DOE/MC/30361 -- 4087
(DE95009734)

Platelet-Cooled Plasma Arc Torch

Final Report

Scott Sieger

October 1994

Work Performed Under Contract No.: DE-AR21-93MC30361

For

U.S. Department of Energy
Office of Environmental Management
Office of Technology Development
Washington, DC

U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Aerojet General Corporation
Sacramento, California

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Abstract

In this 12-month program sponsored by the DOE Morgantown Energy Technology Center, Aerojet designed, fabricated, and tested six platelet cooled electrodes for a Retech 75T (90 MW) plasma arc torch capable of processing mixed radioactive waste. Two of the electrodes with gas injection through the electrode wall demonstrated between eight and forty times the life of conventional water cooled electrodes. If a similar life increase can be produced in a 1 MW size electrode, then electrodes possessing thousands, rather than hundreds, of hours of life will be available to DOE for potential application to mixed radioactive waste processing.

Acknowledgements

We would like to acknowledge the efforts of Mary Spatafore, the DOE contract specialist, and Bill Huber the contracting officer's Representative (COR) at the DOE METC for their management and coordination of this project and Paul Hart, DOE Headquarters, for his support.

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Section 1

Executive Summary

In this 12-month program sponsored by the DOE Morgantown Energy Technology Center, Aerojet designed, fabricated, and tested six platelet-cooled electrodes for a Retech 75T (90 MW) plasma arc torch capable of processing mixed radioactive waste. Two of the electrodes with gas injection demonstrated on the order of ten times the life of conventional water cooled electrodes. The life increase significantly exceeded the success criteria for the program, which was to increase life by at least a factor of two. If a similar life increase can be produced in a 1 MW size electrode, then electrodes possessing thousands, rather than hundreds, of hours of life will be available to DOE for potential application to mixed radioactive waste processing.

1.1 Introduction

The Mixed Waste Integrated Program (MWIP) is currently developing environmentally sound technologies to process, stabilize and store mixed radioactive waste. Mixed radioactive waste contains both organic and inorganic components, plus radioactive elements. An example of mixed radioactive waste is the contaminated dirt which exists at some DOE sites where nuclear material was manufactured.

One way to stabilize mixed waste is to treat it by plasma processing, a continuous feed process in which an electric arc is passed between an electrode, which acts as the anode, and the waste material, which acts as the cathode. Some of the waste constituents off gas, while others become a molten slag. After cooling, what remains is a glassy black rock resembling obsidian. The favorable attributes of this waste form are its low volume and low leach rate.

A drawback to the plasma arc torch method is the need to frequently replace the plasma torch electrodes. Electrodes wear rapidly due to the extreme heating rates which occur where the arc attaches. Increasing electrode life will (1) reduce operating costs associated with electrode change out in a radioactive environment, including replacement and disposal costs; and (2) increase worker and environmental safety by reducing the number of exposures to radioactive materials. The increase in arc life may be an enabling step which makes the application of arc torch to mixed waste vitrification practical.

1.2 Methodology

The objective of this program was to design, build and test three long life platelet electrode designs. Platelet cooling is a proven technology, developed by Aerojet over the last 30 years and implemented in a number of products, including rocket chambers, heat exchangers, and missile structural components. Platelets are thin sheets of metal in which coolant channels are chemically etched using a photographic negative as the etch guide. The sheets are then diffusion bonded together to form a monolithic part with properties of the parent material. The resulting part can have complicated two- and three-dimensional cooling passages impossible to obtain with conventional manufacturing and possessing precise coolant flow control.

The three platelet electrode designs are shown in Figure 1. The first design attempts to improve water cooling effectiveness by running cooling water through small channels inside the electrode wall. Conventional electrodes use backside cooling or large channels. The second design retains the water cooling channels and adds non-radial gas injection at the wall with the objective of swirling the arc gas to promote arc foot rotation. The third design is similar to the first, but a .02-inch thick iridium sleeve is added on the electrode inner diameter. Iridium is a thermally dense material with a 4449 ^{o}F melting temperature. A CAD generated isometric drawing of a platelet electrode is shown in Figure 2.

The program was conducted in FY 1994 according to the schedule shown in Figure 3. The program was structured around a simple Work Breakdown Structure (WBS) consisting of five major tasks:

1.0 NEPA Reporting
2.0 Design
3.0 Fabrication
4.0 Testing
5.0 Management and Reporting

Additional information concerning the WBS can be found in the Management Plan for this program [1].

Since the electrode heating environment is not well defined or understood, this program emphasized testing, rather than analytical prediction, to define the life of the parts. The strategy for technical success, i. e., at least two-fold increase in electrode life, was to build and test three different electrode designs with increasingly sophisticated cooling techniques.

1.3 Results

The electrodes were designed and built at Aerojet in Sacramento, California, then tested at Retech, Inc. in Ukiah, California. Retech manufactures a 1 MW torch, which is a candidate for systems processing mixed radioactive waste, and several smaller torches whose electrodes operate under the same type of conditions as the 1 MW torch. The test rig for this program was a Retech 75T (90 MW) torch which uses a smaller electrode than the 1 MW torch. Two

