Chapter 2
The Virginia Tech Plasma Torch, 3^{rd} Generation (VTPT-3)

"A design is what a designer has when time and money run out." –James Poole

A plasma torch is a device in which a flowing gas is passed through an electric arc, producing plasma. Plasma contains a mixture of ions, electrons, and neutral particles. Although various definitions for plasma exist, a common designation for plasma is any gas over 3000 K. These plasmas are rich with excited species and are useful for a variety of applications such as flame stabilization, IC engine lean burn applications, and exhaust emission control. In addition, plasma torches vary widely in design, depending on their application; but all are primarily based on the production of an electric arc to dissociate feedstock gases.

Virginia Tech has a two-decade history in the design and testing of plasma torches for use in supersonic combustion applications. Due to the progression of designs, and the confusion of referring to all of these designs as the "Virginia Tech Plasma Torch," a convention will be introduced to clarify which design is being discussed. The most recent design, used for a majority of the work in this dissertation, will be referred to as VTPT-3, standing for Virginia Tech Plasma Torch, 3^{rd} Generation. The torch designed by Stouffer in the late 1980s will then be referred to as VTPT-2 (Stouffer, 1989), and the torch used by Barbi and Wagner in the mid 1980s will be VTPT-1 (Barbi, 1986; Barbi et al., 1989). Currently, VTPT-4 has been produced and will be used to validate the integrated injector/igniter design presented in this dissertation. It replaces VTPT-3 since that design is too large to fit in the proposed combustion facility test cell, but maintains the same internal geometry. Based upon the knowledge gained in this study, VTPT-5 was designed in early 2001 and will be used for drag reduction experiments at Arnold Engineering Development Center.

A scaled, cross-sectional diagram of VTPT-3 is shown in Figure 2.1. Each component of the torch is categorized as part of the positive section of the torch (A-B), part of the negative section of the torch (C-E), an insulator (F-I), or a seal (J). This torch was designed to minimize the number of parts, currently twelve, compared to VTPT-2, which has twenty-three. The reduction of parts was found to produce great benefits in the areas of reliability, sealing performance, and the time needed to change electrodes. The discussion of the torch components is organized to deal with like parts in the same section.

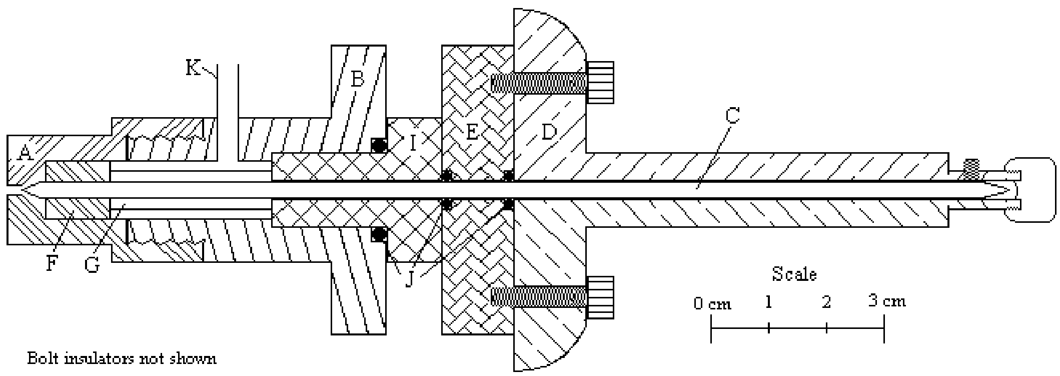


Figure 2.1: Schematic of VTPT-3
(A: Anode, B: Torch Body, C: Cathode, D: Micrometer Drive, E: Cathode Bracket,
F: Flow Swirler, G: Support Rod, H: Bolt Jackets, I: Body Insulator, J: O-Rings, K: Feedstock Lines)

2.1: The Anode and Cathode

Examples of the anode and cathode used with VTPT-3 are shown in Figure 2.2. The size and complexity of the anode used with VTPT-3 prompted the use of softer metals for easier machineability, whereas the smaller anodes of VTPT-2 were made of tungsten. Through a number of erosion tests, it was shown that molybdenum was a good substitute for tungsten, providing a slightly shorter lifetime than tungsten, but being much easier to machine. For tests involving air and nitrogen, copper anodes were used in place of molybdenum, since it was discovered that air and nitrogen plasmas were quite erosive to molybdenum, but less so for copper. The internal geometry of the anode used here is identical to that of the one used on VTPT-2, since the design used for that torch was proven and worked well. The external geometry is quite different though, to allow for easy insertion into the tunnel test cell and quick removal of the anode with a wrench. This circumvented the need for unscrewing six Allen-head cap screws present on the earlier design. The anode screws onto the torch body and can be tightened using two wrenches. Leverage is provided by means of flats machined into the anode and torch body.

