirement:

- The camera operator will be protected from flames that may escape from the boiler.
- The camera system will be safe to install.
- Documentation on use and maintenance will be provided.

Engineering Targets:

- All components will conform to codes and standards governing recovery boiler operation.
- Materials will be selected with properties that ensure compatibility with boiler environment.
- Documentation explaining safe operation will be provided.

Maintenance

Primary Customers: Recovery boiler personnel, Anthony Ross

Customer requirement:

- Tools and parts needed for maintenance will be defined.
- Documentation describing the maintenance procedure and schedule.

Engineering Targets:

- Maintenance schedule will be determined to provide long life.
- Documentation on maintenance will be provided.

Performance

Primary Customers: Recovery boiler personnel, Anthony Ross

Customer requirement:

- Assembly will have the ability to image black liquor droplets high resolution.
- Assembly must be able to provide clear images while in the boiler for 30-minute periods and prevent damage to itself or the camera.
- Assembly must survive multiple trips into the boiler without image degradation or damage.

- A viewing angle adjustment from 0º to 90º is required. This is necessary to enable the user to locate and analyze different regions of the spray.
- Focal length must be adjustable and known.
- Depth of focus must be narrow.

Engineering Targets:

- Camera and assembly will provide clear images. A clear image is defined as an image with enough resolution that data may be obtained.
- The camera system will withstand the recovery boiler environment for 30 minute periods.
- Proper optics cleaning while extension is in the boiler such that view remains unobstructed.
- Focal length will be adjustable and indicated.
- All customer performance criteria will be met.

Materials

Primary Customers: Recovery boiler personnel, Anthony Ross

Customer requirement:

- Assembly will withstand boiler properties.

Engineering Targets:

- Materials will tolerate boiler properties for periods of 30 minutes with no damage or degradation of image resolution.
- Materials will be selected to be economical and resistant to chemical wear.

Life in Service

Primary Customers: Recovery boiler personnel, Anthony Ross

Customer requirement:

- Assembly will have a long life with proper maintenance.

Engineering Targets:

- Assembly will resist the boiler environments for periods of 30 minutes.
- Assembly will perform up to current two-year warranty standard.

Quantity

Primary Customers: Recovery boiler personnel, Anthony Ross

Customer requirement:

- ❖ Prototype is desired for verification of performance.
- ❖ Future sales potential includes the pulp and paper industry.

Engineering Targets:

- ❖ One prototype will be produced to verify performance.

Manufacturing Facilities

Primary Customers: Anthony Ross

Customer requirement:

- ❖ Customer would like to use onsite manufacturing facilities where ever possible.
- ❖ External manufacturers may be utilized where necessary.

Engineering Targets:

- ❖ Timely requests for needed parts will be given.

Testing

Primary Customers: Anthony Ross

Customer requirement:

- ❖ Assembly prototype will be tested in a recovery boiler environment to verify heat and chemical resistance, image resolution and
- ❖ Image resolution and clarity will be such that droplet size determination has a better accuracy then current analysis.

Engineering Targets:

- ❖ Images will be taken from different access points.
- ❖ Images will be taken at multiple angles and distances from the black liquor spray.
- ❖ Images will be taken over 30 minute periods to check image resolution as function time.

Quality and Reliability

Customer requirement:

- ❖ Good imaging.

- Meets reliability standards in warranty.

Engineering Targets:

- Assembly maintains quality image.
- System will consistently produce clear droplet images.

Documentation

Primary Customers: Recovery boiler personnel, Anthony Ross

Customer requirement:

- Drawings
  - 2-D and 3-D drawings of all parts and assemblies
- Instructions on camera lens extension use.
- Maintenance instructions and timelines.

Engineering Targets:

- Provide all necessary documentation in a timely manner.

Table E-1: *Product design specifications and metrics*

Importance is scaled as a portion of 100 — Rated on a scale of 1 - 5

REQUIREMENT	IMPORTANCE	ENGINEERING CRITERIA						
		Assembly Temperature (F)	Clean Lens (min)	Weight (lbf)	Setup time (min)	Transport Volume (in^2)	Image Quality	Length (in)
30 Minutes in boiler	14	5	5				5	2
Useable images	14	4	5				5	2
Transportable	6			5		5		3
Safe to use	15	5		4		3		
Life in Service	6	4	5					
Ease of installation	7			4	5	4		2
Short enough depth of focus	9		3				5	1
Large enough field of view	8						4	
Adequate cooling	10	5					2	2
High Stability	4						5	3
Maintainability	7	4		3				
Total	100							
Importance of criteria		27	18	16	5	12	26	15
Method of Verification		Test	Test	Measure	Measure	Measure	Test	Measure

APPENDIX F: *Top Level Search*

The purpose of this document is to:

- Clearly outline the design decisions that were made.
- Justify design decisions based on criteria.

TOP LEVEL DESIGN CONSIDERATIONS

Fiber Optics

Since the viewing angle is to be adjustable, a fiber optic cable is an appealing option to transfer the image. Fibers are able to transfer light around corners due the phenomenon of total internal reflection (TIF). Fiber optic imaging is accomplished using coherent fiber bundles which are cables consisting of multiple fibers who's relative position to one another is controlled. Each fiber can carry a certain signal flux that is unaffected by the flux of neighboring strands. A bundle used for imaging divides the image into as many separate light signals as there are fibers (thousands) and delivers it to a CCD. An example of a device that uses a fiber bundle for imaging is an endoscope (shown in figure F-1) which is used for viewing the inside of a body.

Figure F-1: An endoscope [4]

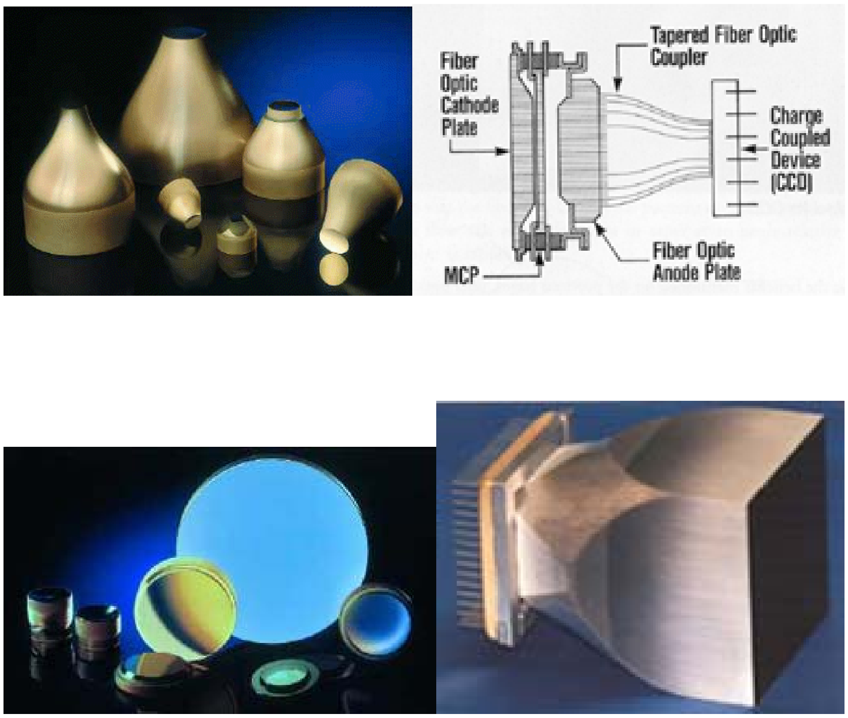


Figure F-2: Below: Faceplates, above left tapers, above & bottom right: taper with CCD [5]

Many components are available for the construction of a fiber-based imaging system. CCD faceplates which provide 1:1 image transfer are available along with tapers which allow for image magnification. Pictures of these components are shown in figure F-2.

Light Transfer

In order to transfer the light from the area to be viewed to the CCD of the infrared camera, the light direction has to be able to change by 90º. Two main ideas were generated that would accomplish this, a mirror based system and a fiber optic based system.

The mirror based system would reflect incoming light from the area of interest through a movable lens for focus adjustment. This could be done by placing a mirror at 45º to the incoming light. This would result in an inverted image, which would not affect the ability to measure droplets. The assembly would fit over Anthony Ross' current short tube lens system. The concept drawing is shown in figure F-3.

The fiber optic based system would consist of distal and proximal optics coupled to an optical fiber bundle. The bundle is flexible, so actuation requires no optical correction. The original concept drawing is shown in Figure F-4.

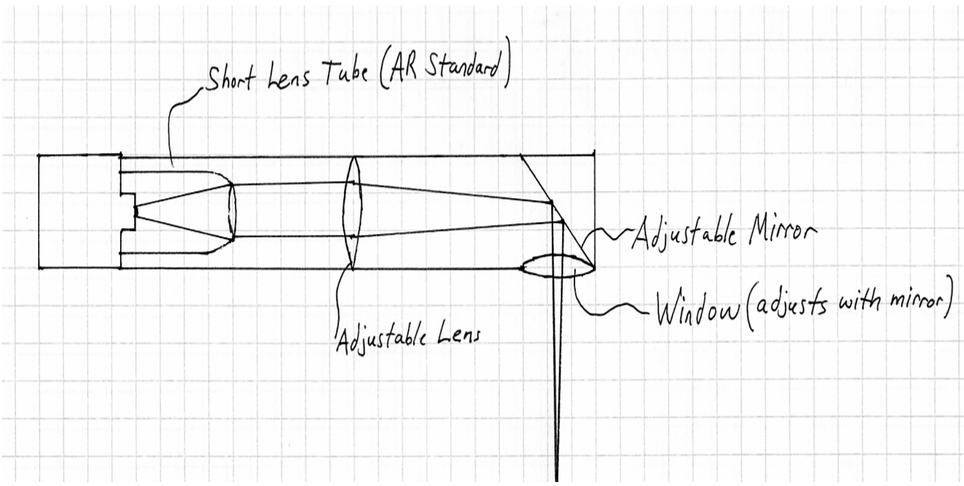


Figure F-3: Concept drawing for mirror based system

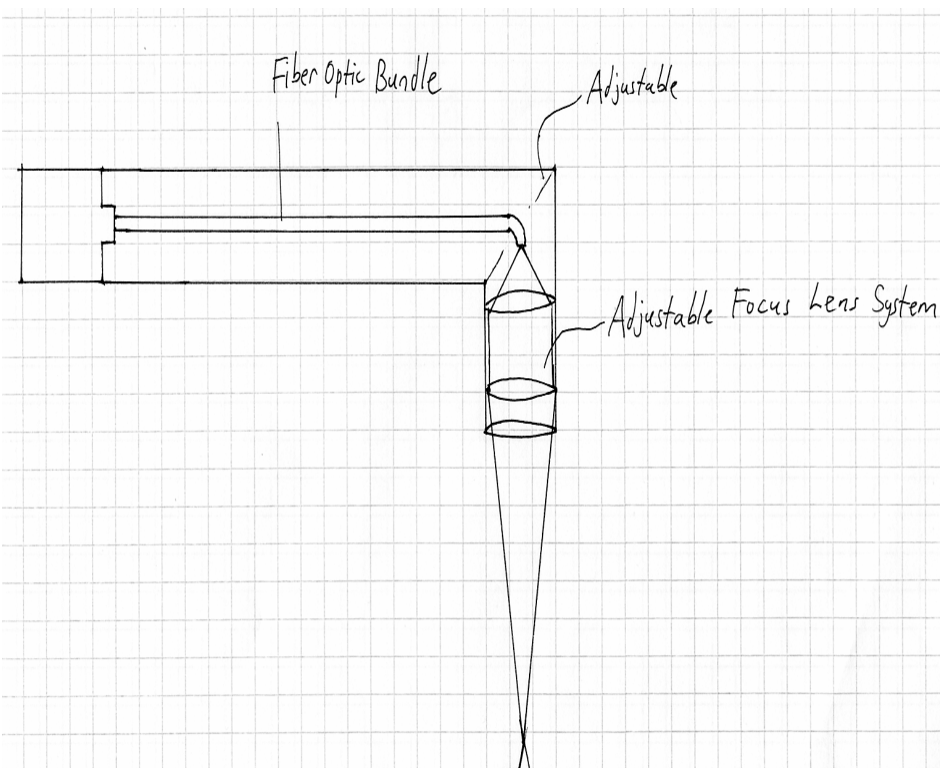


Figure F-4: Concept drawing for fiber optic based system

Tip Actuation

Figure F-5 indicates two techniques that could be used to actuate the tip of the assembly. The unit shown at the bottom right of figure F-5 is actuated by cables, which are tensioned by a dial near the camera housing. The assembly will bend in the direction of the cable being placed under tension. The yellow axes in the figure pass though pins which connect the brackets together and allow them to rotate. This design would allow for the required 0º-90º of actuation.

By connecting the brackets to one another with springs, the force necessary for actuation is reduced. A benefit of using this system is the large amount of space left in the center of the brackets allowing maximum room for large diameter optics, which will increase the amount of light taken in and decrease the depth of focus.

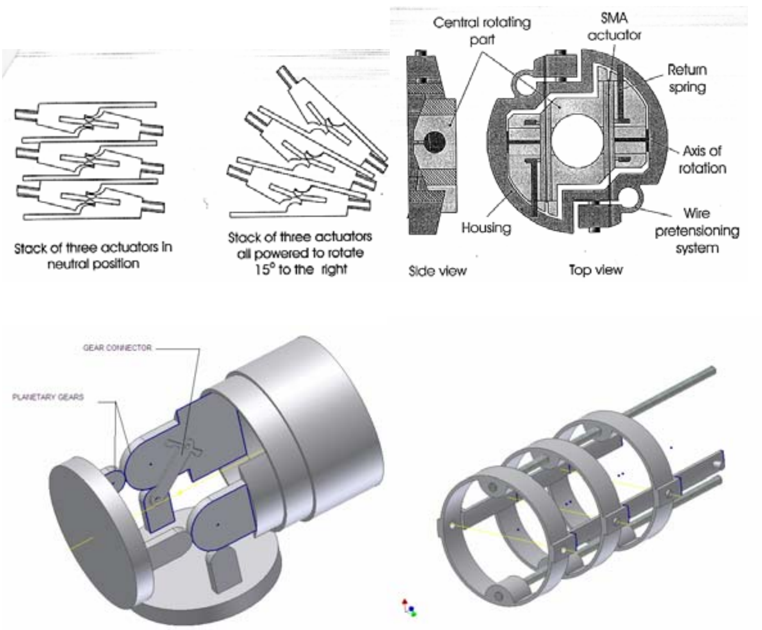


Figure F-5: *Actuation methods, SMA actuator, top row, planetary gear actuator bottom left, bracket actuator bottom right.*

All concepts and ideas were placed into a decision matrix. The light transfer method was evaluated first. It is clear from Table F-1, that the fiber bundle design is the best choice. Knowing that the fiber bundle will be used, its design was then determined. The field of view of the bundle presents a trade-off between detail and coverage. Initially, the best option is the larger field of view to make the assembly able to view more at a given time. The method of actuation is also apparent; the bracket system has shown to be much simpler and more likely to fulfill the design requirements than the planetary gear system (bottom left of Figure F-5).

