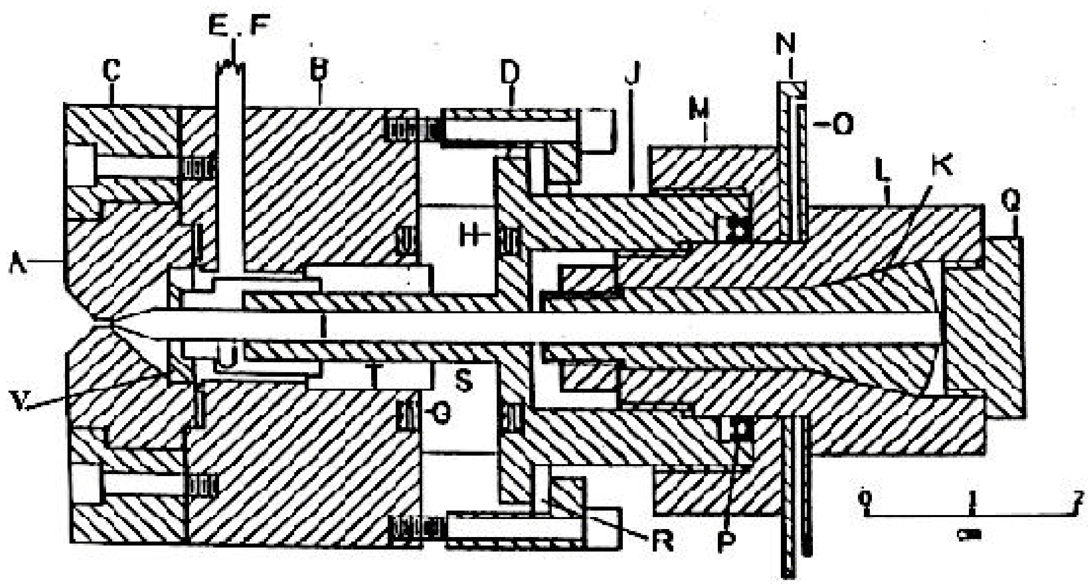
Section 4.0: The Virginia Tech Plasma Torch Design

The Virginia Tech Plasma Torch was originally designed by Stouffer (1989) in 1988-89. It was designed to operate with argon, nitrogen, hydrogen and mixtures of the three. The torch operated at power levels between 0.3-1.6 kW, depending on the current being supplied and feedstock being used. A cross-sectional scaled diagram of the torch is shown in Fig. 4.1. Each component of the torch can be categorized in one of three ways; part of the positive section of the torch (A-G), part of the negative section of the torch (I-Q), or an insulator (R-V).



Adjustable Gap Plasma Torch: A, anode; B, body; C, anode holder; D, pressure ring; E, gas inlet; F, pressure tap; G,H, E-ring seals; I, cathode; J, cathode alignment piece; K, collet; L, cathode adjustment knob; M, gland cap; N, mounting bracket; O, angle indicator; P, dynamic seal; Q, end cap; R,S, insulators; T, alignment piece; U, insulator; V, flow swirler

Figure 4.1: Virginia Tech Plasma Torch Schematic

To adapt the torch to new requirements, modifications were made to the electrode geometry, power connections, insulators and gas seals. These modifications will be discussed later in their respective sections.

4.1: The Positive Section of the Torch

The positive section of the torch is comprised of the anode and anything that is in electrical contact with it. The positive section of the torch is shown assembled in Fig. 4.2(a) and disassembled in Fig. 4.2(b). The anode (A) is held to the torch body (B) by the anode holder (C). Both the anode holder and torch body are made from stainless steel. The anode is made from 2% thoriated tungsten. The anode holder has six axisymmetric sunken thru holes to allow for the six hardened steel Allen-head cap screws to pass through. The cap screws (#3-48) are hardened steel and screw into the torch body. Two radial holes drilled into the torch body cavity allow for a gas inlet (E) and pressure tap (F). The gas inlet and pressure tap are made from stainless steel tubing and attach to the torch body using silver solder. A type-K thermocouple (not shown) is also attached to the torch body using silver solder. This thermocouple was used to gather torch body temperature data. The stainless steel pressure ring (D) was designed to hold the negative and positive sections of the torch together, separated by an insulator (R). As with the anode holder, there are six thru-holes to allow for six Allen-head cap screws (#3-48) to attach the pressure ring firmly to the torch body. The power connection is made by attaching a power clamp (found on car jumper cables) to either the gas inlet (E) or the pressure tap (F).

Throughout the current testing phase of the plasma torch experiments, problems arose because of the Allen-head cap screws. In order to form a tight seal between the anode and torch body, the Allen-head cap screws in the anode holder had to be torqued past their recommended values. Also, the pressure ring (D) could not be tightened down enough to prevent the cathode alignment piece (J) from rotating when a torque is applied to the gland cap (M) to disassemble the torch. These problems were a function of the bolt diameter and inability of the bolts to be tightened to needed values. For future design considerations, larger bolt diameters are recommended.