The cathode is machined from a 0.125-in. diameter, 2% thoriated tungsten welding rod. The ends are machined to a 20° half-angle cone, identical to the cathodes used in VTPT-2, except for the length. Since the electrode geometry for VTPT-3 is identical to VTPT-2, the same arc gap of 0.178 mm is maintained. To make this adjustment, the micrometer was turned until electrical contact between the anode and cathode was made. Then, the cathode was backed out until electrical contact was broken. From this point, the cathode was backed out an additional 0.178 mm to set the arc gap.

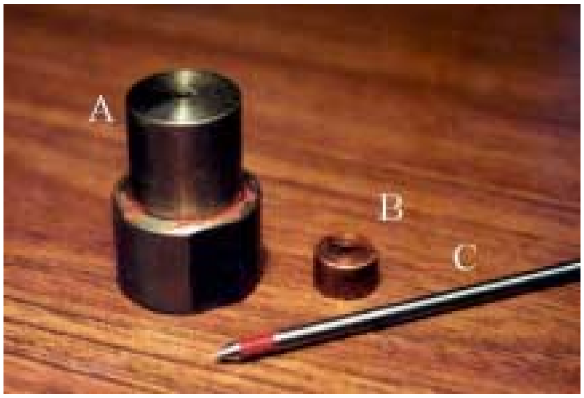
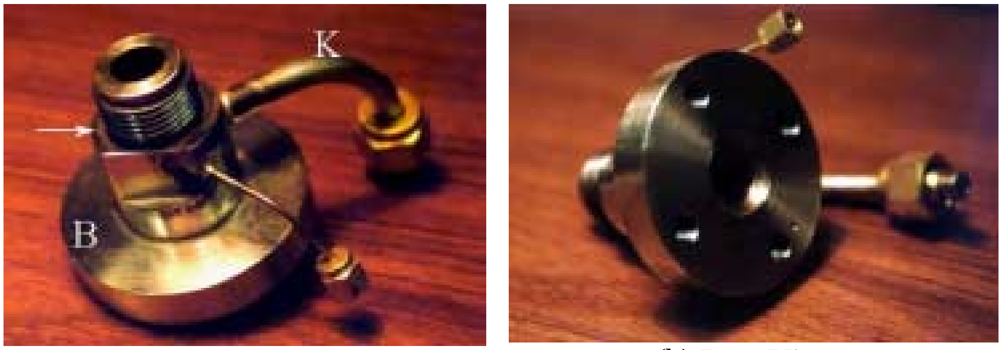


Figure 2.2: Plasma Torch Electrodes
(A: Molybdenum Anode, B: Copper Insert, C: Tungsten Cathode)

2.2: The Torch Body

The torch body is machined from stainless steel to resist corrosion and to provide a hard structural surface into which other torch components can be screwed. A picture of the torch body is shown in Figure 2.3. Two stainless steel tubes are fitted to the torch body to allow for a pressure tap and the input of a torch feedstock. As shown in Figure 2.3, the larger tube is for the feedstock, while the smaller is used for the pressure tap. Nickel lubricant/sealant is spread over the threads to help prevent leaks between the anode and torch body, as well as to prevent galling between the copper anodes and the harder torch body threads. The actual sealing surface between the anode and torch body occurs at the flat interface between the two, highlighted by the arrow in Figure 2.3a. The micrometer drive assembly attaches to the back of the torch body by means of four ¼-in. Allen-head cap screws. An o-ring between the torch body and body insulator prevents feedstock leaks out the back of the torch chamber.



(a) Front View (b) Rear View

Figure 2.3: Plasma Torch Body
(B: Torch Body, K: Feedstock Line)

2.3: The Micrometer Drive Assembly

The micrometer drive, micrometer bracket, and the cathode are collectively referred to as the micrometer drive assembly, which is shown in Figure 2.4. The micrometer drive is a 440 Starrett® depth micrometer used to ensure accurate setting of the arc gap. The micrometer attaches to the micrometer bracket by means of two ¼-in. Allen-head cap screws (chrome-colored in Figure 2.4). The bracket, machined from stainless steel, is then anchored to the torch by means of four additional ¼-in. Allen-head cap screws. Bolt insulators around the bracket screws and the body insulator keep the anode and cathode electrically isolated. An o-ring between the micrometer bracket and micrometer drive provides a secondary seal in case the o-ring between the body insulator and micrometer bracket fails.