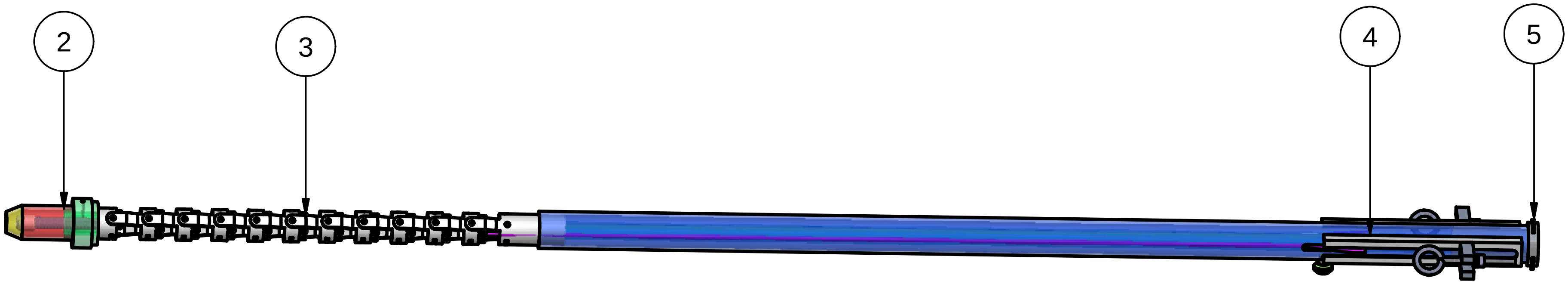
The final bracket design was quite similar to the initial bracket design. The brackets require a sheath to protect the bundle and maintain airflow to the tip. There were two options: a braided steel hose or a silicon hose. The steel hose is more durable and can resist flame much better than silicone hose. Due to the symmetry of the bracket design, two cables and two tensioning mechanisms could be used and the assembly could be actuated up or down 90°. Installing two tensioning mechanisms versus one does not significantly complicate the design. This concept was chosen to increase the versatility of the assembly. Table F-1 shows a summary of the design decisions and the order they had to be made in.

Table F-1: *Top Level Design Decisions Matrix.*

Criteria scaled on a range of 1-5, 5 being the best score possible

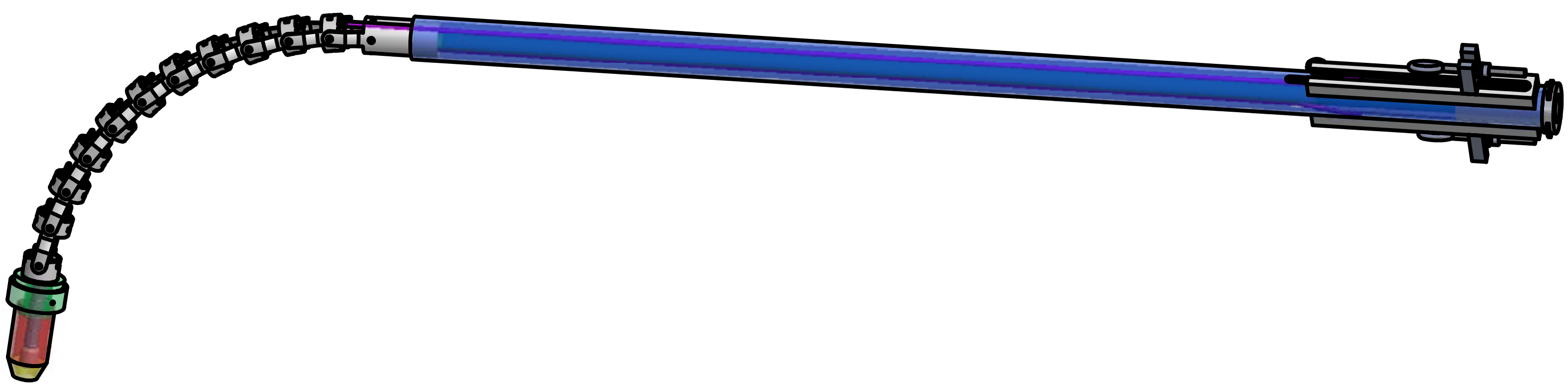
Design order		CRITERIA					
1	***LIGHT TRANSFER METHOD***	Ease of Actuation	Image Quality	Magnification Range	Design Simplicity	cost	Total score
	Mirror Based	1	4	4	1	3	13
	Fiber Optic Based	5	3.5	5	4	2	19.5
2	***FIBER BUNDLE DESIGN***	Magnification	Diameter of image at 15 ft	versitility	Obtanable Data		Total score
	15 Degree Viewing Angle	5	1	1	3		10
	37 Degree Viewing Angle	2	4	4.5	4		14.5
3	***TIP ACTUATION***	Manufacture-ability	# of Mechanical Control Components	Durability	Accuracy of Actuation	Design Simplicity	Total score
	Pin & Bracket System	4	5	4	4	5	22
	Planetary Gear System	1	2	3	3	2	11
3	***ACTUATION ASSEMBLY COVER***	Heat Resistance	Cost	Durability	Flame Tolerance	Thermal Protection	Total score
	Braided Steel Hose	4	2.5	5	3.5	1	21.5
	Silicon Rubber Hose	3	3.5	3	1	4	17.5
5	***TIP ACTUATION CONTROLS***	Design simplicity	Easy of control	Angle of Actuation			Total score
	1 Cable	4.2	4	3			11.2
	2 Cables	4	3	5			12

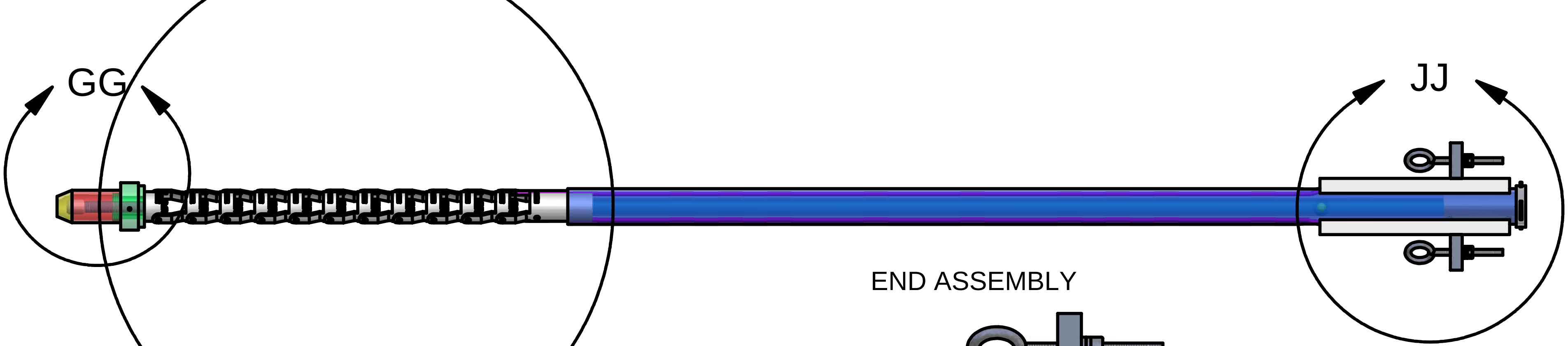
APPENDIX G: *Manufacturing Drawings*



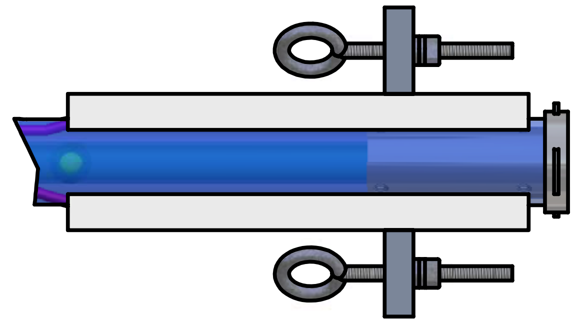
OVERALL LENGTH OF ASSEMBLY IS 85"

Parts List		
ITEM	QTY	PART NUMBER
1	1	FIBER BUNDLE (NOT SHOWN)
2	1	DISTAL END (TIP)
3	1	ACTUATION BRACKETS
4	1	ACTUATION SYSTEM
5	1	PROXIMAL END CCD INTERFACE