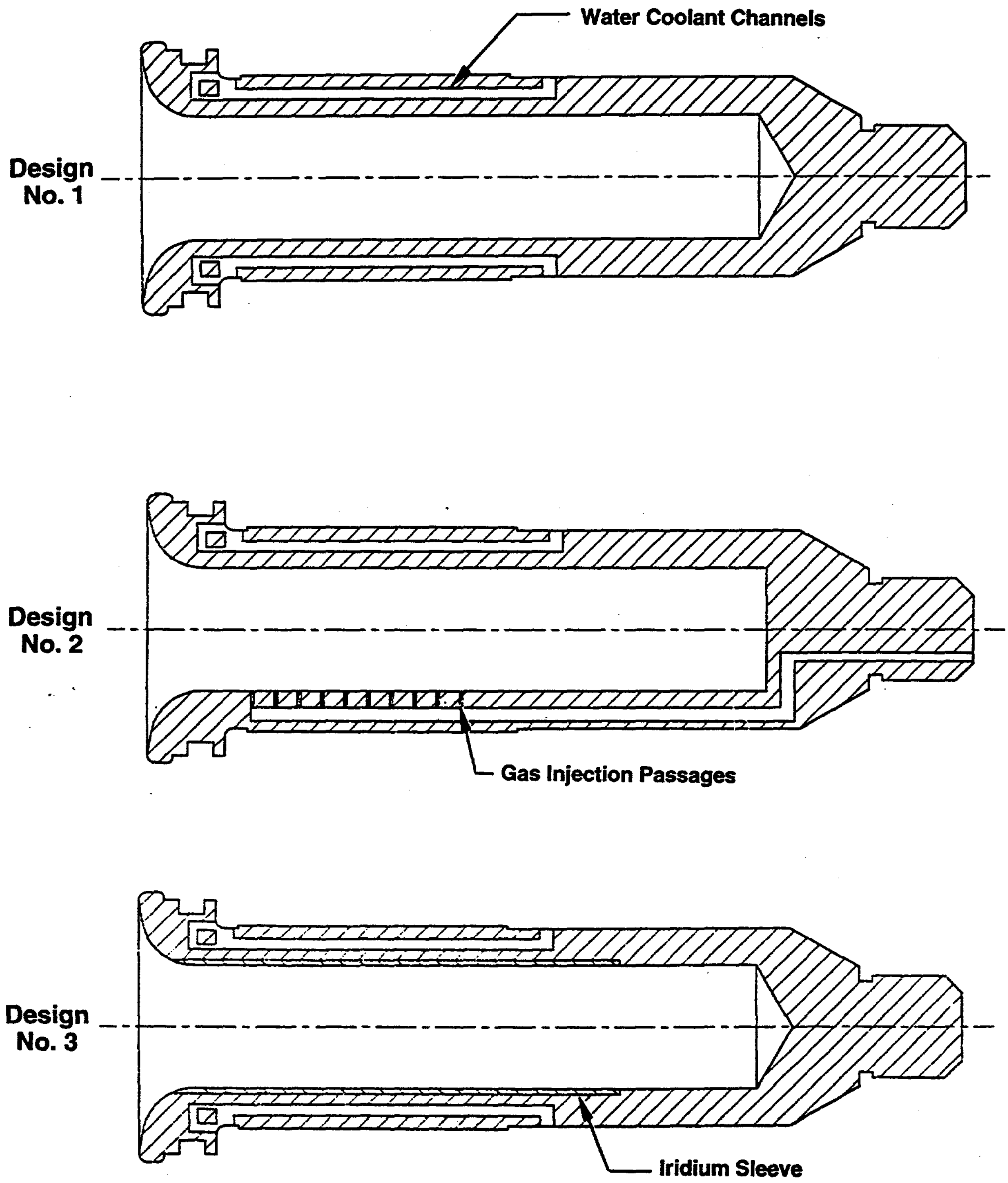


Figure 1. Three Platelet Electrode Designs

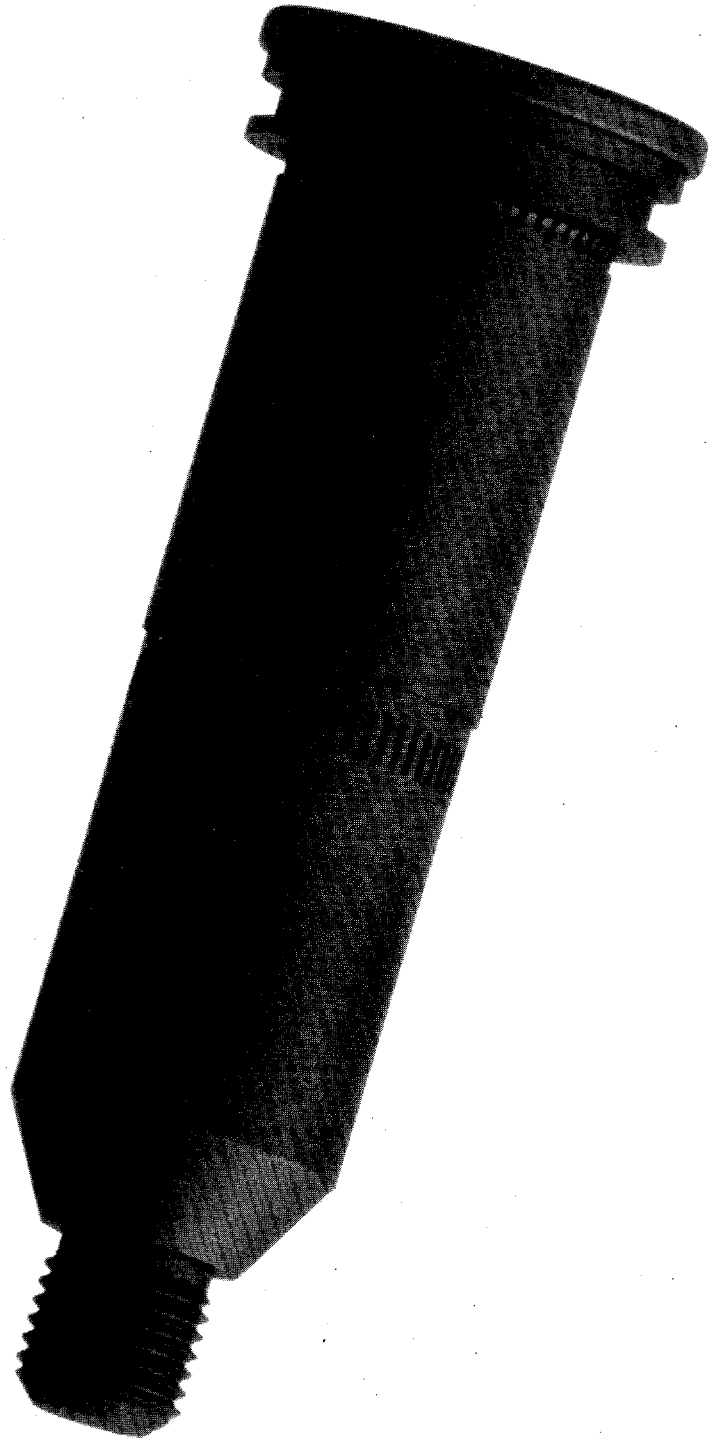
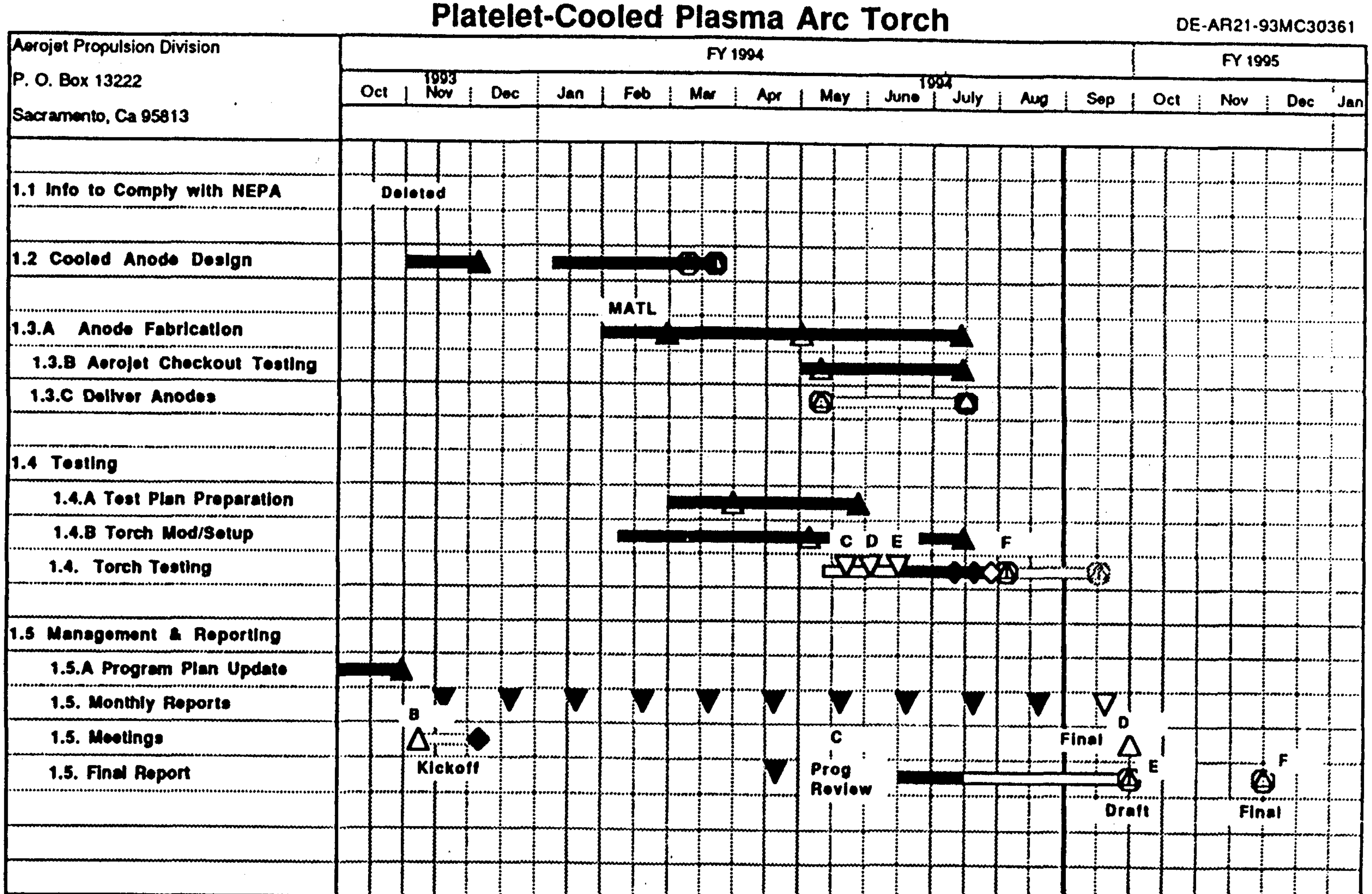


Figure 2. CAD Drawing of a Platelet Electrode

U.S Department of Energy

MILESTONE SCHEDULE STATUS (REV A)

Platelet-Cooled Plasma Arc Torch



Project Manager Signature and Date R W Johnson

Monday, September 12, 1994

Figure 3. Program Schedule

each of the three platelet electrode designs, or a total of six electrodes, were delivered for testing.