The Positive Section of the Torch

(Assembled)

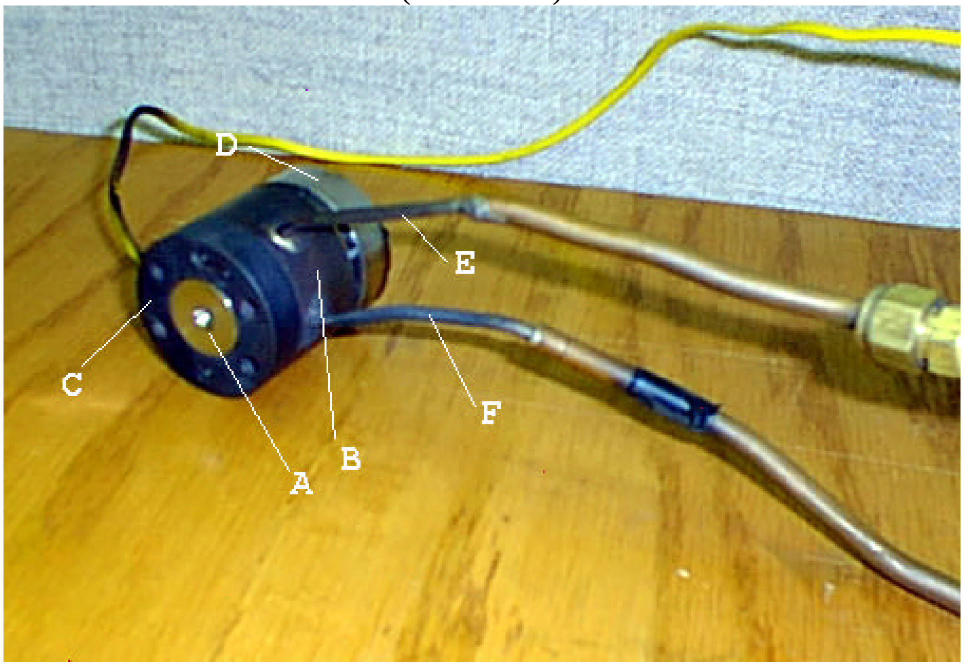


Figure 4.2 (a)

(Disassembled)

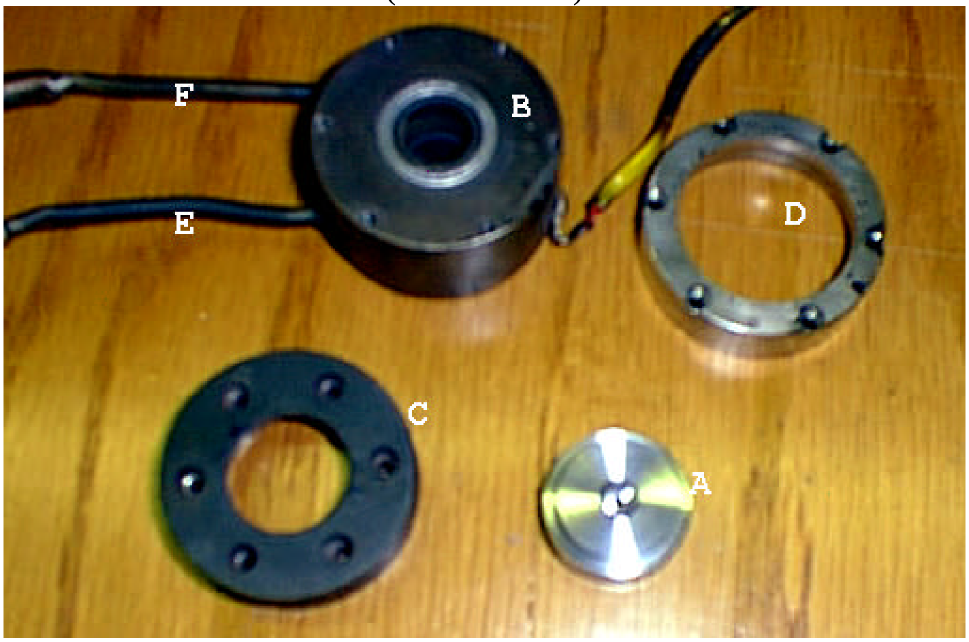


Figure 4.2 (b)

A: Anode, B: Torch Body, C: Anode Holder, D: Pressure Ring, E,F: Gas Inlet & Pressure Tap.

4.2: The Negative Section of the Torch

The negative section of the torch houses the cathode and anything that is in electrical contact with it. The cathode (I) is held by a collet (K), which is fitted to the cathode adjustment knob (L). The adjustment knob is finely threaded (40 threads per inch) and screwed into the cathode alignment piece (J), creating a micrometer drive. Every 100° of knob rotation produces 0.178mm of cathode axial movement. The angular position of the knob can be read on the angle indicator (O). The back of the plasma torch, showing the angle indicator, is displayed in Fig. 4.3.

Originally, a phenolic knob was attached to the cathode adjustment knob to allow for cathode adjustment during operation. This practice of manually adjusting the cathode during operation was discontinued due to the unpredictability and safety issues concerning hydrocarbon operation. This knob does not appear in the figures.

Figure 4.3: Plasma Torch Angle Indicator

N: Mounting Bracket w/ angle reference, O: Angle Indicator, Q: End Cap,
L: Cathode Adjustment Knob

A mounting bracket (N) is attached to the gland cap (M) using four small screws. The mounting bracket has an angle readout attached so that the angle indicator had a nonmoving reference point with which to measure from. Also, it provides a stop so that one can not screw the adjustment knob in so far as to reach the end of the threads. The gland cap is threaded so that it screws onto the cathode alignment piece (J). The angle indicator and mounting bracket are both made of aluminum, while the adjustment knob, gland cap and cathode alignment piece are all made from stainless steel.