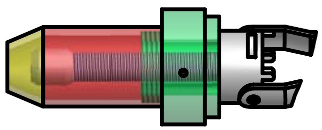




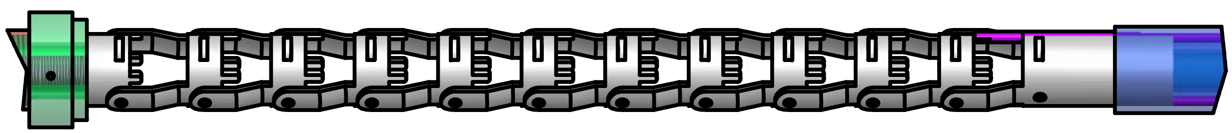
END ASSEMBLY



TIP ASSEMBLY

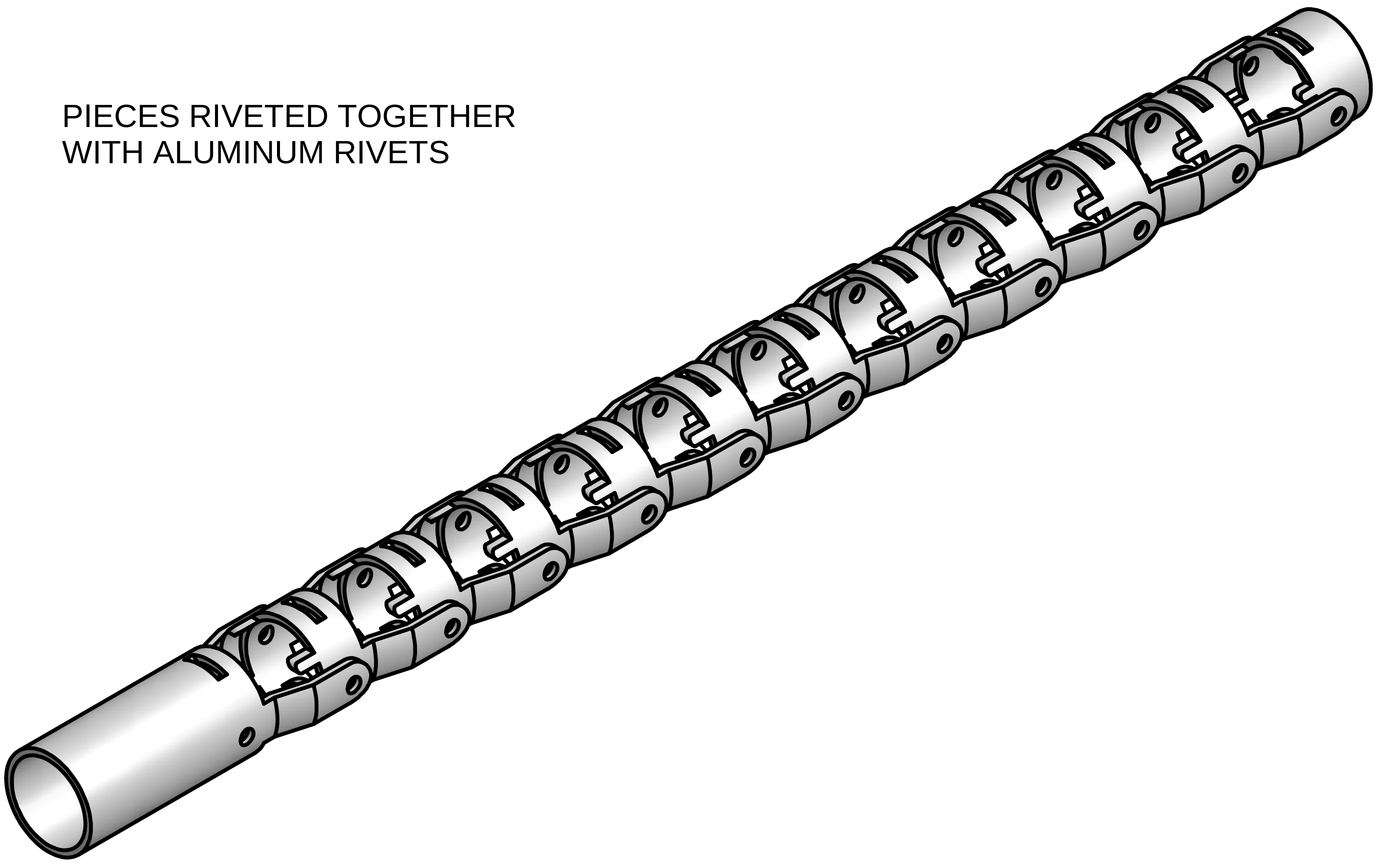


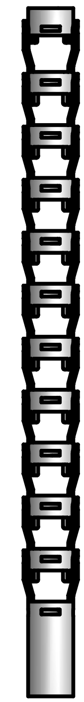
HINGE ASSEMBLY



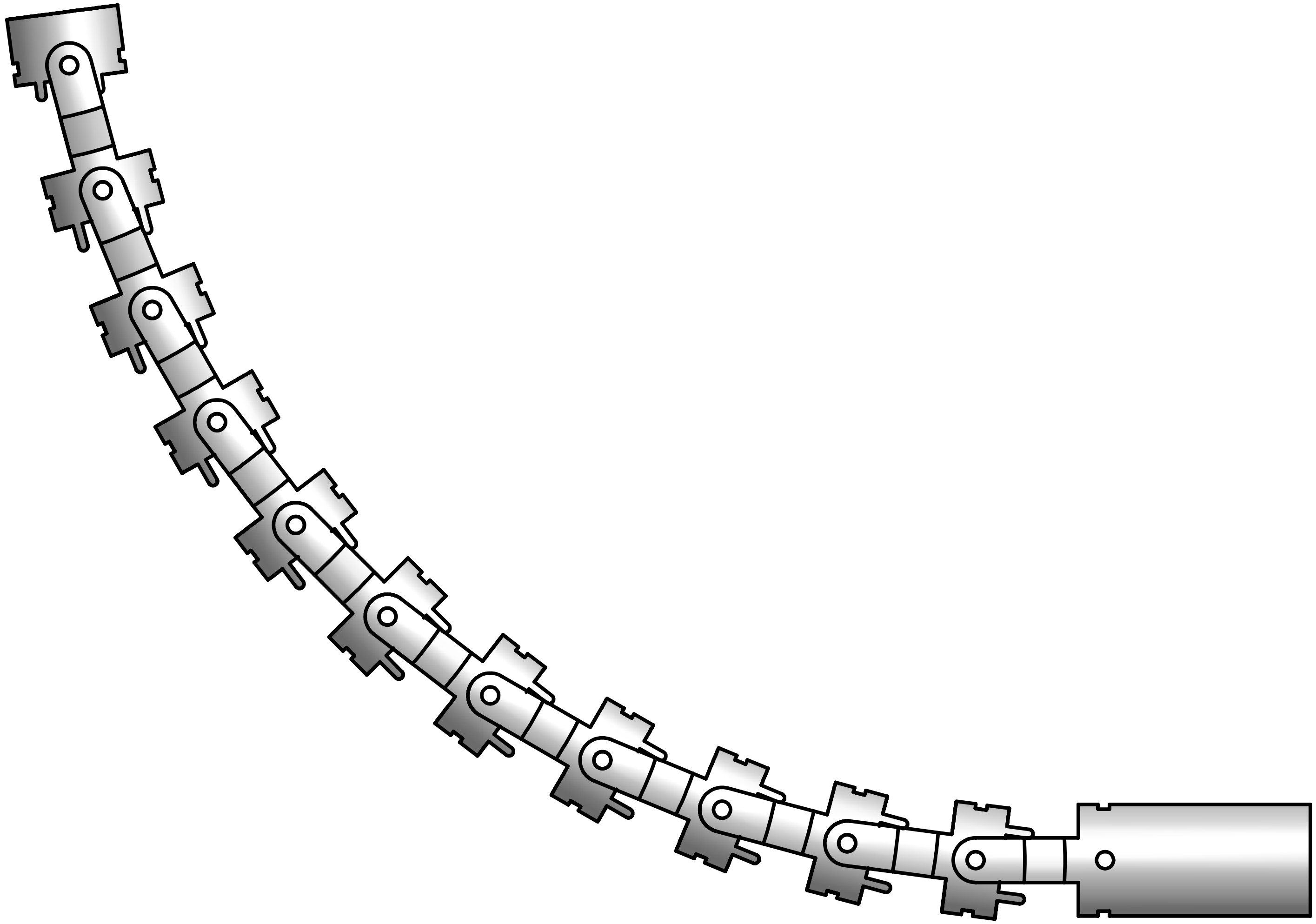
Title MASTER STRAIGHT	Material 304 stainless	Tolerance +-0.003	
Designer William Carter	Company PSU - AR	Revision Number 1	Comments Break Edges 0.010 X 0.010 Chamfer Units in Inches
Project BLACK LIQUOR IMAGING	Scale 0.15:1		
Creation Date 5/11/2005			

PIECES RIVETED TOGETHER
WITH ALUMINUM RIVETS

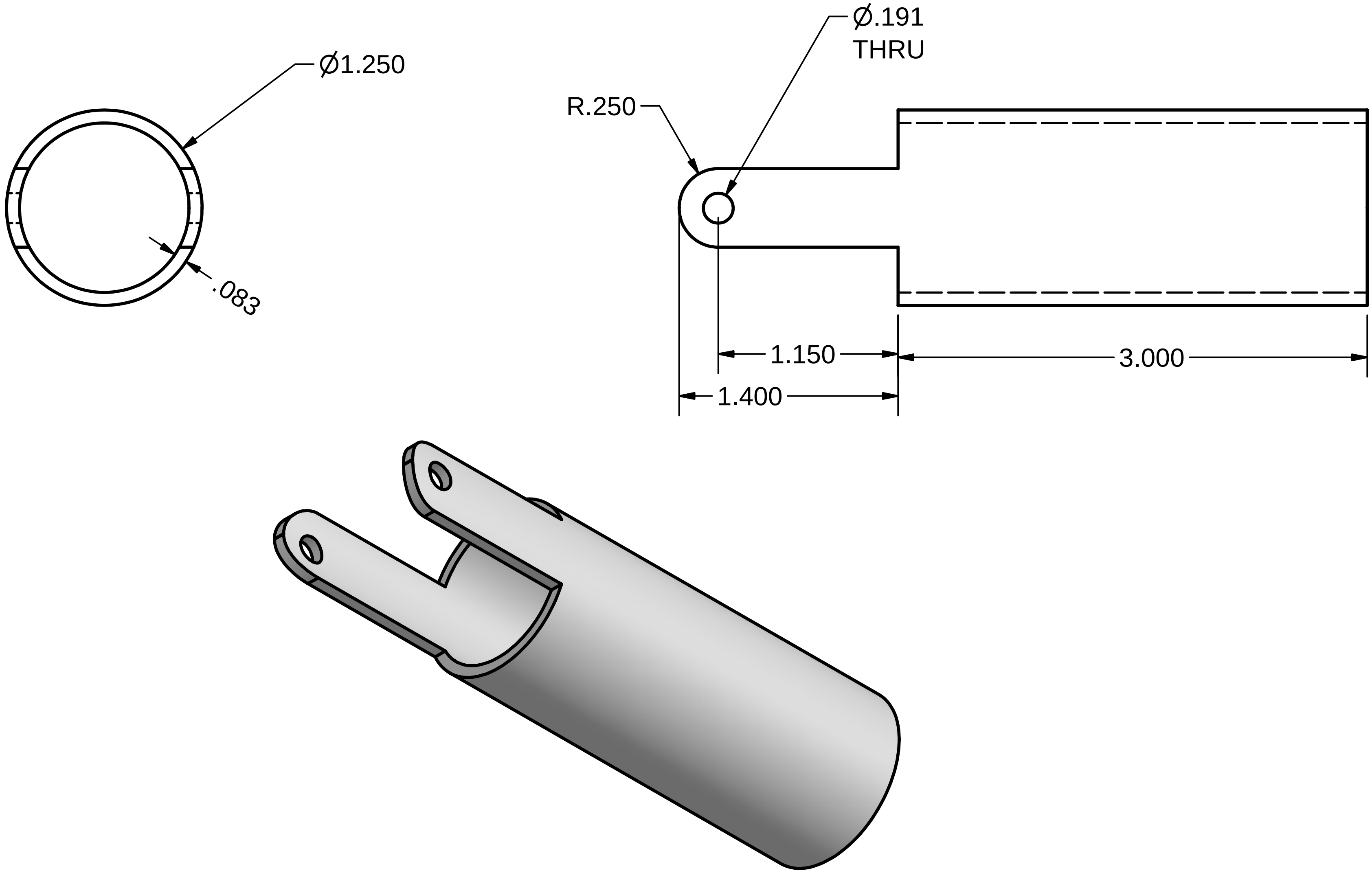




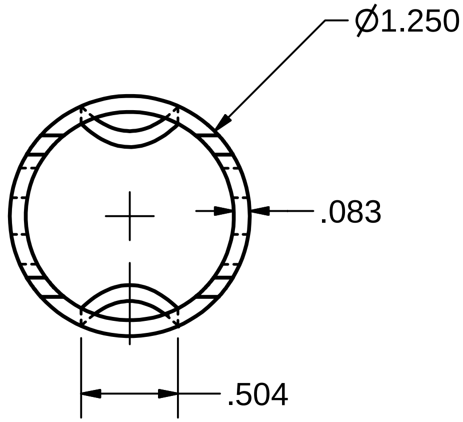
Title ACTUATION ASSM 1	Material 304 stainless	Tolerance +-0.003	
Designer Aaron Brandt	Company PSU - AR	Revision Number 5	Comments Break Edges 0.010 X 0.010 Chamfer Units in Inches
Project BLACK LIQUOR IMAGING	Scale 1:2		
Creation Date 5/11/2005			

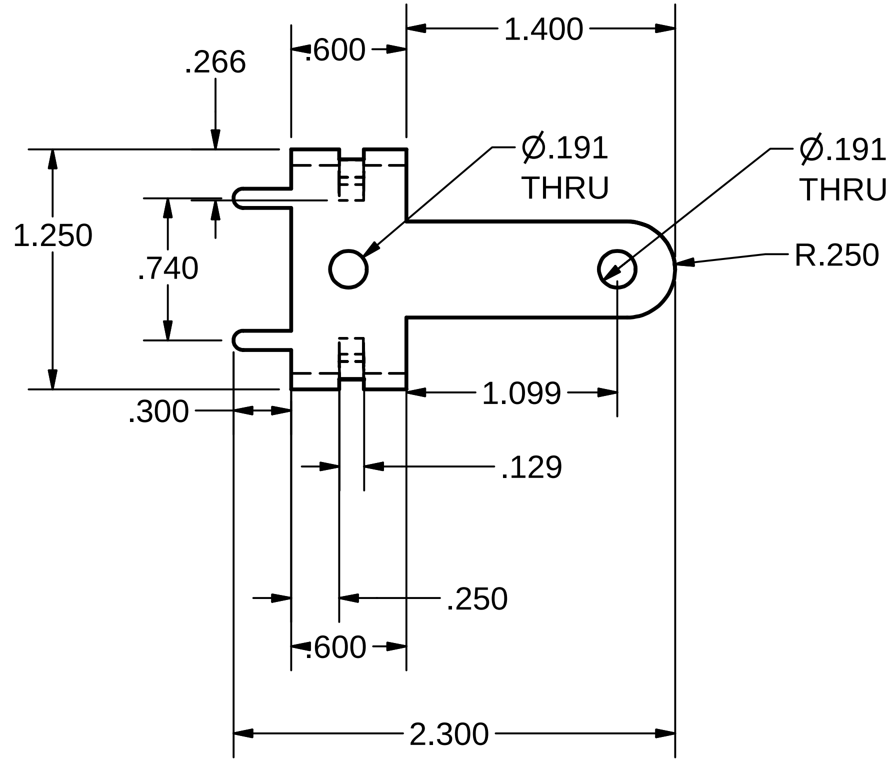


Title CURVED ACTUATION	Material 304 stainless	Tolerance +-0.003	
Designer Aaron Brandt	Company PSU - AR	Revision Number 5	Comments Break Edges 0.010 X 0.010 Chamfer Units in Inches
Project BLACK LIQUOR IMAGING	Scale 1:2		
Creation Date 5/11/2005			

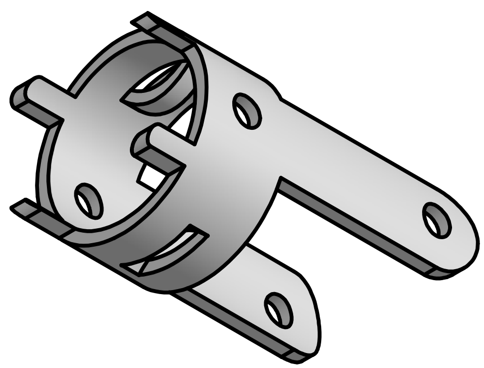


Title FIRST BRACKET	Material 304 stainless	Tolerance +-0.003	
Designer Aaron Brandt	Company PSU - AR	Revision Number 2	Comments Break Edges 0.010 X 0.010 Chamfer Units in Inches
Project BLACK LIQUOR IMAGING	Scale 1:1		
Creation Date 5/11/2005			