Testing was conducted between June and September 1994. The primary data produced by the test program was the measured electrode life. Table 1 summarizes this data.

Table 1. Summary of Electrode Life

Electrode	Life	Comment
R-1	87 minutes	Reference electrodes
R-2	4 hours, 24 minutes	
R-3	8 hours	
R-4	4 hours, 39 minutes	
R-5	5 hours, 37 minutes	
R-6	82 minutes	
AJ1-1	59 minutes	Questionable arc
AJ1-2	62 minutes	attachment location
AJ1-3	not tested	
AJ2-1	> 64 hours	Argon injection
AJ2-2	> 19 hours	Nitrogen injection
AJ3-1	26 minutes	Sleeve melted
AJ3-2	5 minutes	Sleeve melted

Figure 4 shows a photograph of the tested electrodes taken at the end of the test program. Altogether, six Retech reference electrodes were tested to failure. Seven Aerojet platelet electrodes were built, of which six were tested, four to failure. The two electrodes with gas injection are still in good condition and are available for additional testing. The seventh platelet electrode was retained as a spare and is available as a show piece.

The primary result of the test program was the discovery that the two electrodes with gas injection possess exceptionally long life. The first electrode used argon injection, the second nitrogen. Neither electrode failed within the planned test period. The first electrode accumulated 64 hours of testing, the second 30 hours. By comparison, six water cooled Retech electrodes failed after between 1.5 and 8 hours. Thus the demonstrated life increase is between eight and forty-two times the life of the Retech electrodes. The ultimate life of the two platelet electrodes cannot be extrapolated from the test data, but their appearance is still good, suggesting that many additional hours of life might still be possible.

Figure 4. Photograph of Tested Electrodes

Section 2

Introduction

Considerable quantities of mixed radioactive waste exist at some DOE sites. On the Mixed Waste Integrated Program (MWIP) DOE is actively seeking environmentally sound, cost effective disposal methods. One possible method is plasma arc torch treatment, wherein the waste is melted then resolidified into a solid form and stored in the ground. This can be accomplished in a continuous feed process using a plasma torch as the heat source. A discussion of the process may be found in [2].

Proposed systems use a 1 MW torch manufactured by Retech, Inc. in Ukiah California [3-9]. This torch uses a hollow type, backside water cooled electrode which acts as the anode. An electric current passes between the anode and the mixed waste, which serves as the cathode. This arrangement is called a transferred arc since the arc attaches directly to the waste. Nitrogen is used as the torch gas. A good discussion of this type of electrode is found in [10].

A drawback to the plasma arc torch process is the need to frequently replace the plasma torch electrodes. Since the waste material inside the torch is radioactive, opening the torch to replace the electrode exposes both the environment and the technician, and the procedure would have to be carried out with suitable care and precautions, such as protective dress, dosage monitoring, extra supervision, and reporting, with attendant cost increase. The development of a long life electrode is therefore an enabling step which may make the use of plasma arc technology practical for mixed radioactive waste applications.

Section 3

Purpose

The purpose of this program was to develop and test three different platelet electrode designs with increased life compared to existing conventional electrodes. The success criteria was established as two times the life of the existing electrodes. Life was to be demonstrated by testing in an existing plasma arc torch. Increase in torch life without loss of electrical power efficiency or arc stability were also goals of the program.

Section 4

Background

Rapid failure of electrodes is a common characteristic of many plasma torch devices. Electrodes fail because of the high heat flux produced where the arc jumps from the electrode to the work piece, or to another electrode. Heat fluxes are so high that even when water cooling is present to prevent bulk melting of the electrode, localized surface erosion cannot be prevented. Estimates for the heat flux place it on the order of 1500 BTU/in^2/s. For situations where the electrode is inexpensive and the replacement procedure is uncomplicated, the short life may not be a serious drawback. Spare electrodes are inventoried and the spent electrodes are replaced as needed. However, for applications such as mixed radioactive waste processing where electrode replacement is impractical, dangerous or costly, it would be advantageous to have a long life electrode.

Aerojet has had success increasing the life of cooled parts through the use of platelet cooling as evidenced by the use of platelets in many DoD and NASA development and flight programs, including man-rated programs such as the Space Shuttle. The keys to platelet success are the ability to create intricate channels with precise coolant flow control. Platelets are thin sheets of metal in which coolant channels are chemically etched using a photographic negative as the etch guide. The sheets are then diffusion bonded together to form a monolithic part with properties of the parent material. The resulting part can have complicated two- and three-dimensional cooling passages impossible to obtain with conventional manufacturing.

The platelet cooling concept was invented and patented by Aerojet in the 1960's and was first applied to rocket injectors and chambers. Since then thirteen specific types of platelet thermal management devices have been fabricated and tested [11]. One example of a platelet device used to extend the life of a part is an injector built for NASA Lewis which ran 4200 cycles without failure [12] where the existing injector was failing after 918 cycles. Another example of a platelet product extending life is the 40,000 lbf thrust oxygen/hydrogen combustion chamber tested recently at the Marshall Space Flight Center [13]. This chamber is a precursor for an advanced low cost, full scale chamber for the Space Shuttle Main Engine. Another platelet device recently reported in the literature [14] is the High Endoatmospheric Defense Interceptor (HEDI) transpiration cooled forebody.

Section 5

Methodology

The method pursued on the program was to demonstrate life by testing. There is no substitute for testing when a life demonstration is needed. Analytical predictions are unreliable and can not account for or predict in advance the numerous anomalies and real effects which occur due to handling, exposure to dirt and other contamination, plus non steady arc operation effects.

In practice, life prediction analytical techniques are generally developed from data, rather than the other way around. This is especially true for arc electrodes because the processes inside the electrode leading to heat transfer at the wall are poorly understood. Even the electrode material failure mechanism is not known. What is known that the appearance of the electrode degrades with time, and failure occurs by either (1) a rupture of the inner wall producing a water leak; or (2) a distortion of the inner wall shape caused by erosion or yielding. In both cases the arc shuts down and cannot be restarted, so the electrode has to be replaced.

The program was initially divided into five work breakdown categories.

1.0 NEPA Reporting
2.0 Design
3.0 Fabrication
4.0 Testing
5.0 Management and Reporting

EPA approval for the program was granted based on environmental statements submitted during contract negotiations, so task 1.0 was eliminated. Design activity on task 2.0 began in November 1993. At this time Aerojet planned to test at Idaho National Laboratory (INEL) using a 40 kW plasmatron operated by Dr. Peter Kong. That torch produces a non-attached arc and uses argon as the plasma gas. The benefit of testing using the INEL torch would have been the capability for advanced diagnostics possibly leading to a better understanding the fundamental physical processes involved.