The negative section of the torch is allowed to float with respect to ground. Originally, the power connection was made through the mounting bracket (N), but it was decided that a stronger more durable connection was needed. Therefore, a power bracket was designed to fit around the gland cap. This power connection is shown assembled to the positive section of the torch in Fig 4.4(a) and disassembled in Fig. 4.4(b). It is made of stainless steel ring, with an inner diameter just large enough to fit over the gland cap. A threaded hole accommodates a 3/8" bolt, which serves as both a tightening mechanism on the gland cap and as a power connection point.

The Negative Section of the Torch

(Assembled)

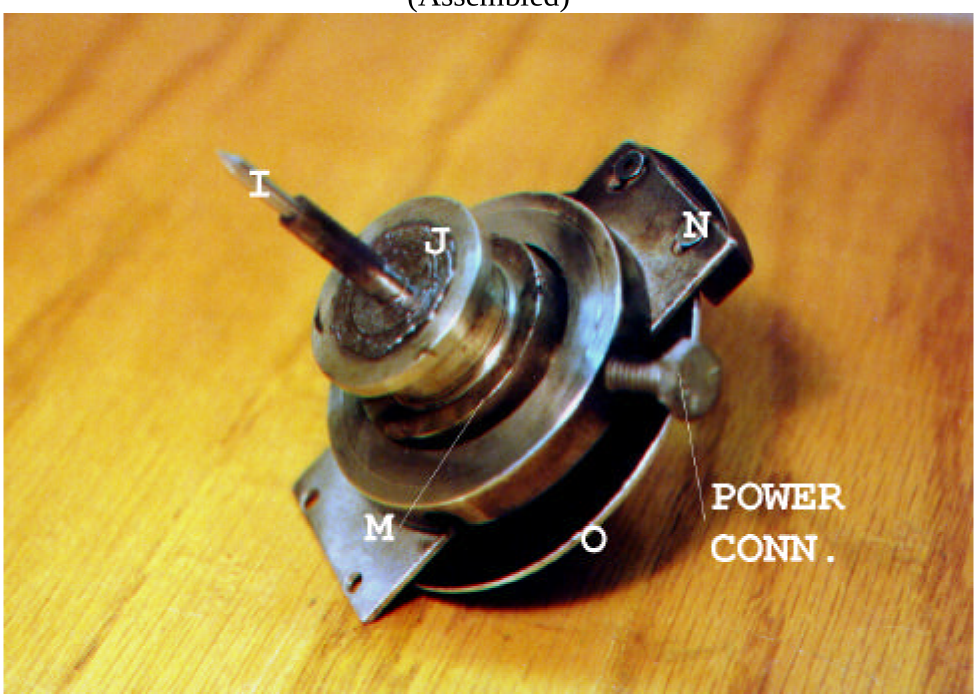


Figure 4.4(a)

(Disassembled)

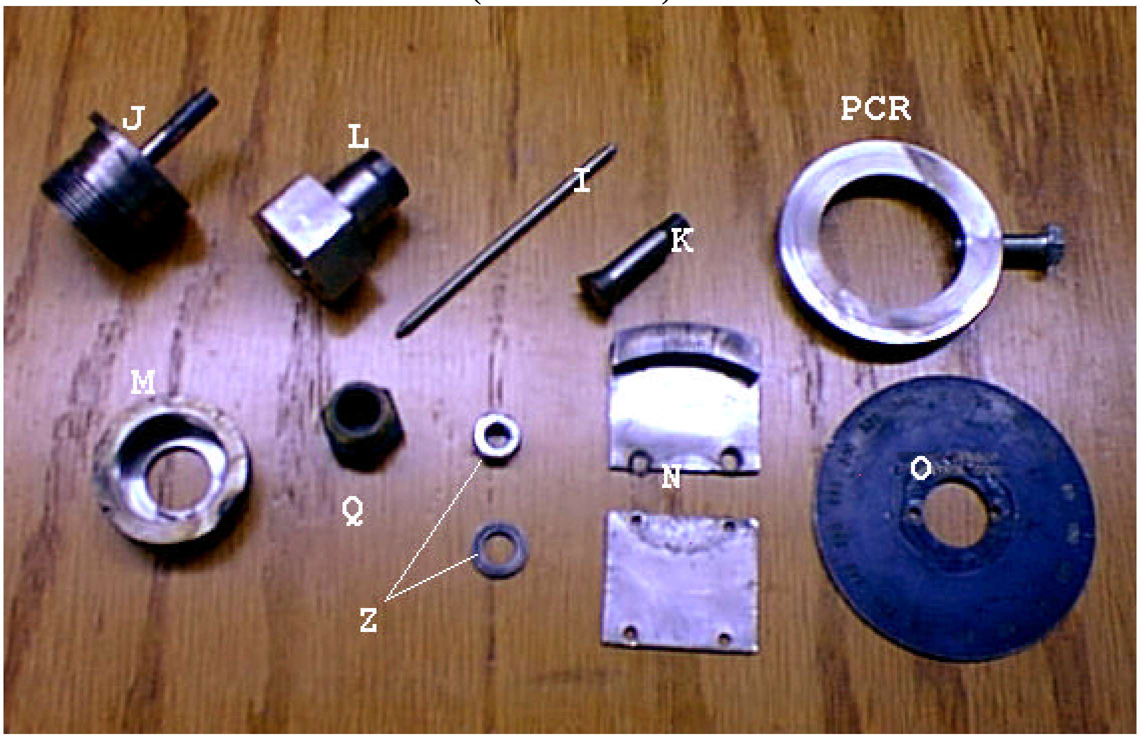


Figure 4.4(b)