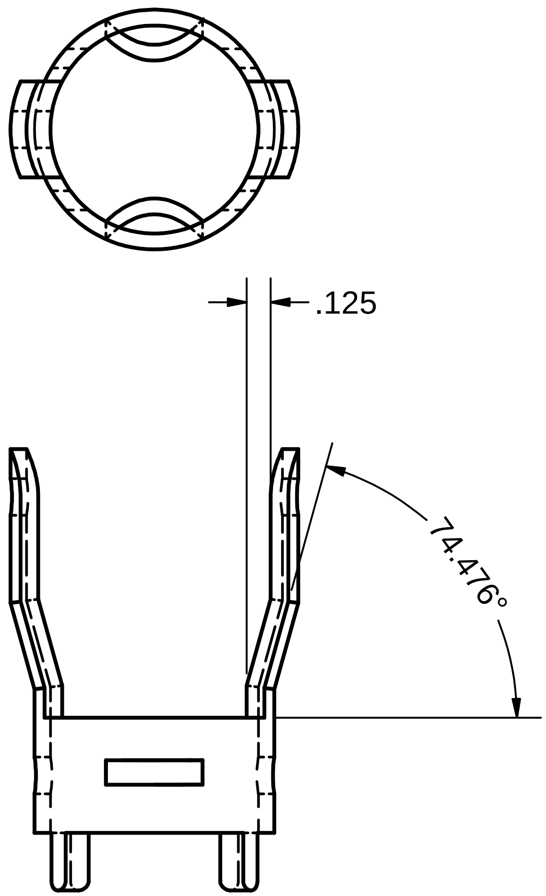


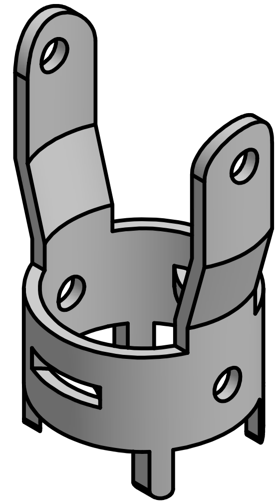


10 EACH FOR ASSEMBLY

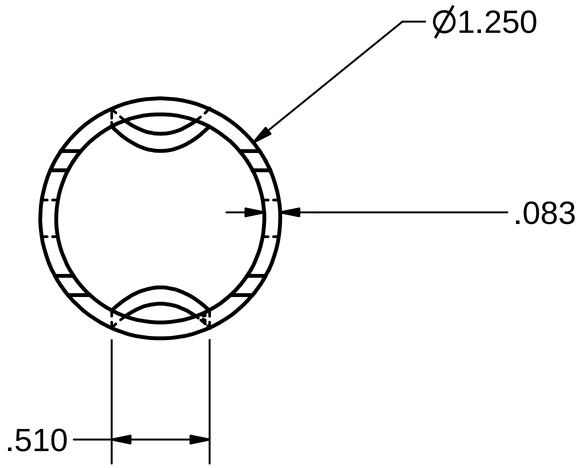


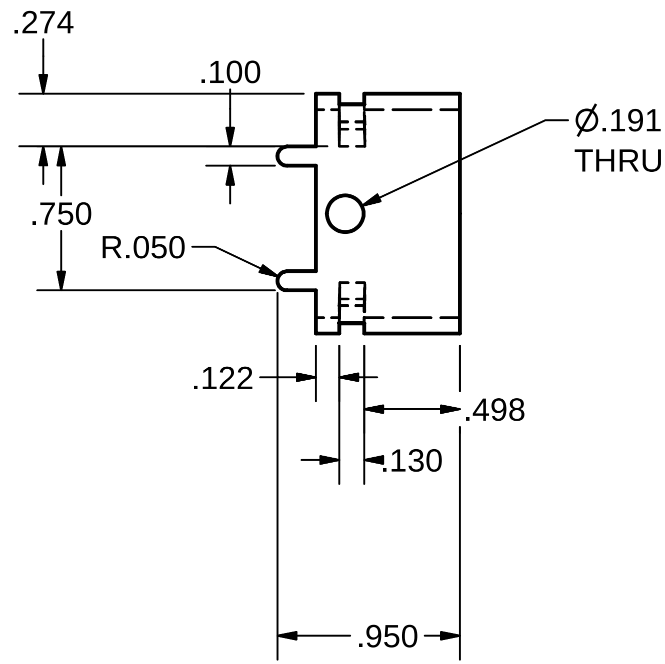
Title CENTER BRACKET	Material 304 stainless	Tolerance +-0.003	
Designer Aaron Brandt	Company PSU - AR	Revision Number 3	Comments Break Edges 0.010 X 0.010 Chamfer Units in Inches
Project BLACK LIQUOR IMAGING	Scale 1:1		
Creation Date 5/11/2005			

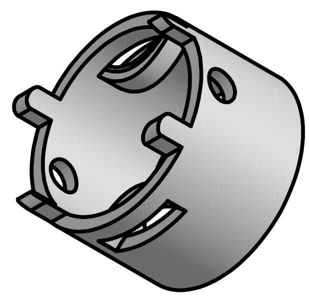




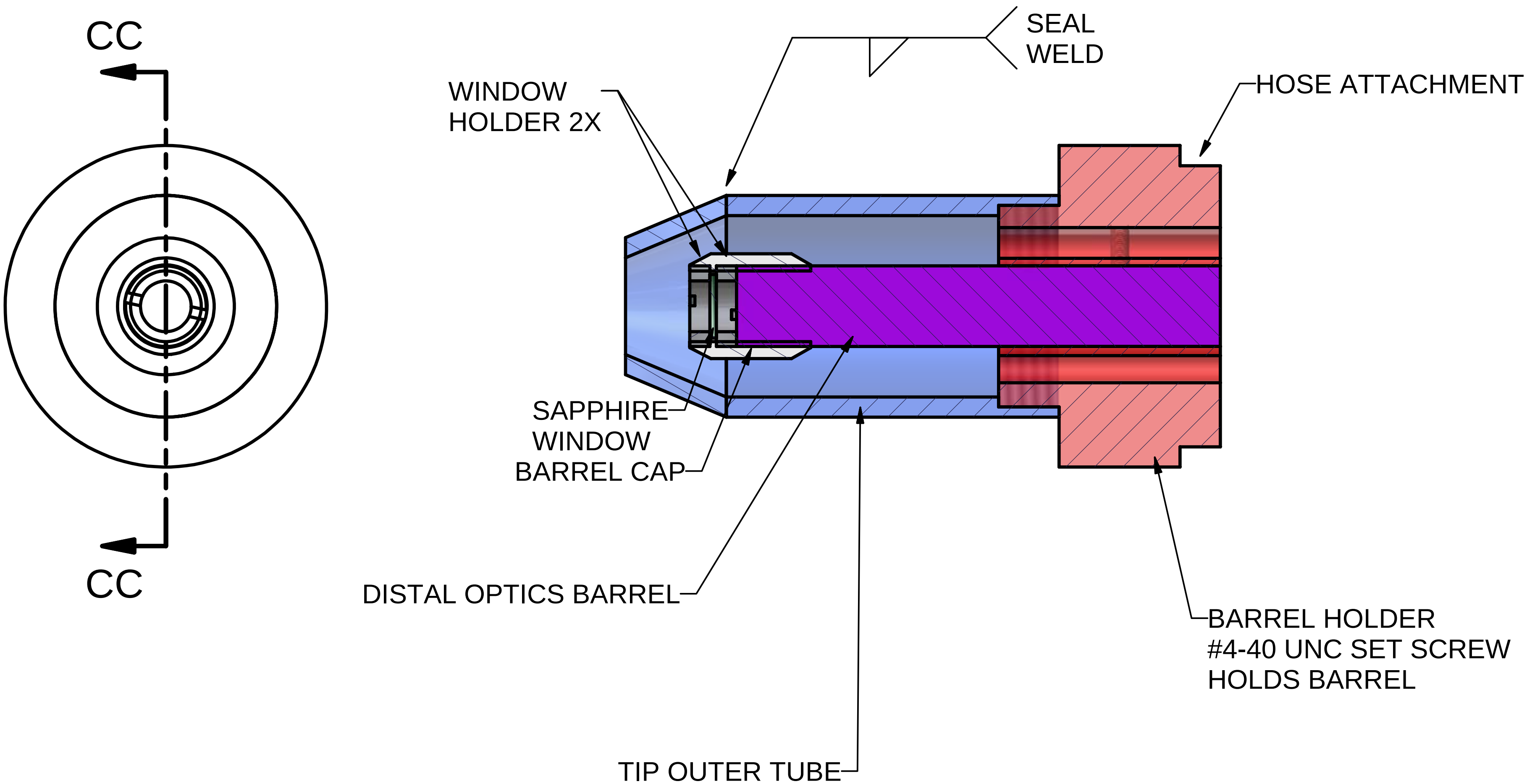
Title BRACKET BEND	Material 304 stainless	Tolerance +-0.003	
Designer Aaron Brandt	Company PSU - AR	Revision Number 3	Comments Break Edges 0.010 X 0.010 Chamfer Units in Inches
Project BLACK LIQUOR IMAGING	Scale 1:1		
Creation Date 5/11/2005			



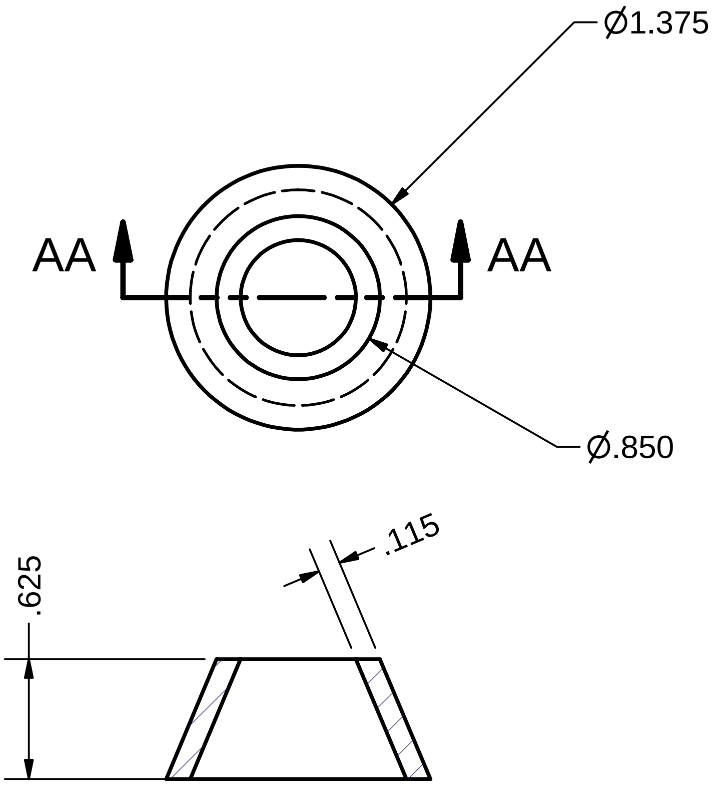




Title END BRACKET	Material 304 stainless	Tolerance +-0.003	
Designer Aaron Brandt	Company PSU - AR	Revision Number 3	Comments Break Edges 0.010 X 0.010 Chamfer Units in Inches
Project BLACK LIQUOR IMAGING	Scale 1:1		
Creation Date 5/11/2005			



Title TIP ASSEMBLY	Material 304 stainless	Tolerance +-0.003	
Designer Brent Illingworth	Company PSU - AR	Revision Number 3	Comments Break Edges 0.010 X 0.010 Chamfer Units in Inches
Project BLACK LIQUOR IMAGING	Scale 1:1		
Creation Date 5/11/2005			



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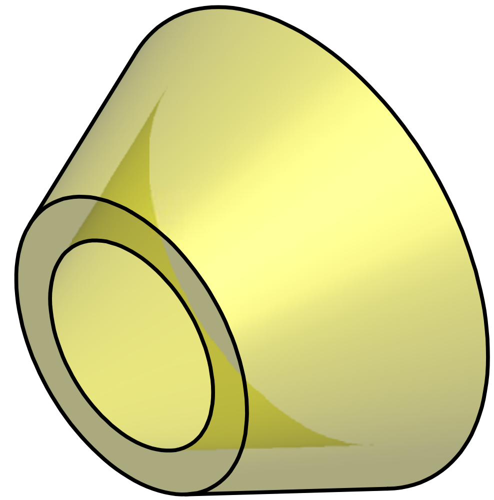
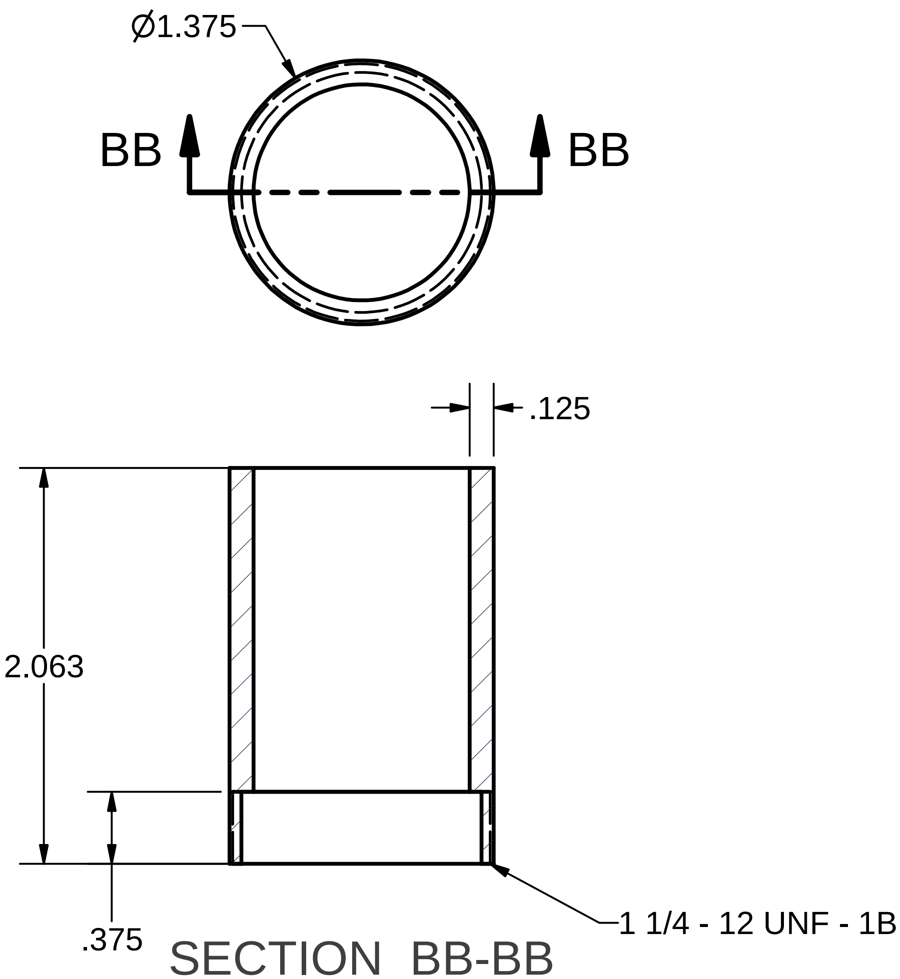


Title TAPERED TIP	Material 304 stainless	Tolerance +-0.003	
Designer Brent Illingworth	Company PSU - AR	Revision Number 2	Comments Break Edges 0.010 X 0.010 Chamfer Units in Inches
Project BLACK LIQUOR IMAGING	Scale 1:1		
Creation Date 5/11/2005			