In response to a DOE request at the 7 December kickoff meeting for this program, Aerojet evaluated and found significant benefits to working with the Retech 75T torch, which is more similar to the full-scale 600T transferred arc torch intended for use on the PHP program. Although the 75T electrode is smaller than the 1 MW electrode, it is geometrically similar and has the same method of operation. Therefore, test results generated in the 75T are expected to be valid for the 600T electrode. These facts led Aerojet to submit a letter [15] to DOE proposing testing using the 75T. The change was was subsequently approved by DOE.

5.1 Design Requirements

Design of platelet electrodes for the Retech torch started in January 1994. Per conversations with Retech the following design requirements were imposed.

Table 2. Electrode Design Requirements

Water inlet pressure	150 psia
Water pressure drop	50 psia (maximum)
Water flow rate	3 gpm (later updated to 3-5 gpm)
Argon flow rate	1.0 scfm (max)
Attachment point	0.75 inch from open end

These requirements are consistent with existing Retech 75T torch operating conditions. Water pressure limits are imposed for rig and personnel safety, while flow rate and pressure drop are imposed because the anode is plumbed in series with a downstream water cooled nozzle. The electrode is required to fit in the existing 75T housing.

A sketch of the Retech 75T electrode showing some dimensions is provided in Figure 5. The outer diameter of the straight section is 0.75 inch. The inner diameter is 0.5 inches. Cooling water enters at the threaded end, flows between the electrode outer diameter and a sleeve (not shown), then exits upstream from the flange at the open end of the electrode. Electrical current comes in at the closed end where the electrode threads into the torch assembly. Current runs along the walls of the electrode and jumps off the wall into the hollow cavity and attaches to waste material in the rotating tub located below the torch.

Figure 6 shows a schematic of the 75T set up. The torch is positioned above a rotating tub containing waste material. The torch position can be controlled in three axes. The entire assembly is contained in a double walled, water cooled tank.

A schematic of the cooling water set-up is shown in Figure 7. The electrode is cooled in series with the torch nozzle and water pressure and flow rate are provided by existing pumps. Therefore, it was necessary to design the electrode to have approximately the same water flow rate and pressure drop as the Retech electrodes. Torch gas flow rates were initially estimated by Retech as 5 scfm, so the secondary injection design flow rate through the platelet electrode wall in design no. 2 was set at a maximum of 1 scfm. This flow rate was selected as a rule-of-thumb with the reasoning that the secondary flow should not be negligible, but should be less than the primary gas flow.

Since the platelet electrode was fitting into an existing arc it would have to be designed as a retrofit, with the same geometrical features and operating constraints of the existing electrodes. Retech allowed for minor changes to the torch to accommodate