I: Cathode, J: Cathode Alignment Piece, K: Collet, L: Cathode Adjustment Knob, M: Gland Cap, N: Mounting Bracket w/ Angle Reference, O: Angle Indicator, Q: End Cap, Z: Nut and Washer for Collet

4.3: Insulators

There are seven insulators in the torch. Originally, there were five (R-V in Fig. 4.1), but two additional insulators (not shown in Fig 4.1) were added to solve some arcing problems experienced during testing. All seven insulators are shown in Fig. 4.5. Insulator R is made from glass phenolic. The purpose of insulator R is to provide electrical insulation between the positive and negative sections of the torch and also to allow enough pressure to be applied by the pressure ring, D, to provide an effective gas seal at the E-ring seals, G and H. Glass phenolic is less brittle than most ceramics and is ideal in this type of application. Also, the temperatures in this region of the torch are low enough to allow glass phenolic to be used.

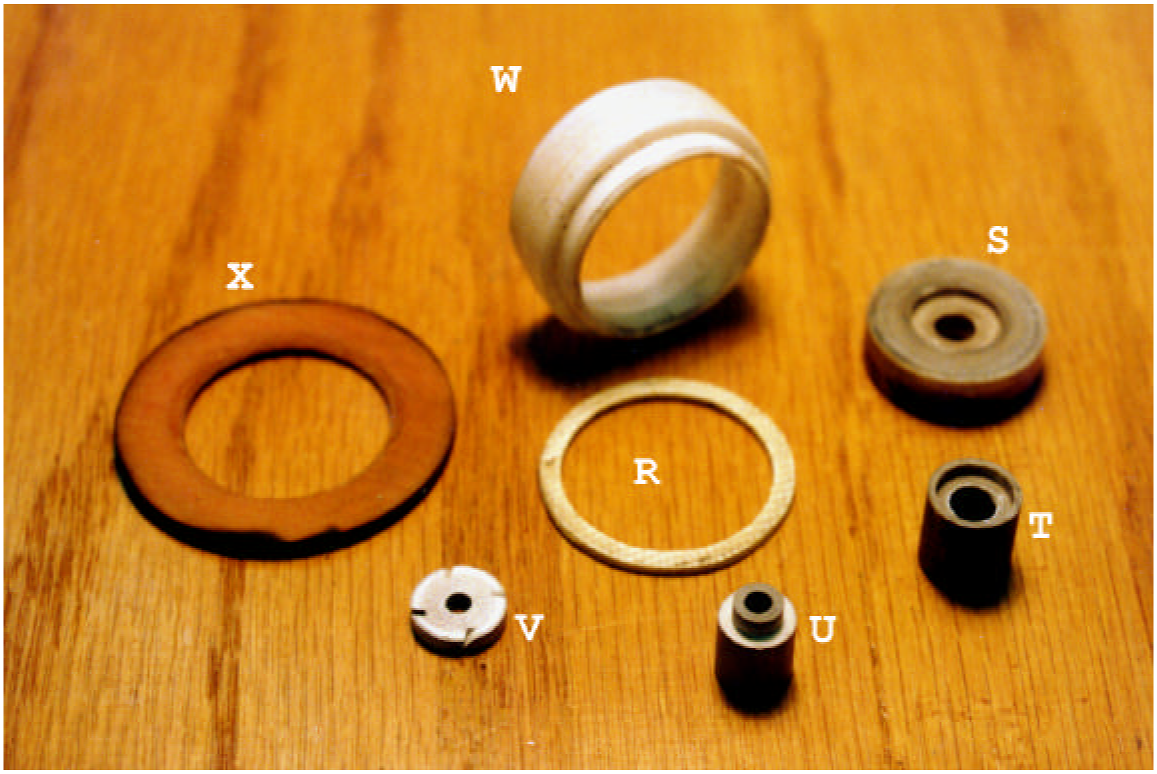


Figure 4.5: Plasma Torch Insulators

R: Glass Phenolic Ring, S: Macor® Glass Ceramic Insulator, T: Alignment Piece, U: Boron Nitride Insulator, V: Boron Nitride Flow Swirler, W: Nylon Pressure Ring Insulator, X: Phenolic Ring Insulator

Insulators U and V are made from boron nitride, grade M26, used specifically for plasma torches (Carborundum, Amherst, NY). Boron nitride is a soft white material with the consistency of chalk. These two insulators are exposed to extremely high temperatures. Boron nitride can be used in a hydrogen environment up to 3250K, making it safe for this type of application. Also, the flow swirler, V, needs to be easily machined because of the grooves, which must be cut into its side. Boron nitride fills all of these requirements, and through intense testing, has proven its reliability.

The insulator, W, shown in Fig. 4.6 with the pressure ring, is constructed from nylon. When testing on this project started in 1997, arcing occurred between the cathode alignment piece, J, and the pressure ring, D. To solve this problem, the cathode alignment piece and pressure ring were machined so that there was a larger gap between them, hopefully providing enough distance to prevent arcing. However, this attempt yielded limited results. Nylon screws replaced the Allen-head cap screws for the pressure ring to electrically isolate it from both the cathode and anode, but they could not provide enough force to keep the positive and negative sections of the torch together during high-pressure operation. Insulating tape was wrapped around the cathode alignment piece, but it was impossible to cover all sections adequately to prevent arcing. Finally, a nylon insert was designed to provide 100% coverage of the arcing problem areas. Once in place, the nylon insulator prevented any further arcing problems in that area. Another insulator, X, was made from paper-phenolic, which screwed onto the cathode alignment piece and provided electrical separation between the pressure ring, D, and the gland cap, M. Once these two new insulators were in place, no arcing problems were experienced again anywhere within the torch.