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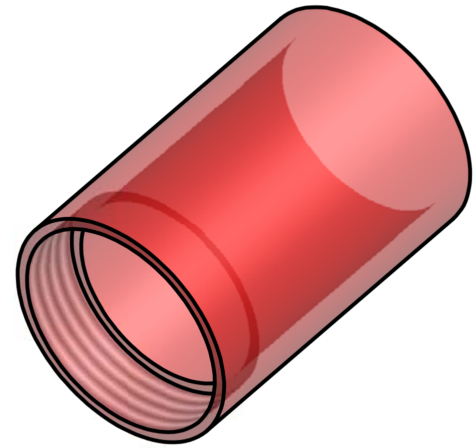
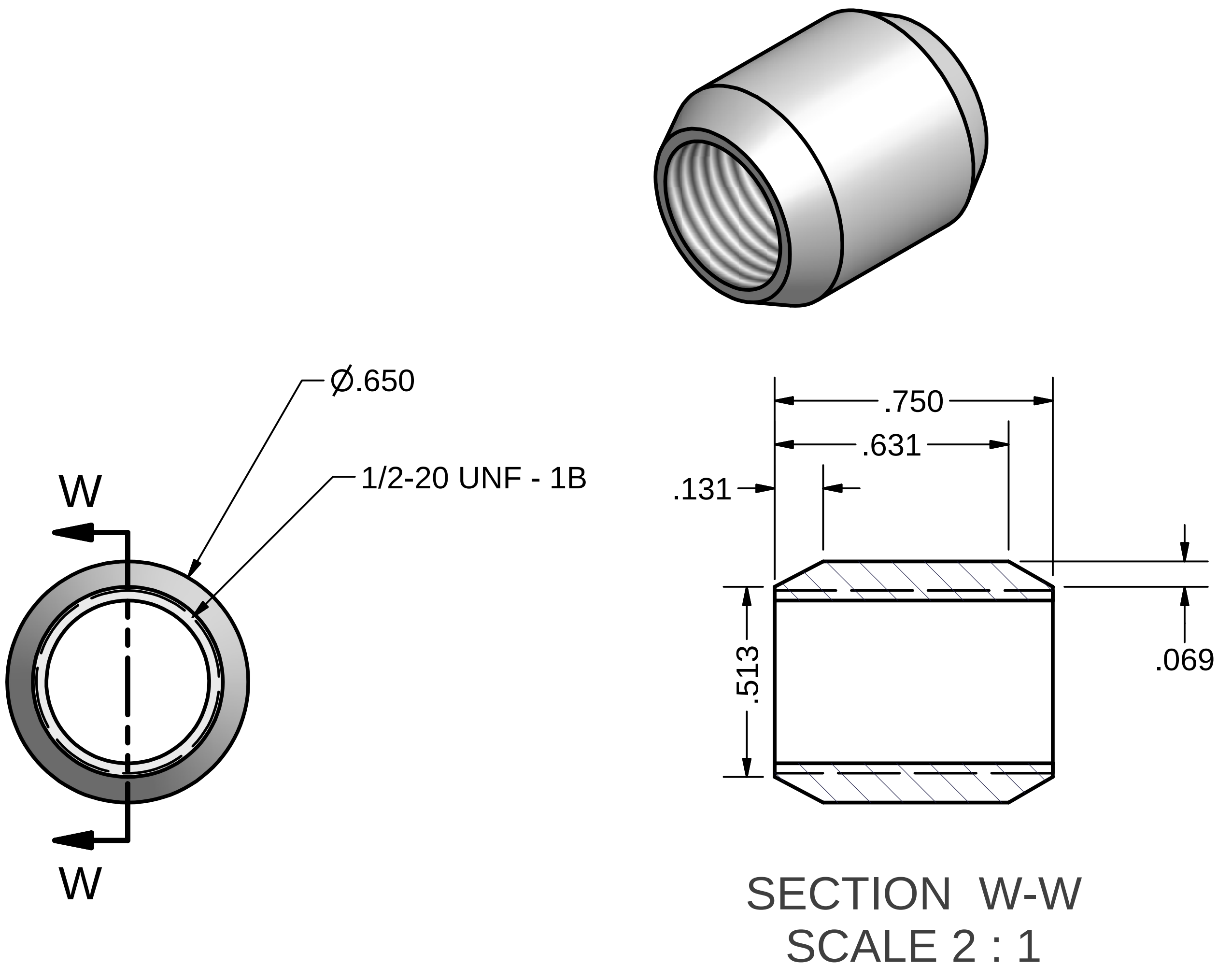
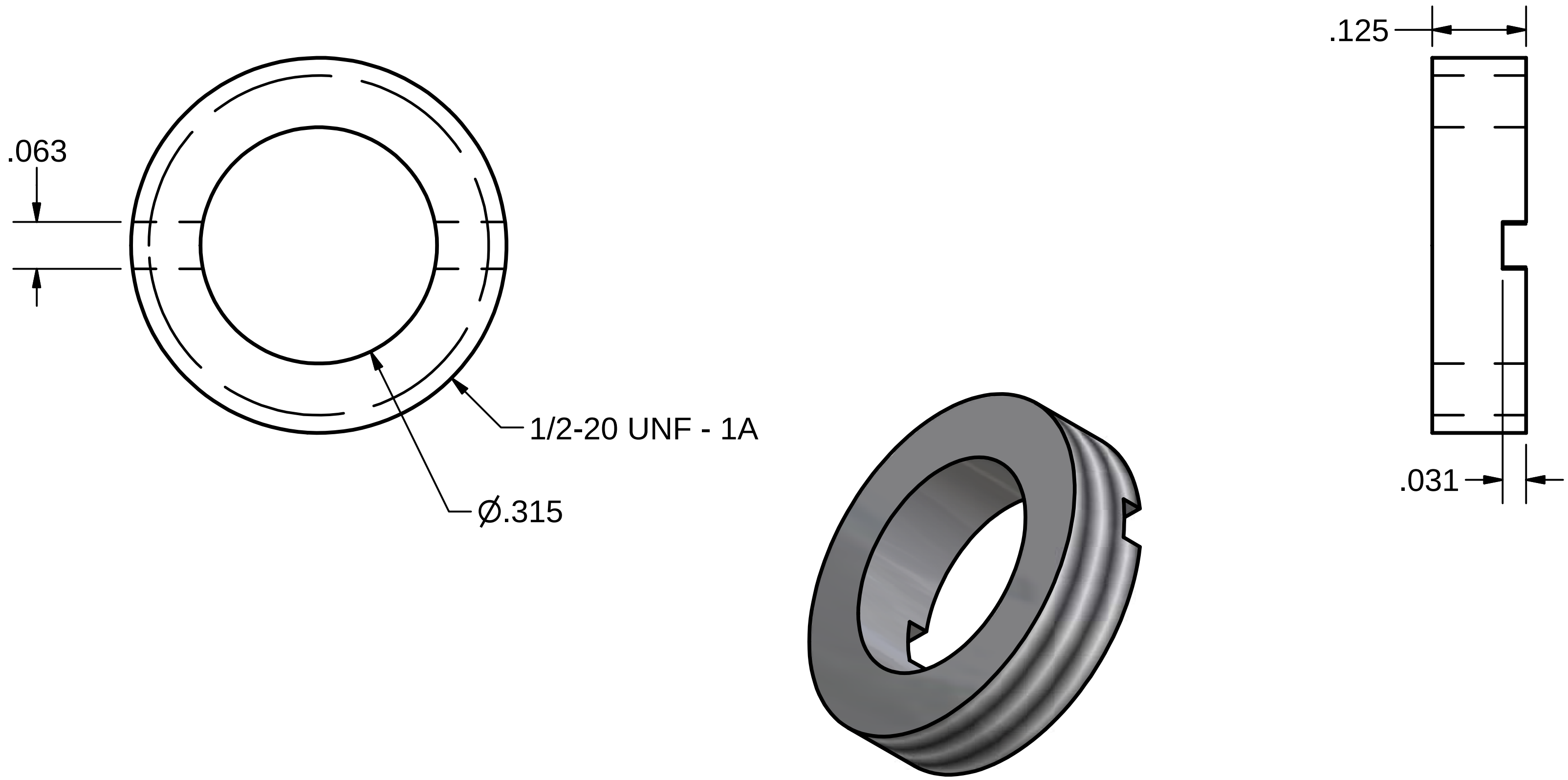


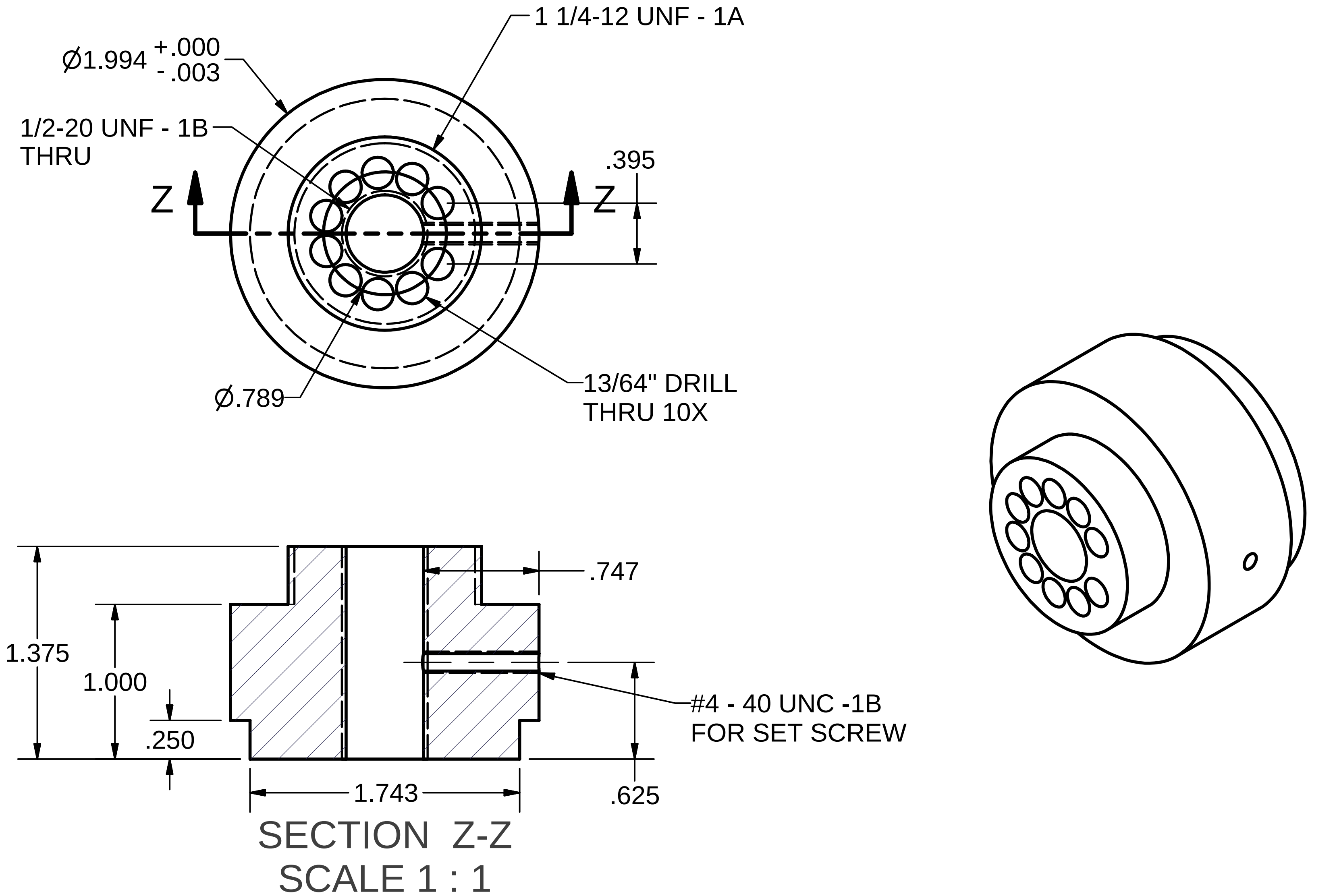
Title TIP OUTER TUBE	Material 304 stainless	Tolerance +-0.003	
Designer Brent Illingworth	Company PSU - AR	Revision Number 1	Comments Break Edges 0.010 X 0.010 Chamfer Units in Inches
Project BLACK LIQUOR IMAGING	Scale 1:1		
Creation Date 5/11/2005			



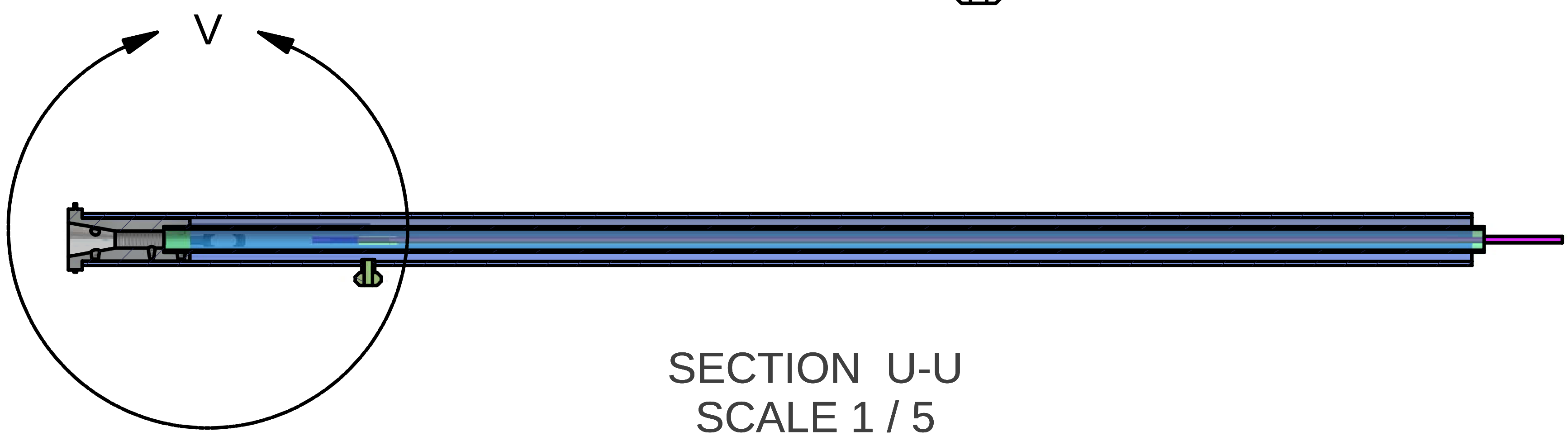
Title BARREL CAP	Material 304 stainless	Tolerance +-0.003	
Designer Brent Illingworth	Company PSU - AR	Revision Number	Comments Break Edges 0.010 X 0.010 Chamfer Units in Inches
Project BLACK LIQUOR IMAGING	Scale 2:1		
Creation Date 5/11/2005			



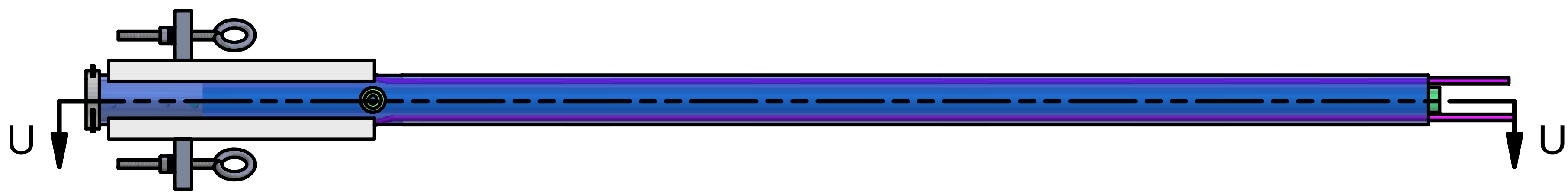
Title WINDOW HOLDER	Material 304 stainless	Tolerance +-0.003	
Designer Brent Illingworth	Company PSU - AR	Revision Number 1	Comments Break Edges 0.010 X 0.010 Chamfer Units in Inches
Project BLACK LIQUOR IMAGING	Scale 4:1		
Creation Date 5/11/2005			