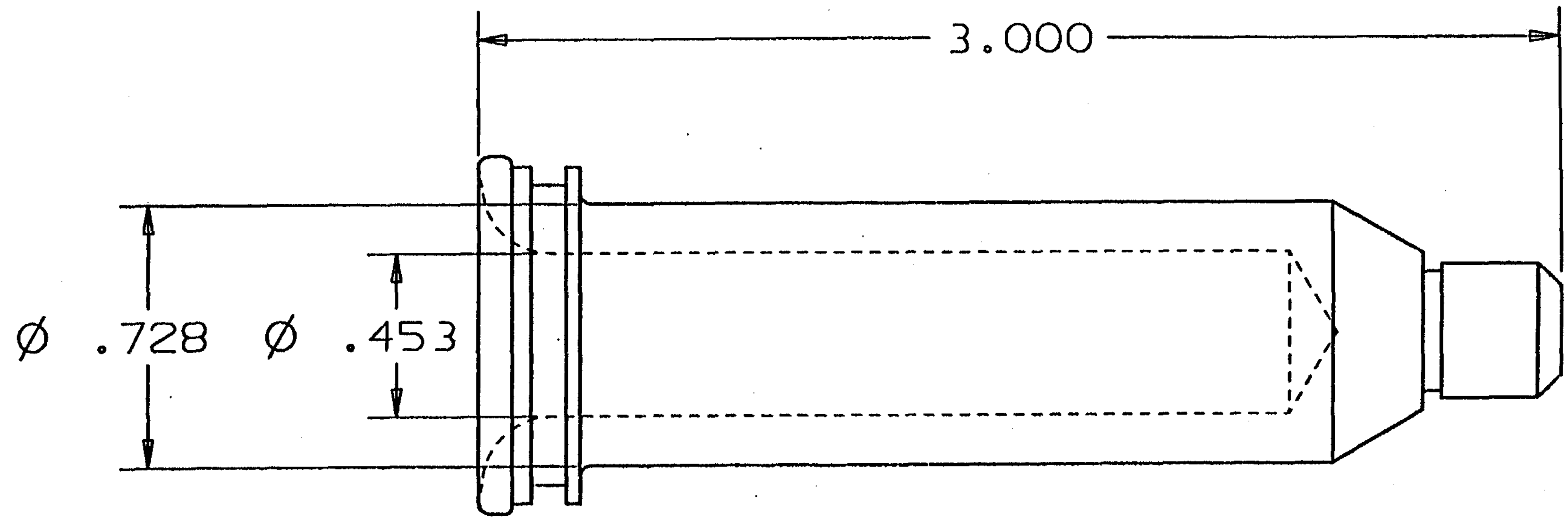


Figure 5. Cross Section of 75T Electrode

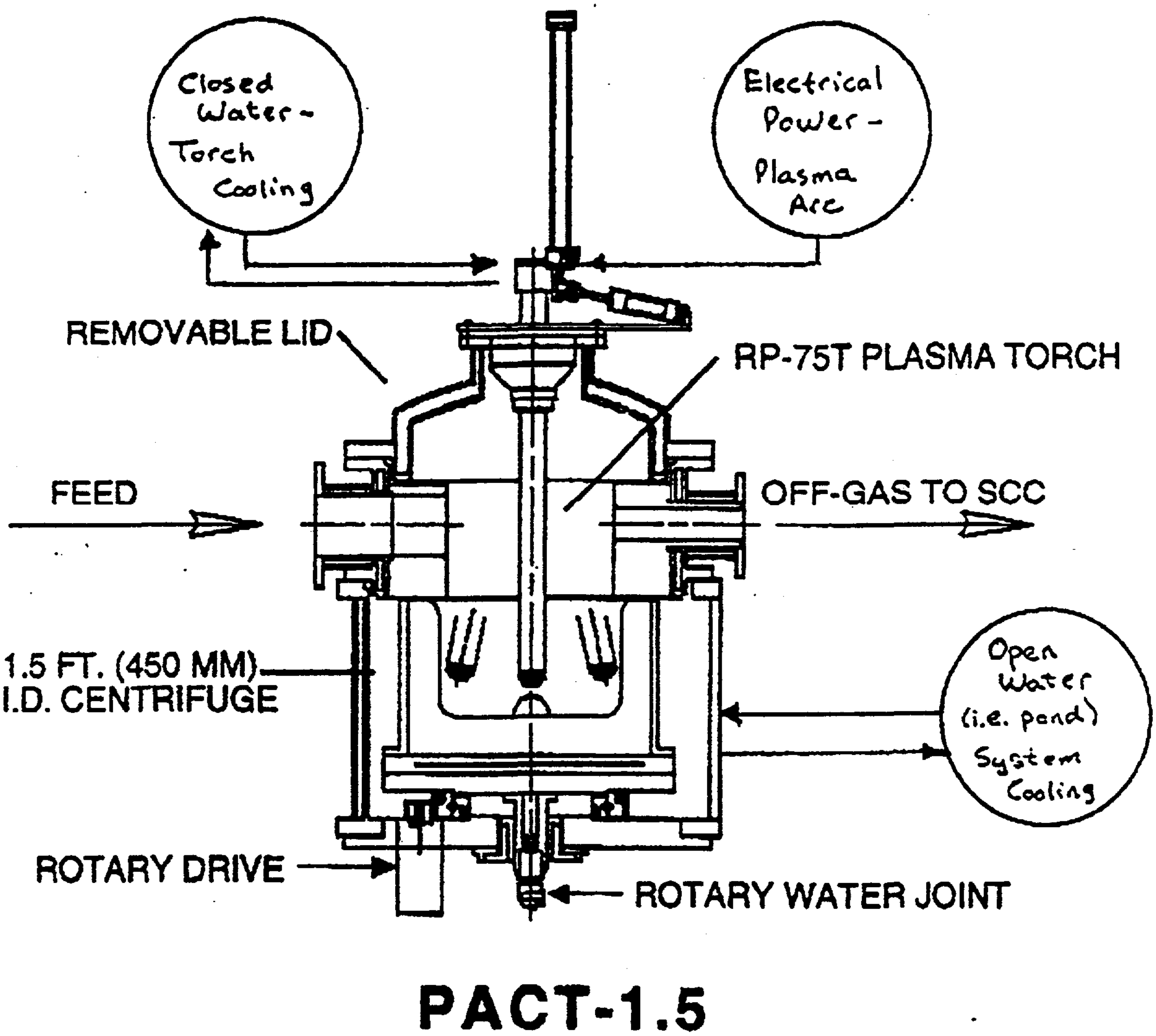


Figure 6. 75T Torch Set-Up

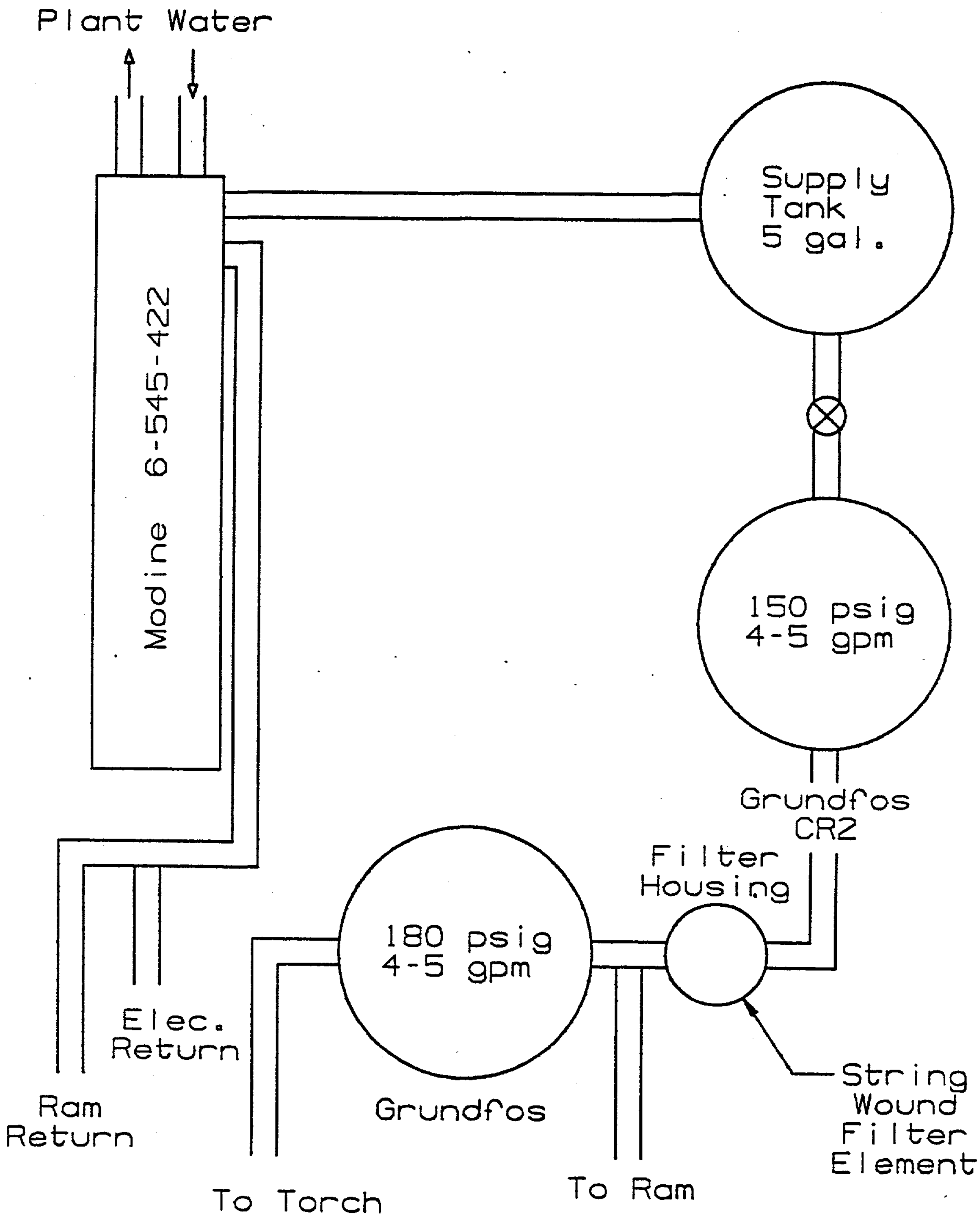


Figure 7. Torch Water Cooling System Schematic

differences in water cooling feed and gas injection. The use of water channel passages was accommodated by adding an O-ring in the torch housing to prevent intermanifold leakage. The water feed tube was modified to carry both water and gas.

In the Retech system the DC current is regulated but the voltage varies continuously because the arc length and electrical resistance change with the rotation of the tub and the height of the waste material. Nitrogen gas injected at the open end of the electrode flows into the electrode on its inner diameter, then returns outward along the center axis. The gas is injected tangentially to cause the gas to swirl.

5.2 Design Methodology

Design activity began with the hypothesis that electrode life could possibly be increased by three mechanisms: (1) replace back side cooling with small water cooling channels to increase cooling effectiveness; (2) inject gas at the wall to promote gas swirl and create a cool or inert gas barrier at the wall; and (3) put a high temperature material on the electrode inner wall. Following these ideas, three platelet electrodes were designed.

Electrode design no. 1 is a copper platelet electrode with water cooling. Figure 8 shows a cross section. Water enters the electrode by means of 28 large channels located about 1.5 inches from the open end. The large channels then split to form smaller, high velocity channels which extend approximately 0.67 inch in length. The water exits near the flange at the open end of the electrode. This approach improves water cooling effectiveness compared to back side cooling by increasing the surface area for heat transfer and by reducing the distance between the hot gas side and the water cooling. The axial location of these channels was placed to correspond to the planned arc attachment location.

Electrode design no. 2 has water cooling plus non-radial swirl gas injection to facilitate rotation of the arc foot. Figure 9 shows a cross section. The injected gas may also form a cool gas barrier along the inner wall. In the case where the injected gas is inert, such as argon, the erosion rate of the electrode may be reduced because there are no oxidizing gases near the wall. Gas enters the electrode via six .030 inch diameter holes located in the threaded stub at the closed end. It then passes through channels alongside the water channels and is injected at ten axial stations located 0.125 inches apart axially. Each station has six injection slots, 60° apart circumferentially.