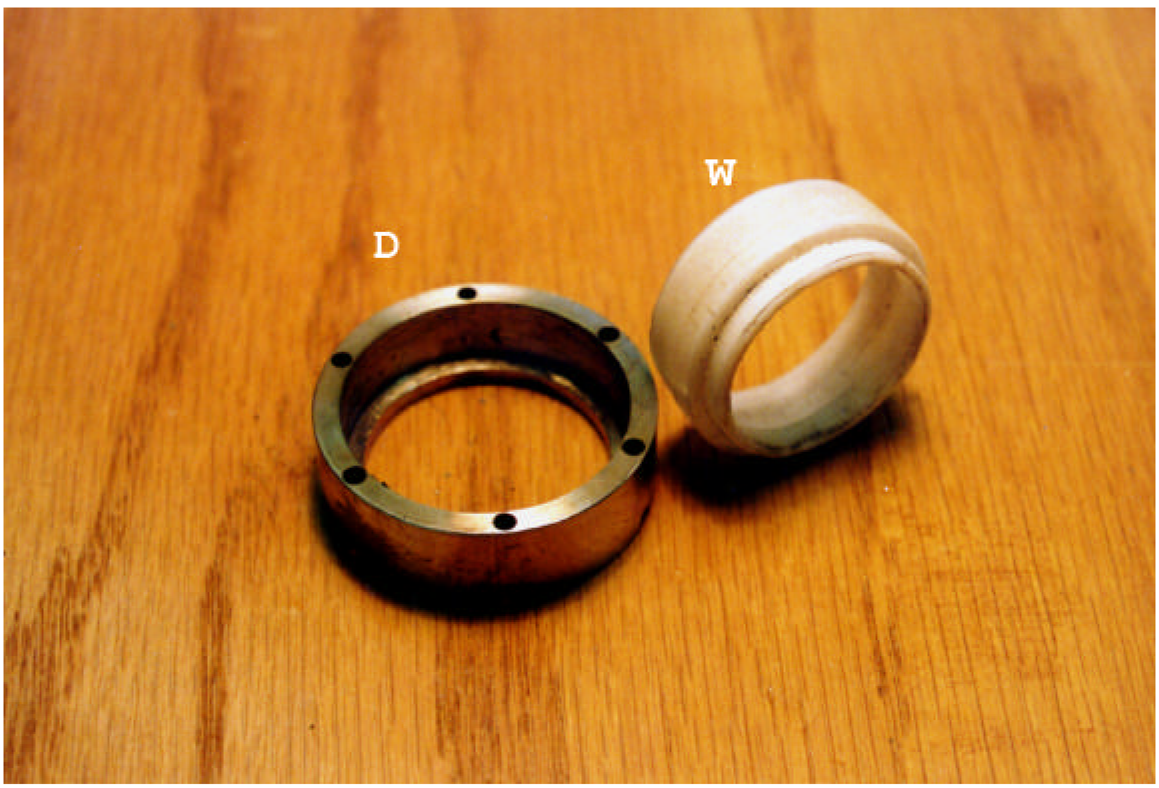


Figure 4.6: Nylon Insulator and Pressure Ring

D: Pressure Ring, W: Nylon Pressure Ring Insulator

Insulators S and T are constructed from machineable Macor® glass ceramic (Corning). Macor® glass ceramic is an excellent material for this type of application, where temperatures are higher than at insulator R and a hard material is needed. These insulators need to be hard in order to provide effective alignment for the cathode. Softer materials would yield, causing poor electrode alignment. Insulator T is used as both an alignment piece for the cathode and a support for insulator U. It needs to have a tight fit in order to provide adequate alignment. The top and bottom of insulator S are covered with a nickel lubricant to help provide better sealing at the E-rings. Nickel lubricant has excellent lubricating and sealing characteristics, even at high temperatures. However, when using this type of lubricant, insulators S and T must be cleaned regularly with acetone to prevent any short-circuiting between the positive and negative sections of the torch due to stray lubricant. Microscopic lines of nickel, which are undetectable to the human eye, can form, preventing the torch from operating properly.

4.4: Gas Seals

Gas seals are extremely important in any combustion application for safety and proper operation of the equipment. In a plasma torch, gas leaks can cause chamber pressure drops leading to poor torch operation. Also, the amount of gas flowing out of the anode throat will not be what is read from the digital flow meters. Especially when working with toxic or hydrocarbon gases, it is essential that all the gases pass through the anode throat so that unburned hydrocarbons or toxic gases do not accumulate in the test cell. Perhaps the most dangerous aspect of gas seal failure is that of flameout. Flameout occurs when combustible gases leak out of the torch and then ignite. A photograph demonstrating this is shown in Fig. 4.7. In this case, the dynamic seal, P, failed and allowed ethylene to escape, which then ignited and formed a diffusion flame out the back of the torch.