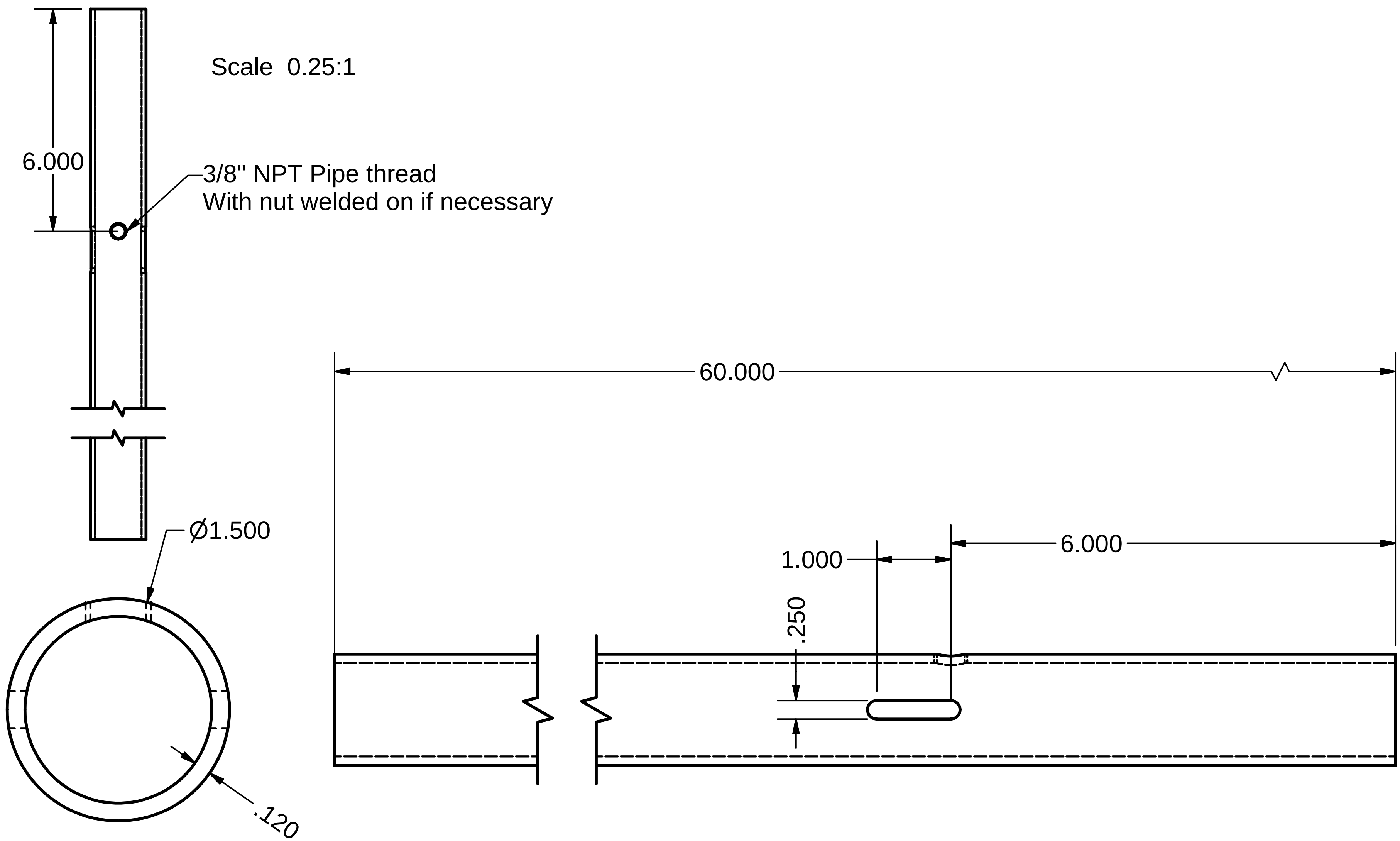
Title BARREL HOLDER	Material 304 stainless	Tolerance +-0.003	
Designer Brent Illingworth	Company PSU - AR	Revision Number 5	Comments Break Edges 0.010 X 0.010 Chamfer Units in Inches
Project BLACK LIQUOR IMAGING	Scale 1:1		
Creation Date 5/11/2005			



SECTION U-U
SCALE 1 / 5



Title MASTER TUBE ASSEMBLY	Material 304 stainless	Tolerance +-0.003	
Designer Will Carter	Company PSU - AR	Revision Number 4	Comments Break Edges 0.010 X 0.010 Chamfer Units in Inches
Project BLACK LIQUOR IMAGING	Scale 0.2:1		
Creation Date 5/11/2005			

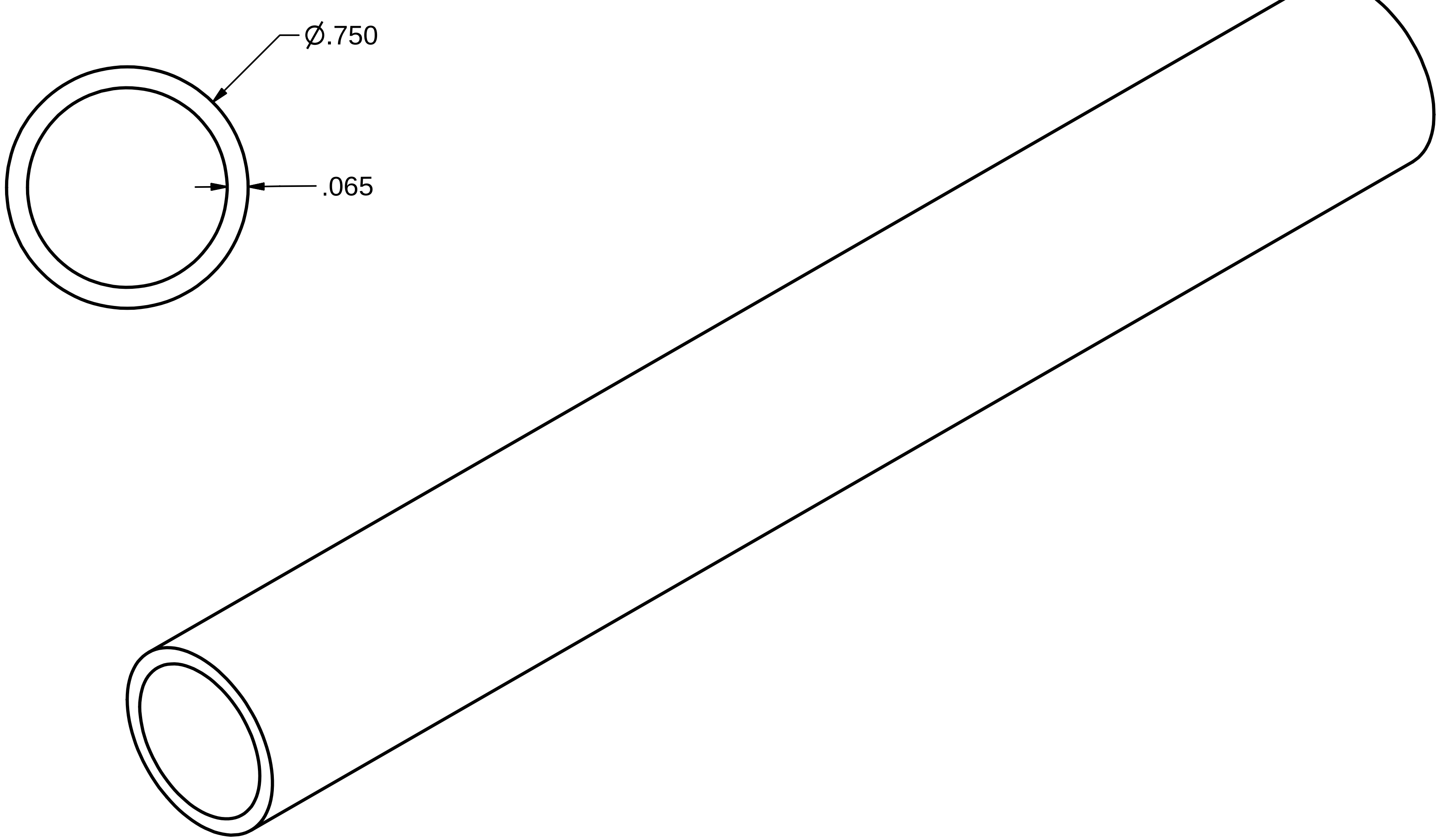


SCALE 1 / 2

SCALE 1 : 1

Title 1.5" Outer Tube	Material 304 stainless	Tolerance +-0.003	
Designer William Carter	Company PSU - AR	Revision Number 2	Comments Break Edges 0.010 X 0.010 Chamfer Units in Inches
Project BLACK LIQUOR IMAGING	Scale N/A		
Creation Date 5/11/2005			

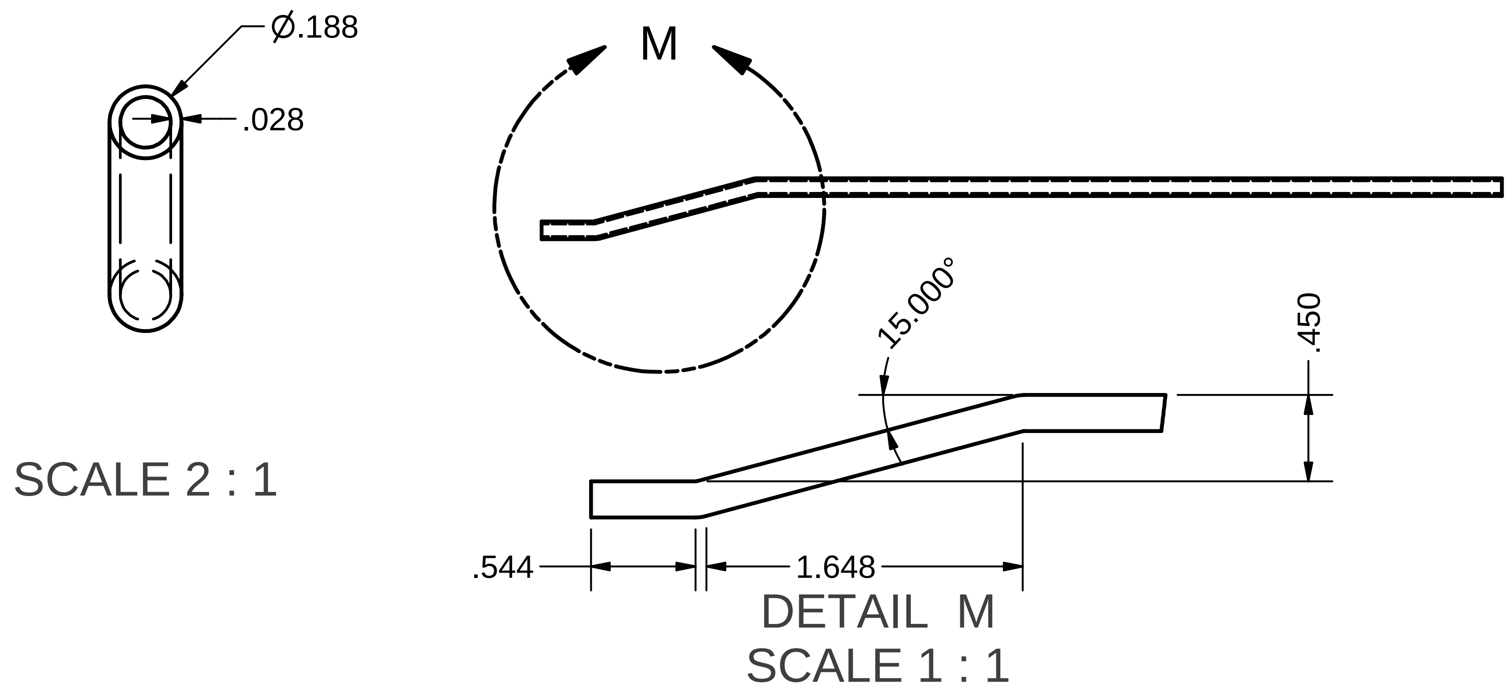
INNER TUB 3/4" 18 GAGE
50" LENGTH



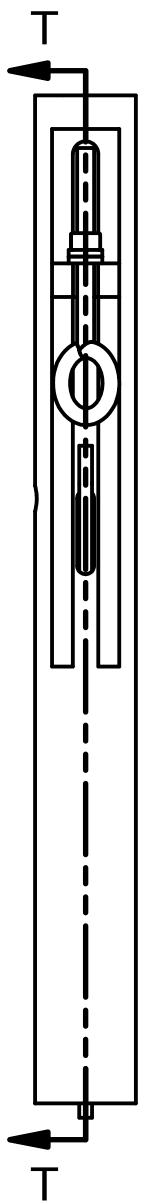
Title INNER TUBE	Material 304 stainless	Tolerance +-0.003	
Designer William Carter	Company PSU - AR	Revision Number 1	Comments Break Edges 0.010 X 0.010 Chamfer Units in Inches
Project BLACK LIQUOR IMAGING	Scale N/A		
Creation Date 5/11/2005			