Electrode design no. 3 is internally identical to design no. 1 in its water cooling layout, but a 2-inch long, .020 inch thick iridium sleeve is added at the inner diameter at the open end. Figure 10 shows a cross section. Good thermal conductance without design complexity and cost led to the selection of the sleeve design approach. The sleeve fits to the copper electrode body in

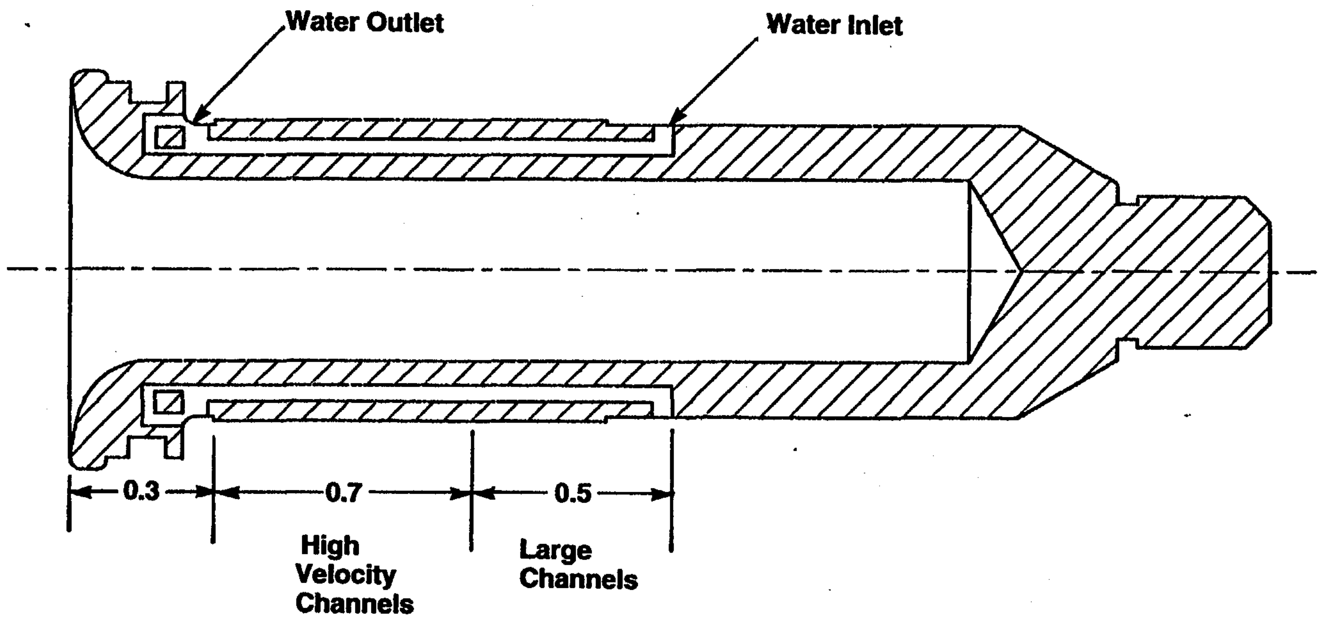


Figure 8. Platelet Electrode Design AJ1

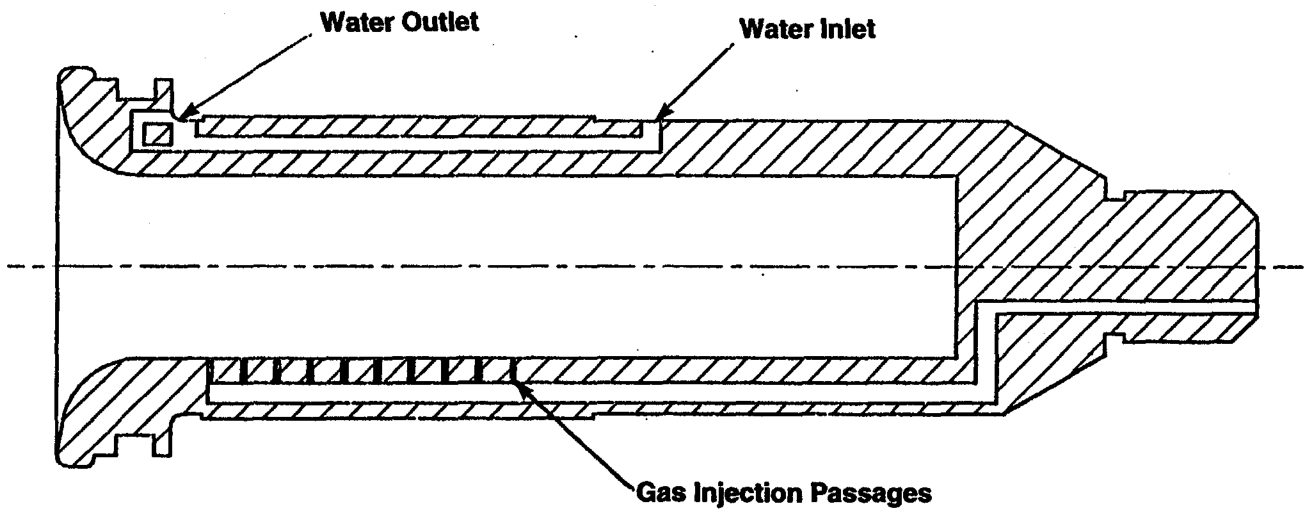


Figure 9. Platelet Electrode Design AJ2

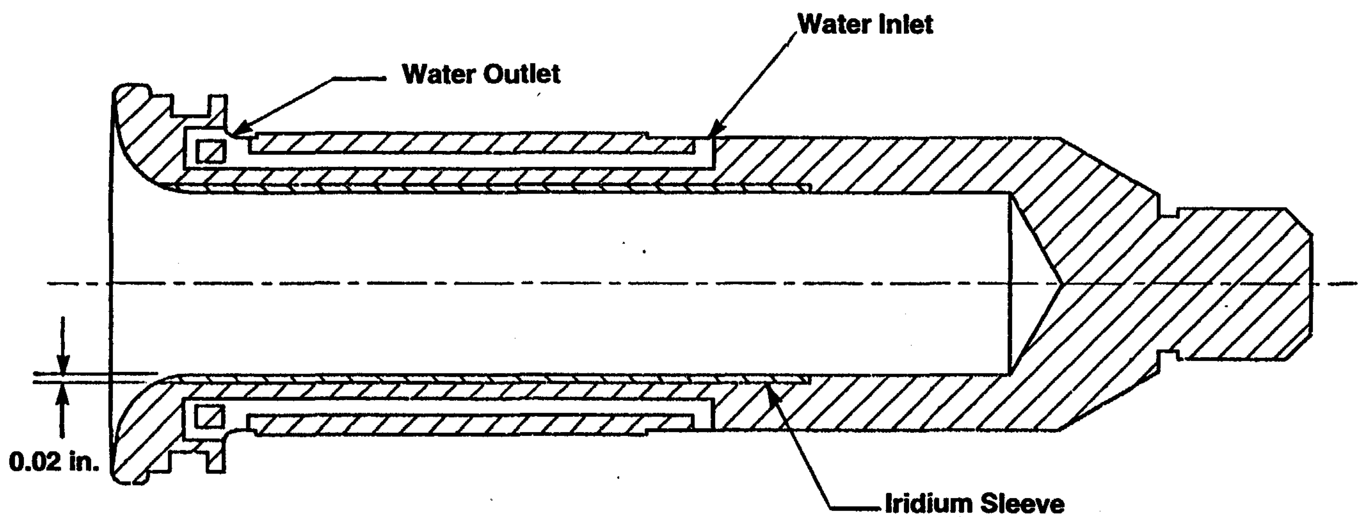


Figure 10. Platelet Electrode Design AJ3

a match machined groove. Iridium was selected as the sleeve material because has a high melting temperature, 4449 °F compared to 1981 °F for copper, and it also possesses high thermal and electrical conductivity. Drawbacks to iridium are its cost, and difficulty in machining, which make it impractical to consider making the entire electrode out of iridium. One potential problem with the sleeve approach is the possibility of inadequate thermal contact between the iridium and the copper body.

Zirconium copper (ZrCu) was selected as the electrode material for this program because of its extensive characterization in diffusion bonding. Copper alloys are a common material selection for electrodes, especially those used as anodes, because of their high electrical and thermal conductivity, reasonably high melting point, plus good mechanical strength and workability. The thermal and electrical conductivity of ZrCu and oxygen-free high purity copper (OFHC) are similar. It is not clear that the strength added by the zirconium is necessary, so other copper alloys or even OFHC may be considered for future applications subject to development of appropriate diffusion bonding data bases.