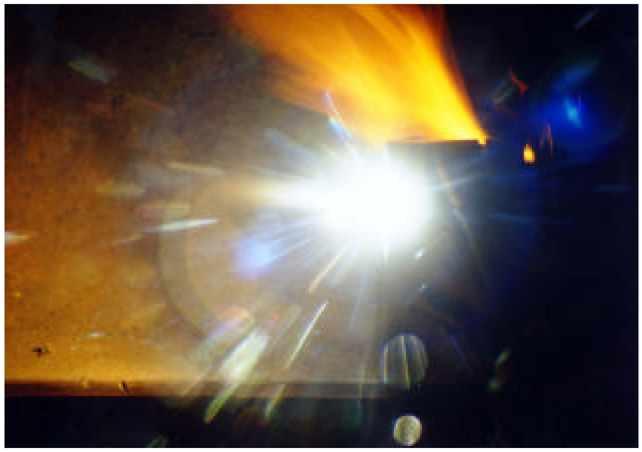


Figure 4.7: Example of Gas Seal Failure

Several gas seals are used to seal the torch. The first is located between the anode and torch body. A circular seal is cut from a graphoil sheet and placed under the anode. When the anode holder is tightened onto the torch body, this graphoil ring crushes and forms an effective gas seal. Graphoil is 99.5% graphite and is an extremely good conductor of electricity. It can also be used in applications up to 3250K. Each time the anode holder is removed, this seal should be replaced because the graphoil has already been crushed and may not provide an effective seal the second time it is used.

Another way for gases to leak out from the torch is between the Macor® insulator, S, the cathode alignment piece, J, and the torch body, B. Two E-ring seals were used here to prevent leakage from the sides of the torch. The E-rings were made from Inconel X-750 and were silver-plated. A nickel lubricant/sealant was also used to insure a proper seal.

Leakage from the back of the torch can occur one of two ways. Gas can leak between the end cap, Q, and the cathode adjustment knob, L, or between the cathode alignment piece, J, and the cathode adjustment knob. Teflon thread sealant tape was wrapped around the threads of the end cap before it was screwed into the cathode adjustment knob to prevent leakage through the threads. Teflon thread sealant tape comes in very thin white strips and is designed to prevent gas leakage through threads as well as lubrication for easy removal. Another seal, P, was used to prevent gas leakage between the cathode alignment piece, J, and cathode adjustment knob, L. This is a dynamic seal to accommodate the rotational and axial movement of the cathode adjustment knob. It is an Enerseal Mark I spring-energized seal from the Advance

Products company. The seal consists of an inner stainless-steel spring, surrounded by a 10% Ekonal-filled Teflon jacket. The Teflon jacket forms the sealing surface between the cathode alignment piece and the cathode adjustment knob.

4.5: The Flow Swirler

The flow swirler, V, is an essential part to the Virginia Tech Plasma Torch design. Without it, the arc would remain fixed at one spot on the anode wall and produce high rates of electrode erosion. The flow swirler is shown in Figs. 4.8 and 4.9. The flow swirler is designed so that all of the flow that enters the anode nozzle must pass through the flow swirler. The flow swirler induces vorticity into the flow, producing several benefits. First, the vortex provides convective cooling to part of the anode throat. It also stabilizes the arc in the center of the anode throat. Finally, the vortex causes the arc to rotate, allowing hot spots of the anode to cool, reducing electrode erosion. With the grooves cut at 45° from the axial direction, the flow swirler has a theoretical swirl number of 1.0 just downstream of the flow swirler exit passages, with the swirl number being defined as the tangential velocity of the flow, V_θ, divided by the axial velocity, V_x. As the flow accelerates through the anode nozzle, the swirl number is expected to change.