Figure 2.4: The Micrometer Drive Assembly
(D: Micrometer Drive, E: Micrometer Bracket)

2.4: The Bolt and Body Insulators

The bolt and body insulators, shown in Figure 2.5, are made from Teflon®. The bolt insulators act as protective jackets, preventing electrical contact between the bolts, which are electrically connected to the anode, and the micrometer bracket. One of the bolt jackets is shown fitted onto an Allen-head cap screw, demonstrating this concept. The body insulator acts as an insulator between the torch body and micrometer bracket, and also serves as a guide piece to align the cathode. The low hardness of Teflon® and the heat stress caused by the demanding testing schedule caused the body insulator to warp and forced its occasional replacement. All Future insulators, such as those used on VTPT-4, will be machined from PEEK® (poly-ether-ether-ketone), a harder and higher temperature resistant material, to overcome this problem.

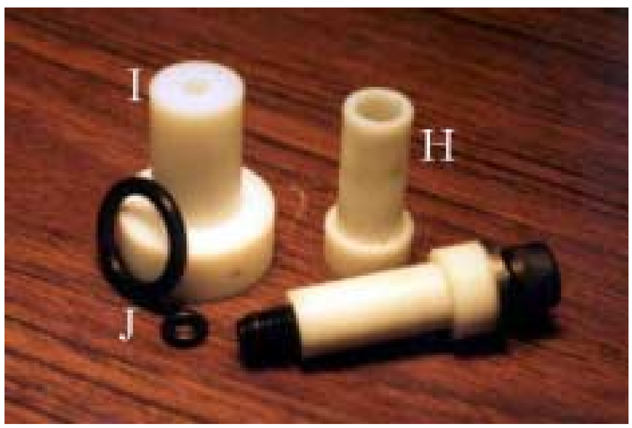


Figure 2.5: Bolt and Body Insulators
(I: Body Insulator, H: Bolt Jacket, J: O-Rings)

2.5: The Flow Swirler and Support Rod

The flow swirler and support rod are both components housed within the torch chamber and are shown in Figure 2.6. The flow swirler, machined from boron nitride, is an adaptation from the design used on VTPT-2. It maintains the 45° channel orientation, but uses three flow channels instead of four and is 0.5-in. long, rather than 0.1-in. The reduction in the number of flow channels increased the structural integrity of the flow swirler, which had previously been a design concern. In addition, the added length of the swirler is due to the lengthening of the torch anode, facilitating easy removal of the swirler from the anode body if needed. The combined area of the flow channels is four times greater than the anode constrictor area, ensuring that choking occurs in the anode throat and not in the flow swirler. The flow swirler slides into the anode and is pressed against the converging section of the anode constrictor by the pressure supplied from the support rod. To prevent the flow swirler from cracking, the upper portion of the flow swirler was chamfered to match the angle of the anode converging section. In addition, the support rod was machined from Teflon® to provide some cushioning effect in case the anode was screwed on too tightly. Although temperatures in this region of the torch are higher than the region where the bolt and body insulators are used, the support rod never experienced any kind of failure, so the low hardness of Teflon® for this piece was not a factor.

Figure 2.6: Flow Swirler and Support Rod
(F: Flow Swirler, G: Support Rod)

2.6: Design Issues

By now, the simplicity and functionality of the design is quite evident. In practice, VTPT-3 was observed to be quite reliable and durable. However, mention of a few key observations should be made for future users. First, the converging angle of the anode is quite important. For one set of anodes manufactured during this project, this feature was ignored and was machined to the half angle of a drill bit (approximately 60°). These anodes had poor starting capability and proved quite troublesome. In addition, the constrictor length was another major source of problems. Again, loose tolerances produced some anodes with longer constrictors than others. These anodes also had poor startability, and required a much higher current to operate, resulting in a greatly reduced lifetime. Finally, over-tightening of the micrometer bracket screws caused a slight warping of the body insulator, which subsequently caused misalignment of the cathode.

Current torch designs now use PEEK® to overcome this problem; but nevertheless, it should be stressed that load-bearing parts should be made of tough materials to ensure proper cathode alignment.