A design review was conducted at Aerojet in February 1994. Design information and a top level drawing were forwarded to Retech for their review and comment. They found no discrepancies, but commented that their newer electrodes were capable of flowing 4-5 gpm as compared with 2-3 gpm for the older electrodes. In response to this information, the water flow rate capability of the platelet electrodes was increased by slightly enlarging the cooling water channels.

5.3 Design Analysis

Analysis was conducted to support electrode design in four areas: (1) water flow analysis to produce the correct flow rate and pressure drop; (2) heat transfer analysis to determine the approximate wall temperature history; (3) material selection and design for the high temperature sleeve; and (4) and life analysis. The water flow analysis was successful and all electrodes had adequate water flow rates during the test program. The thermal contact between the iridium sleeve and the copper body was questionable. A life analysis was attempted, but not accomplished due to the uncertainty in the wall heating conditions plus lack of information regarding the material failure mechanism.

The output of the water flow rate analysis was the specification of water cooling channel dimensions. The following analytical approach was adopted. A minimum coolant channel width of .017 inch was selected based on the etch capability for available .008 inch thick platelet stock. A channel land minimum of .016 inch was selected to ensure a robust diffusion bond between channels. The minimum hot gas side wall specified by Retech of .06 inch was selected. Channel height then became the only design variable, and since water flow rate and inlet temperature were specified, it was possible to select channel height based on pressure drop and flow rate only. In order to obtain 5 gpm a flow rate at 50 psi pressure drop the calculated channel height was .042 inch.

The electrode wall temperature history was calculated using a one-dimensional thermal model which contains numerous guesses or approximations to the boundary conditions at the electrode wall. The arc foot rotates rapidly, perhaps on the order of several hundreds of times per second, causing a very high but transient heating rate at the attachment points. Wall temperatures undoubtedly rachet due to momentary arc attachments. For this calculation, a rotational rate of 300 hz and a transient heat flux of 750 BTU/in2/s were assumed. Figure 11 shows the calculated temperature time history for the electrode hot gas side wall during a typical operating period. Note that the wall temperature rachets up and down between 564 °F and 1003 °F as the arc attaches periodically. Away from the hot gas side at the water channel the copper temperature remains constant at 336 °F. The reader is cautioned that this calculation represents only a crude estimate since the heating boundary conditions are not known.

The burn out safety factor (BOSF) was also calculated for the case above and determined to be 2.1, based on water flow and heat flux conditions in Table 3.

Table 3. Summary of Burn Out Safety Calculations

Hot side heat flux	39.3 BTU/in^2/s
Channel heat flux	11.4 BTU/in^2/s
Water Velocity	42 fps
Water Pressure	100 psia
Water Temperature	100 F
Saturation Temp.	327 F
Burn Out Heat Flux	23.9 BTU/in^2/s
BOSF	2.1

The significance of the 2.1 BOSF is that the platelet electrodes should not experience film boiling in the channels if the estimated steady heat flux is representative of actual conditions. Film boiling leads to failure by locally reducing the heat transfer coefficient on the coolant wall. The method for calculating burn out heat flux is given in [16]. This method gives 13.3 BTU/in-s. Small diameter effects data [17] indicate burn out heat flux will increase by a factor of 1.8. Thus, the burn out heat flux is 23.9 BTU/in2-s and the burn out safety factor is 23.9/11.4 = 2.1.

The favorable properties of iridium leading to its selection as the high temperature material are summarized in Table 4. Iridium is almost three times as dense as copper and requires about twice the heat to melt an identical volume of metal. Thus it was hypothesized that the iridium could have significantly greater

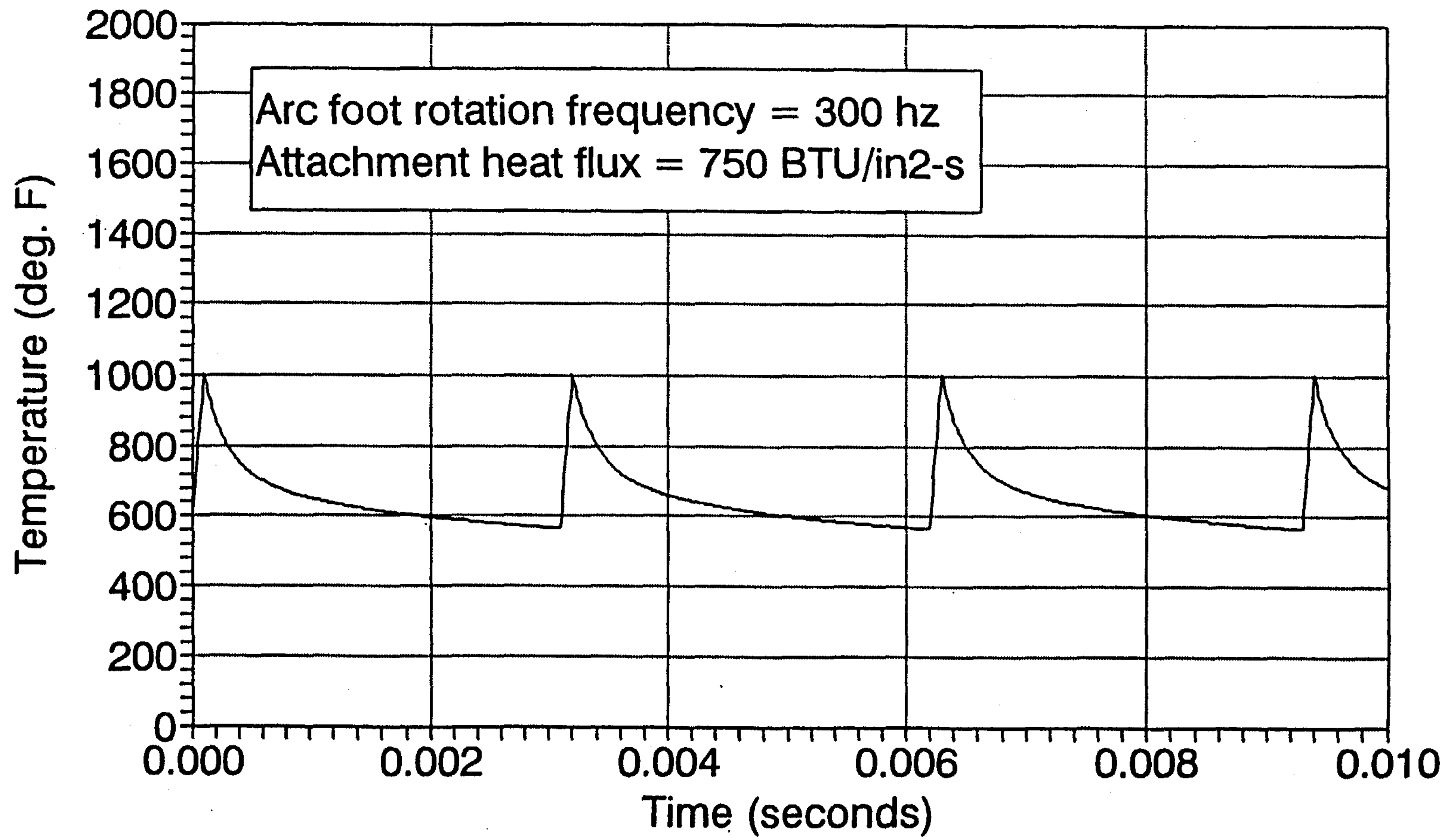


Figure 11. Predicted Temperature for Electrode AJ1

Table 4. Iridium Thermal Material Properties

	k BTU/ft/hr/F	rho lb/ft^3	T_{melt} °F	C_p BTU/lb/°F	C_p*dT BTU/lb	H_f BTU/lb	Q_{melt} BTU/ft^3
Iridium	86	.813	4449	.031	172	47.7	178.6
Copper	172	.324	1981	.092	191	91.1	91.4

life capacity than copper if the arc heat could be adequately removed.