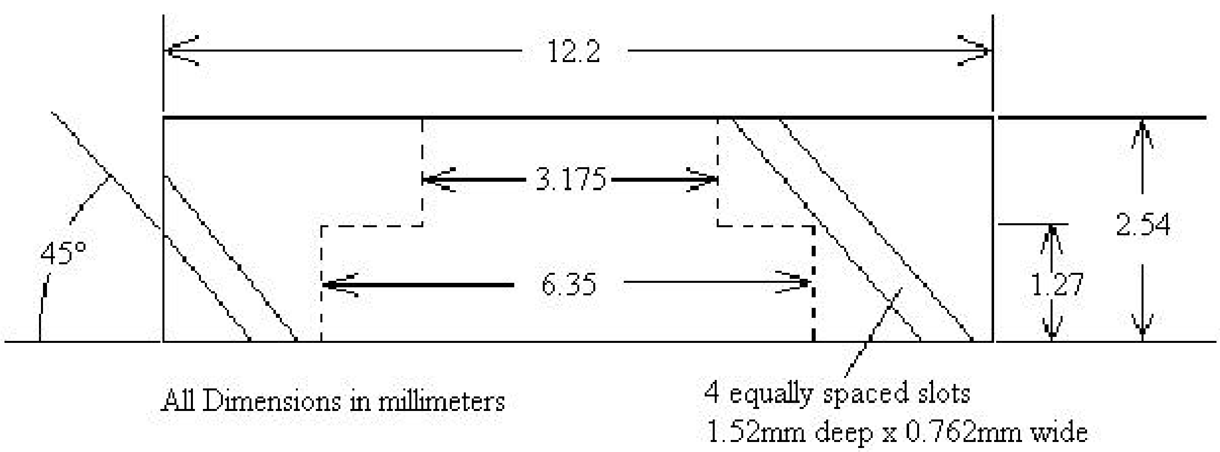


Figure 4.8: Cross-Section of the Flow Swirler

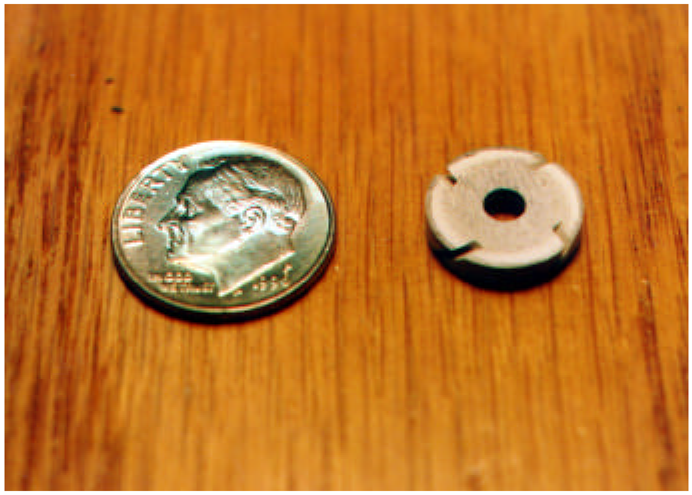


Figure 4.9: Photograph of the Flow Swirler

The flow swirler must fit into the torch body chamber, and be sturdy, reliable and able to withstand extremely high temperatures. In addition to these material requirements, the flow swirler must also provide the right amount of swirl to the flow. Recall that too much arc rotation does not allow hot spots of the anode to cool off enough before the arc makes another pass and too little rotation leaves the arc in one place too long. Many different flow swirlers were designed and tested by Stouffer (1989). Variables such as number of flow passages, passage angle and passage area were changed and tested. The final design, shown in Figs. 4.8 and 4.9, has four equal area flow passages at 45° from vertical. Each flow passage is 1.52mm (0.060in) deep and 0.762mm (0.030in) wide for an area of $1.16\text{x}10^{4}\text{mm}^{2}$ ($1.80\text{x}10^{-3}\text{in}^{2}$) per flow passage. The total area for the flow passages must be larger than the area of the anode throat, otherwise, the flow will choke in the flow swirler and not in the anode throat. The area of the anode throat is 2.01mm^{2} ($3.12\text{x}10^{-3}\text{in}^{2}$), while the total area for the four flow swirler passages is 4.65mm^{2} ($7.20\text{x}10^{-3}\text{in}^{2}$). A shoulder machined into the anode, which the flow swirler rests on, blocks part of the flow exiting the flow swirler. Therefore, the true exit area of the flow swirler is only 3.03mm^{2} ($4.70\text{x}10^{-3}\text{in}^{2}$), but this is still larger than the anode throat area. In addition, the tip of the cathode also fills a large portion of the anode throat area. This margin of error allows the torch to operate with choked flow at the anode even if the anode throat erodes to a larger diameter.

4.6: The Electrodes

The electrodes in any plasma torch are perhaps the most influential element in determining whether or not the design will be effective. Both the anode and cathode in the plasma torch are made from 2% thoriated tungsten (i.e. it is a 2% thorium alloy). A picture of the anode and cathode is shown in Fig. 4.10. The electrodes were originally designed by Barbi (1986), modified by Stouffer (1989) to obtain greater life, and again modified for the present application to operate with hydrocarbon gases.