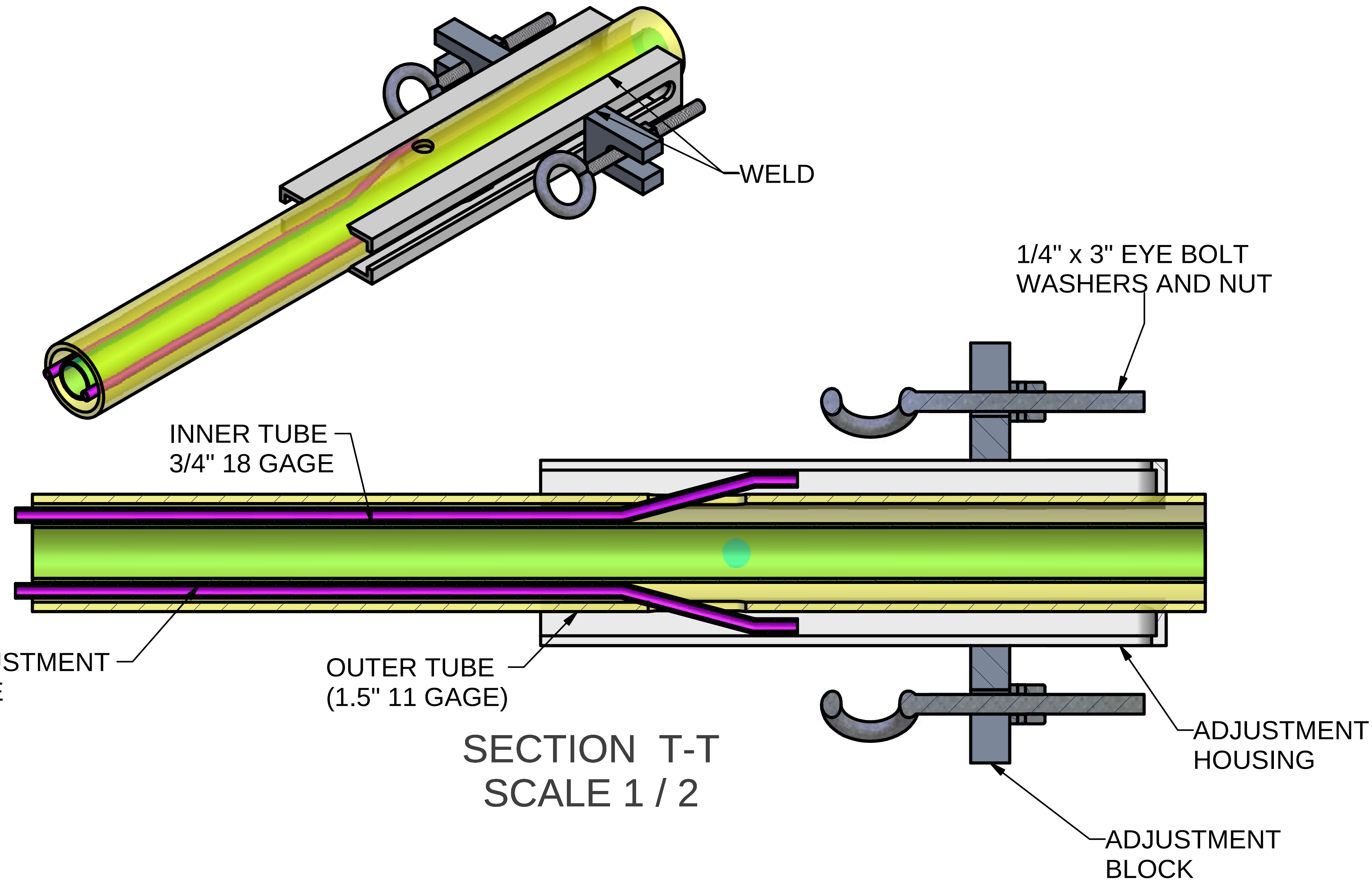
2 EACH:
3/16" TUBE
22 GAGE
50" OVERALL LENGTH

15˚ BENDS



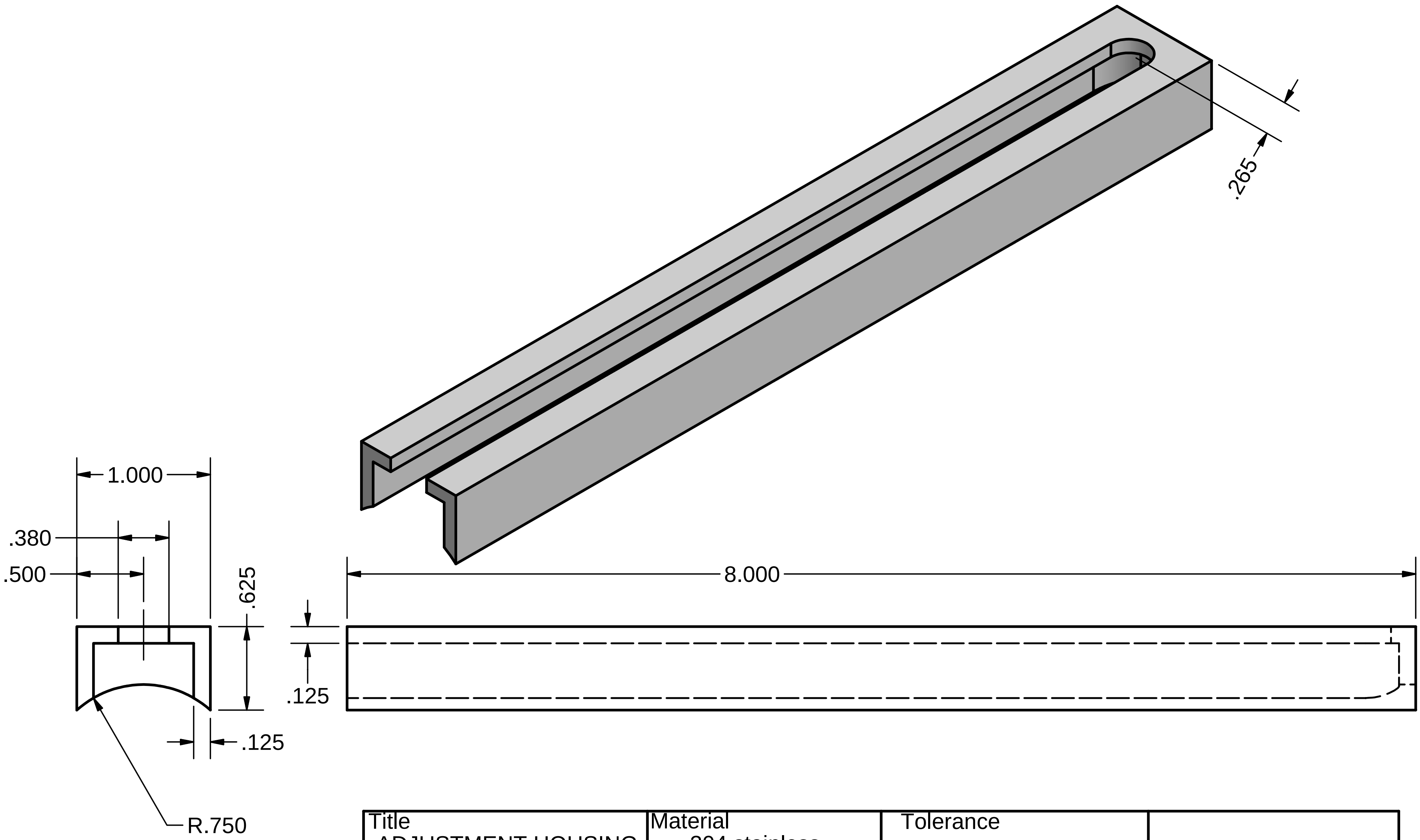
Title ADJUSTMENT TUBE	Material 304 stainless	Tolerance +-0.003	
Designer William Carter	Company PSU - AR	Revision Number 2	Comments Break Edges 0.010 X 0.010 Chamfer Units in Inches
Project BLACK LIQUOR IMAGING	Scale SEE ABOVE		
Creation Date 5/11/2005			



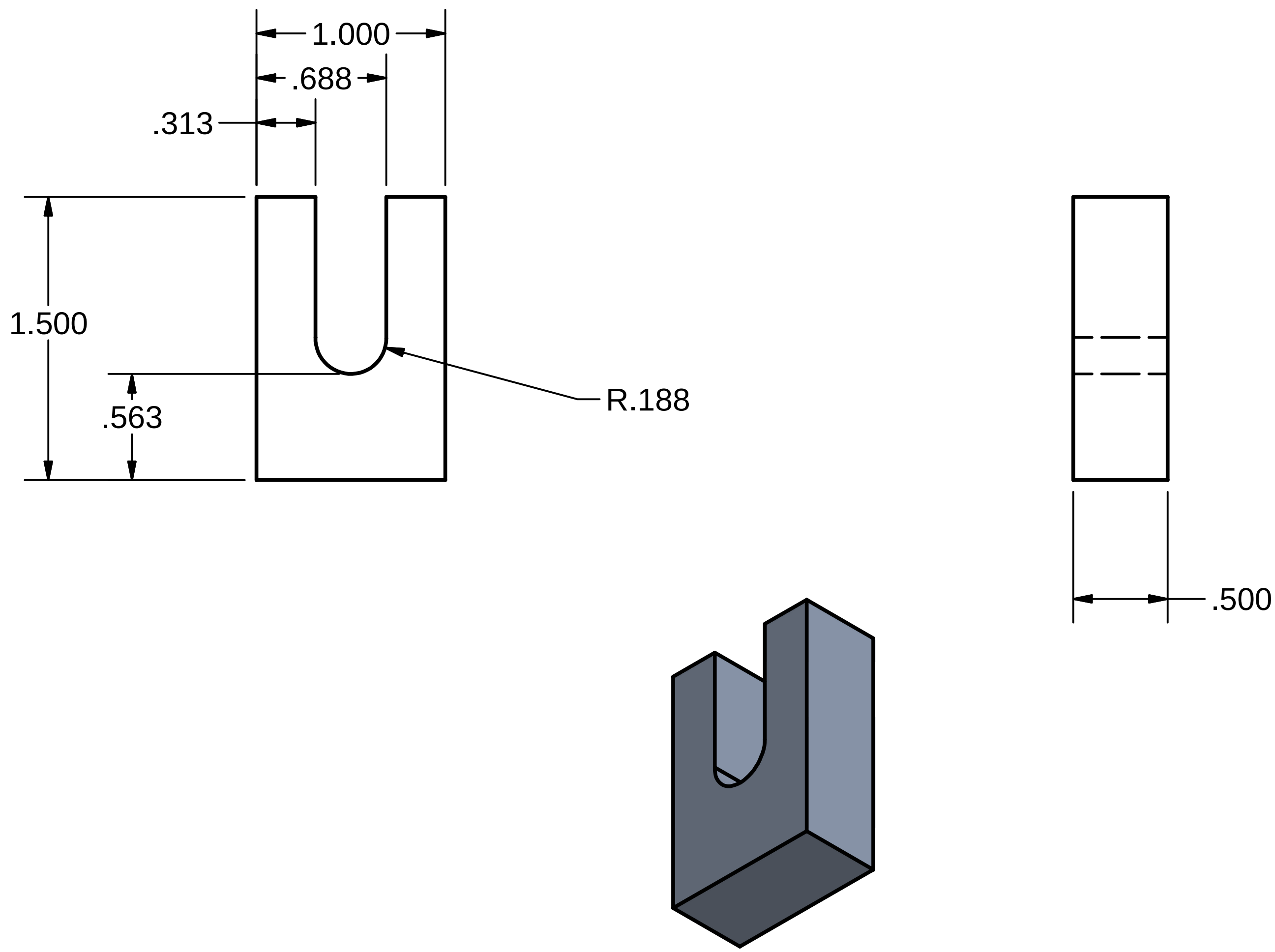


SECTION T-T
SCALE 1 / 2

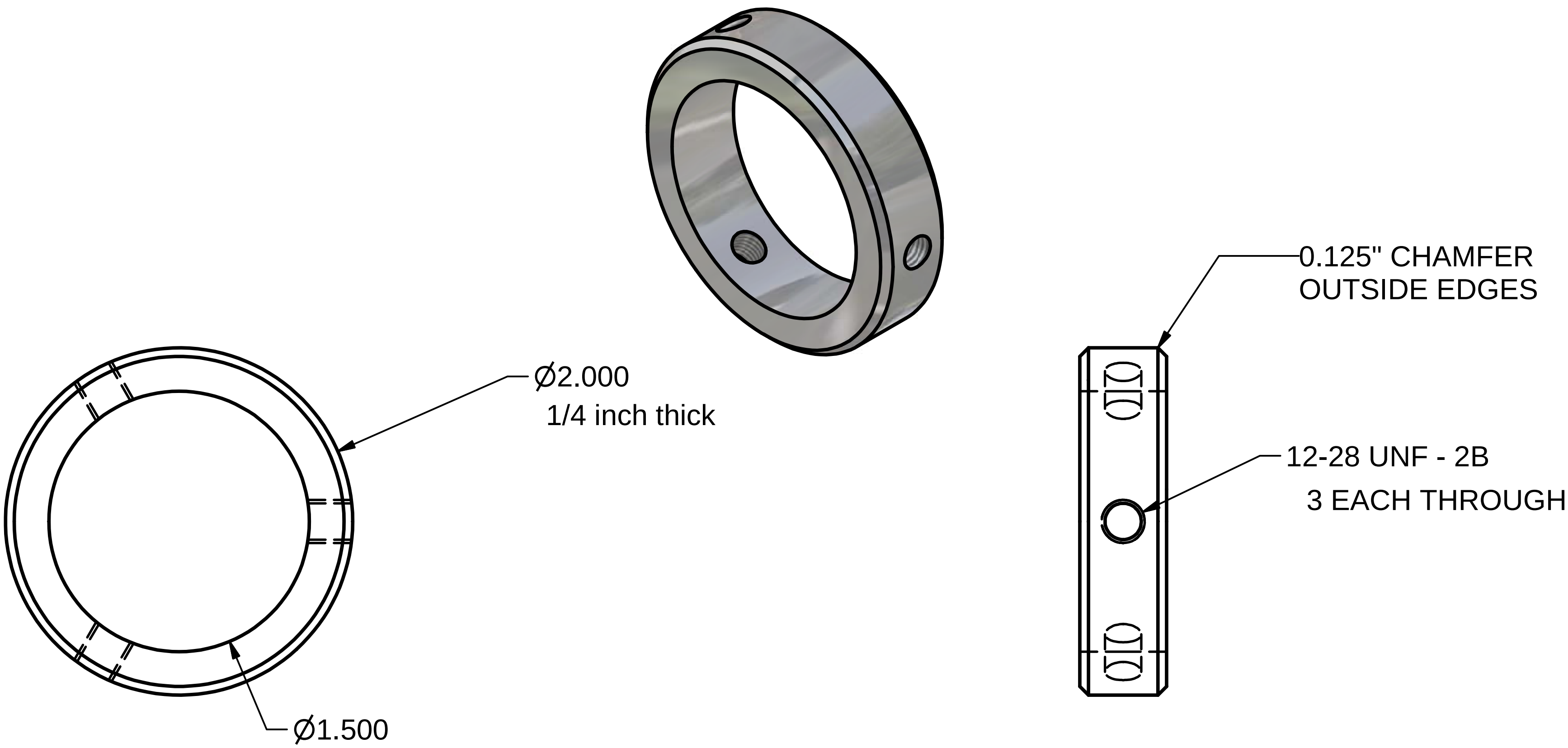
Title MID ASSEMBLY	Material 304 stainless	Tolerance +-0.003	
Designer William Carter	Company PSU - AR	Revision Number 4	Comments Break Edges 0.010 X 0.010 Chamfer Units in Inches
Project BLACK LIQUOR IMAGING	Scale 1:2		
Creation Date 5/11/2005			