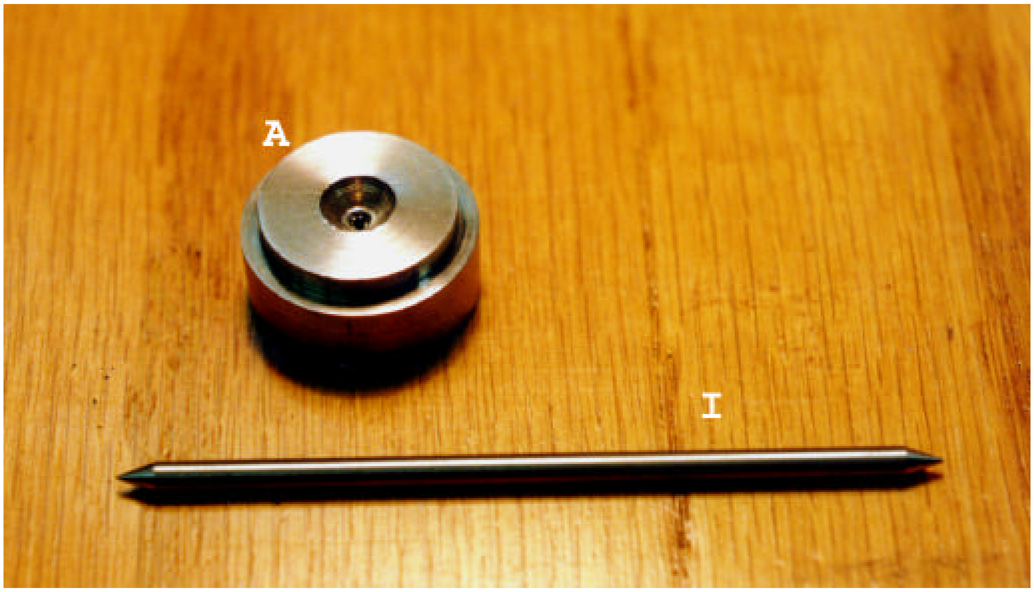


Figure 4.10: Virginia Tech Plasma Torch Electrodes

A: Anode, I: Cathode

The anode is a converging-diverging nozzle with a 45° half-angle for both the converging and diverging sections. A schematic of the anode is shown in Fig. 4.11. The anode is made from 2% thoriated tungsten rather than pure tungsten because of its improved machineability. Machineability is an important consideration when creating anodes because the throat is such a small diameter that special drill bits are needed. Originally, the throat had a diameter of 0.813mm (0.032in), but this was increased to 1.60mm (0.063in) because of the arcing problems mentioned earlier. It was thought that decreasing the pressure in the torch body chamber would produce a more stable arc and eliminate the arcing problems. This solution, coupled with the newly designed insulators, solved the arcing problems. The increased anode throat area was then larger than the flow passages of the flow swirler. Therefore, flow swirlers with greater flow passages were needed so the flow would not choke in the flow swirler, but rather in the anode throat.

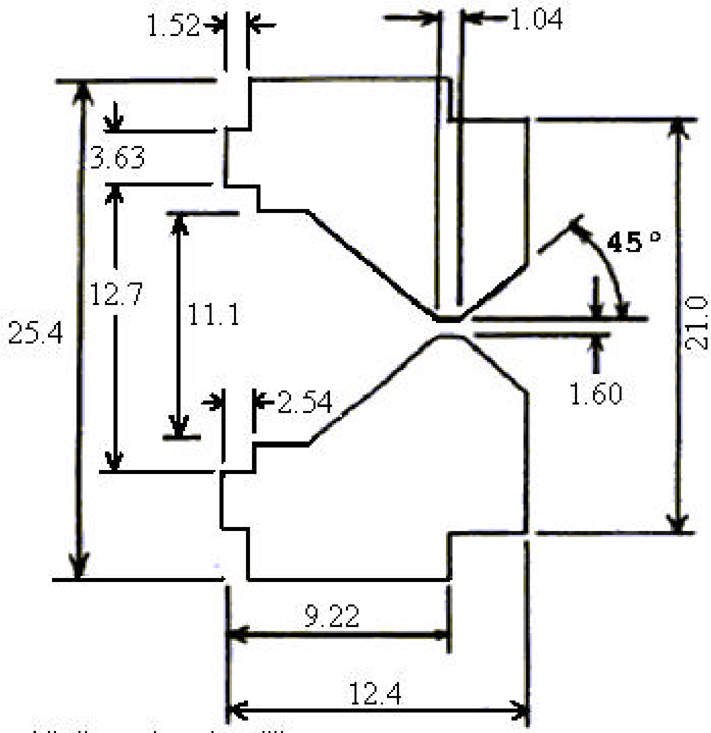


Figure 4.11: Plasma Torch Anode Schematic

The cathode is also machined from 2% thoriated tungsten. It is made from a 3.175mm (0.125in) tungsten-welding rod. 2% thoriated tungsten was chosen for the cathode because of its low thermionic work function. (i.e. it has very low rates of electrode erosion.) The end is machined to a 20° half-angle cone. Originally, the cathode had only one pointed tip, but by machining both ends to a point, double the use of a single piece of tungsten could be obtained. The new cathode design is shown in Fig. 4.12.

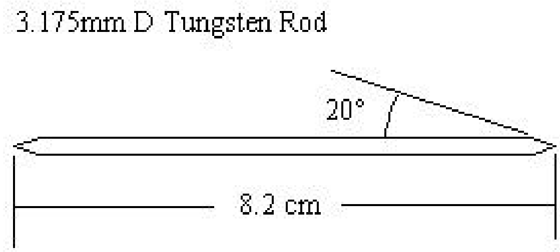


Figure 4.12: Plasma Torch Cathode Schematic

The torch was modified by Stouffer (1989) to improve electrode alignment. Since the arc gap is very small between the anode and cathode, small errors in alignment can cause large changes in the operation of the torch. The arc gap of the electrodes is defined by ‘G’ in Fig. 4.13. One effect of poor electrode alignment is the asymmetry produced in the electric and magnetic fields. Also, the flow symmetry is altered as the flow passes past the cathode tip and down the anode throat. Both of these effects can affect where the arc attaches and hence how the torch operates.

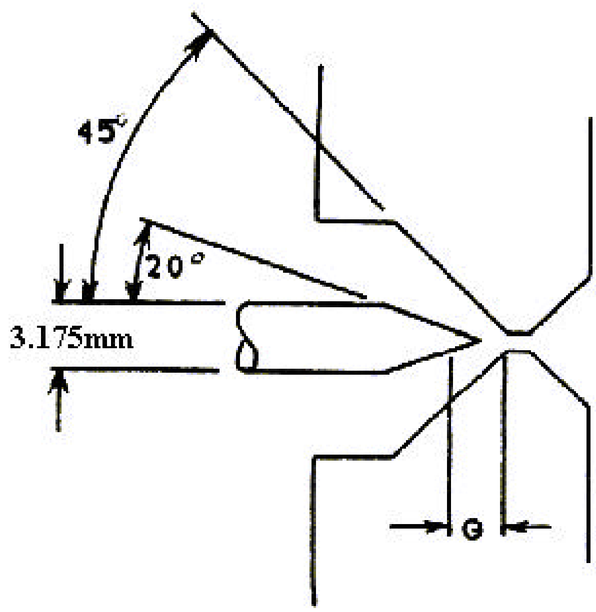


Figure 4.13: Definition of Arc Gap, G