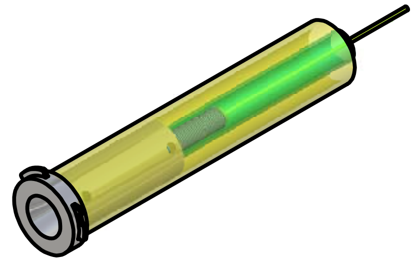
Title ADJUSTMENT HOUSING	Material 304 stainless	Tolerance +-0.003	
Designer William Carter	Company PSU - AR	Revision Number 3	Comments Break Edges 0.010 X 0.010 Chamfer Units in Inches
Project BLACK LIQUOR IMAGING	Scale 1:1		
Creation Date 5/11/2005			

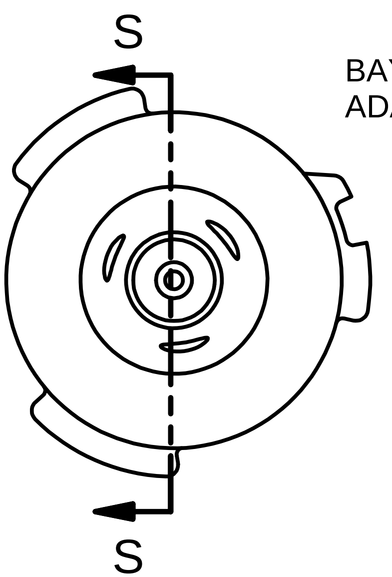


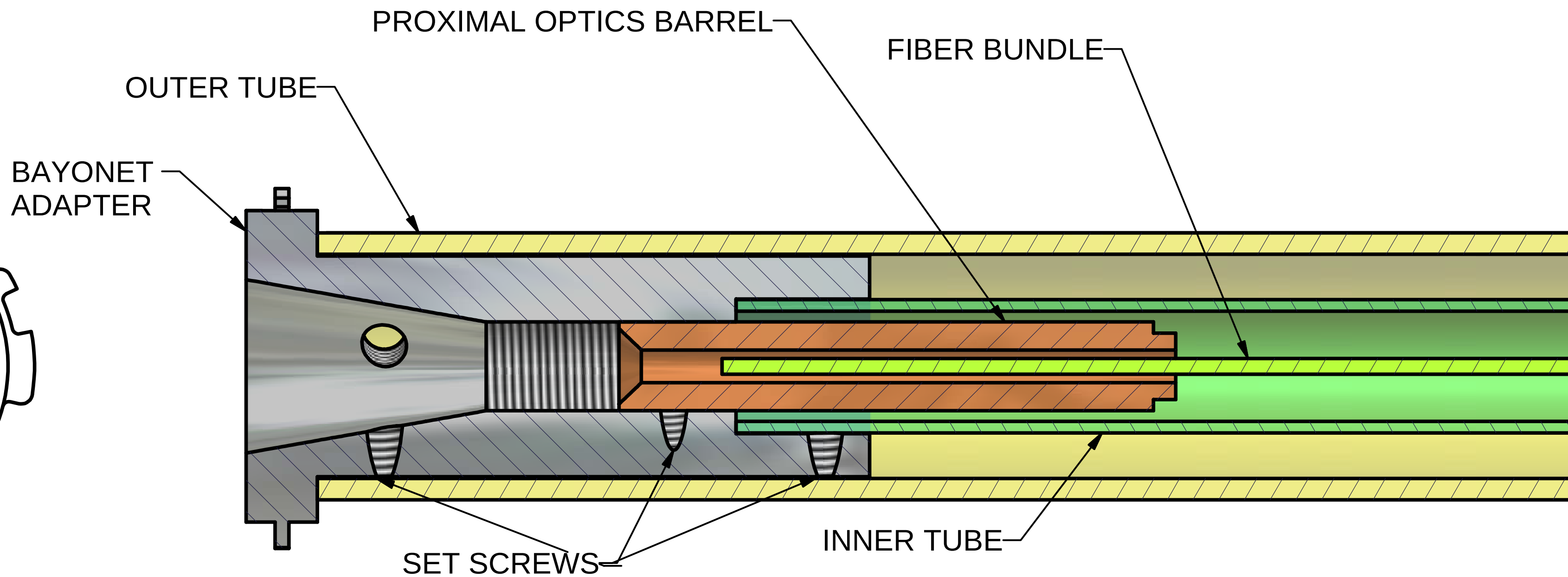
Title ADJUSTMENT BLOCK	Material 304 stainless	Tolerance +-0.003	
Designer William Carter	Company PSU - AR	Revision Number 1	Comments Break Edges 0.010 X 0.010 Chamfer Units in Inches
Project BLACK LIQUOR IMAGING	Scale 1:1		
Creation Date 5/11/2005			



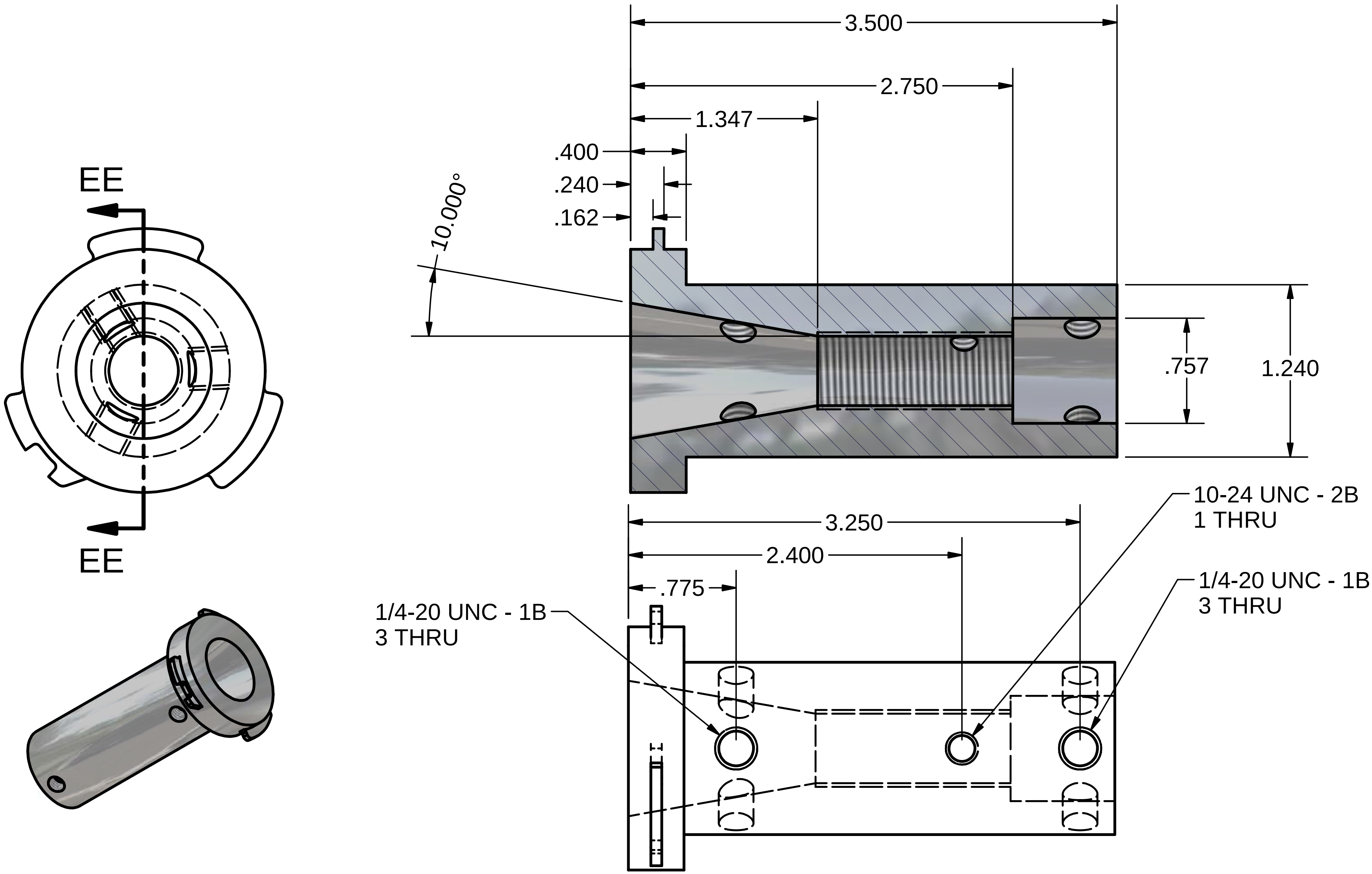
Title 2 INCH ADAPTER	Material 304 stainless	Tolerance +-0.003	
Designer William Carter	Company PSU - AR	Revision Number 1	Comments Break Edges 0.010 X 0.010 Chamfer Units in Inches
Project BLACK LIQUOR IMAGING	Scale 1:1		
Creation Date 5/11/2005			



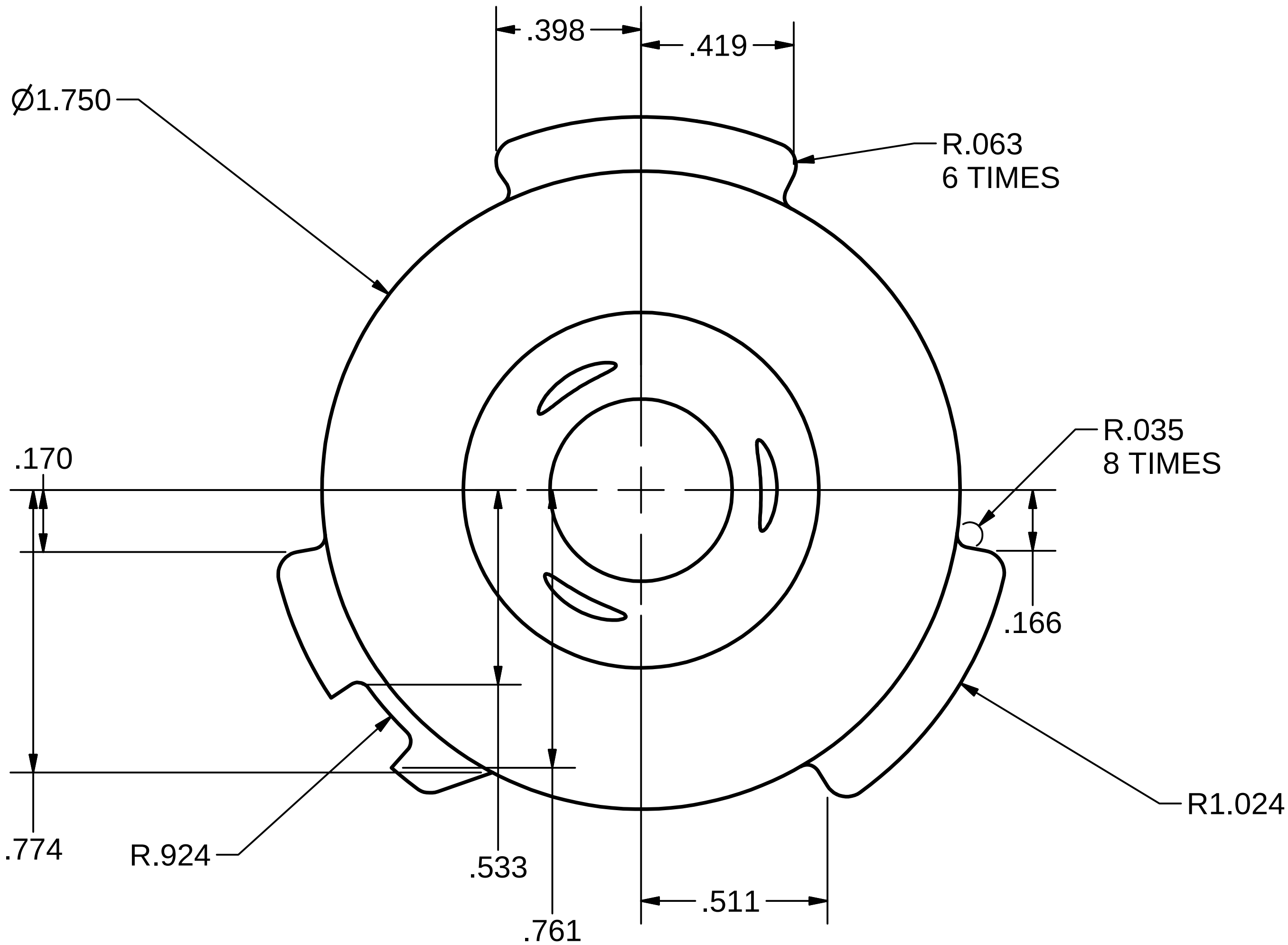




Title END ASSEMBLY	Material 304 stainless	Tolerance +-0.003	
Designer William Carter	Company PSU - AR	Revision Number 7	Comments Break Edges 0.010 X 0.010 Chamfer Units in Inches
Project BLACK LIQUOR IMAGING	Scale 1:1		
Creation Date 5/11/2005			



Title BAYONET ADAPTER	Material 304 stainless	Tolerance +-0.003	
Designer William Carter	Company PSU - AR	Revision Number 4	Comments Break Edges 0.010 X 0.010 Chamfer Units in Inches
Project BLACK LIQUOR IMAGING	Scale 1:1		
Creation Date 5/11/2005			



Title BAYONET DETAIL	Material 304 stainless	Tolerance +-0.003	
Designer William Carter	Company PSU - AR	Revision Number 4	Comments Break Edges 0.010 X 0.010 Chamfer Units in Inches
Project BLACK LIQUOR IMAGING	Scale 2:1		
Creation Date 5/11/2005			