Two issues were raised relative to thermal conductance of the sleeve approach. The first was the thermal contact as manufactured. The second was thermal contact as the electrode heats during testing. Thermal conductance between two materials in contact is a function of pressure and surface finish [18]. Data in the literature only goes up to about 1000 psi, but linear extrapolation suggests that adequate thermal conductance might be obtained around 10,000 psi pressure. The interface conductance for a copper/iridium pair was estimated to be 500 BTU/hr-ft^2-F. This is about twice the conductance of the .020 inch iridium thickness, so the interface conductance was thought to be adequate.

The interface conductance calculation was based on data [19,20] for steel/aluminum with air in the gap and a 30/65 micro inch RMS surface finish. Copper/iridium conductance was derived from the steel/aluminum data using a scaling method described in [19]. The following properties were used.

Table 5. Material Properties Used to Determine Thermal Conductance

Material	Hardness	Conductivity BTU/hr-ft-°F
Aluminum	19	128
304	149	9
Copper	72	226
Iridium	230	86

Conductance is dependent on the hardness of the softer of the metals in the pair. The hardness of the copper, relative to aluminum, reduces interface conductance, but this loss is offset by the increase in thermal conductivity of the copper/iridium pair relative to steel/aluminum.

The second concern with the sleeve approach was the difference in coefficient of thermal expansion CTE between iridium and copper. A possible concern was that the copper would pull away from the sleeve and the sleeve would become dislodged. The estimated diameter expansions for the copper body and iridium sleeve are shown below.

Table 6. Calculation of Differential Growth Between Iridium Sleeve and Cooper Body

Material	Temperature F	CTE 10^{-6} in/in/F	Expansion in
Iridium	1400	3.8	.0028
Copper	200	9.8	.0010

The copper body is cool on the outer diameter, so its outward growth is small, about .001 inch. The iridium sleeve is hot and an unconstrained sleeve would grow about .0028 inch in diameter. Since the copper grows less than the sleeve, the sleeve will remain in compression. This calculation suggests that heating will improve the contact pressure, since the sleeve gets hotter than the body. However, if the copper body reaches 500 °F or above, the body will begin to grow away from the sleeve.

Figure 12 shows the predicted temperature-time history for the iridium sleeve electrode under the same assumed boundary conditions as used for design no. 1. The hot gas side temperature rachets between 825 °F and 1821 °F. The temperature of the copper body at the interface with the sleeve remains nearly constant at 337 °F, so the temperature fluctuations occur entirely within the sleeve.

A life analysis was attempted, but as this effort was pursued it was recognized that both the heat transfer and the life failure mechanisms were too uncertain to permit a reliable or meaningful prediction. The effort to develop a life model would have been be non-trivial, and beyond the resources of the program, even if it could be done. This was not a drawback to accomplishing the program objective since the life would be demonstrated by testing, but it did present some initial concern because there was no way to know in advance how operational parameters might effect life. The lack of predictive heat transfer models is not unusual for the plasma torch industry. Papers in the literature [21] have recently appeared where heating conditions are studied parametrically, but in general manufacturers rely on experience and intuition in the design of their electrodes.

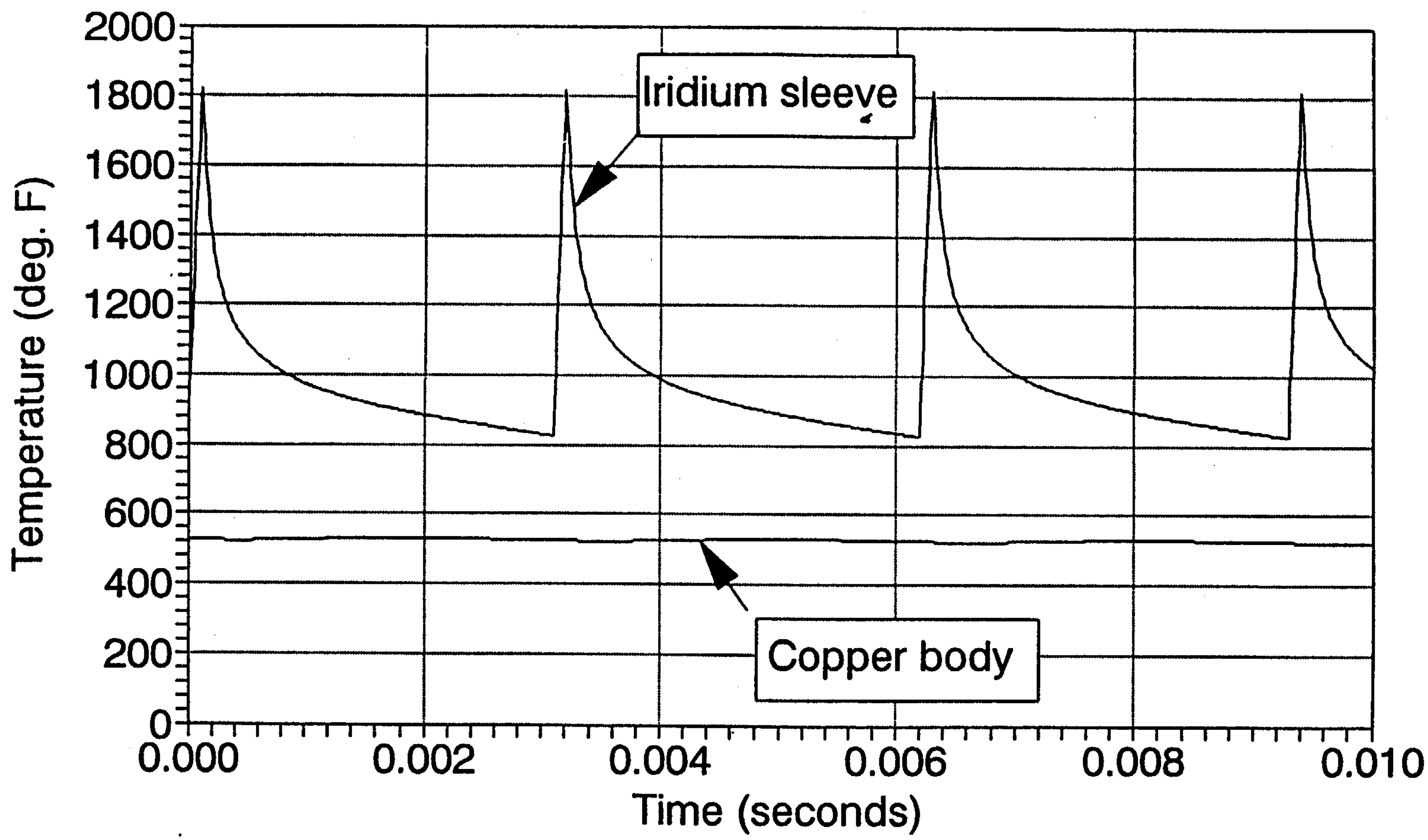


Figure 12. Predicted Temperature for Electrode AJ3

5.4 Fabrication Methodology

Fabrication occurred between March and July. The fabrication process is summarized in Figure 13. First, platelet artwork was prepared for all three designs. Platelet stock was then obtained from stores, chemically etched and inspected. All etched features fell within acceptable tolerances. End plates for the diffusion bond runs and proof tooling for post-bond pressure proof were fabricated.

The electrodes were diffusion bonded in two stacks with platelets for six electrodes in each stack. The first six pack contained platelets for electrode design nos. 1 and 3. There were no leaks detected during the post-bond leak check, indicating a good diffusion bond around the coolant channels. Five units from this stack were subsequently final machined and delivered for testing.

The second six pack contained platelets for design no. 2. In the post-bond leak check, five out of the six units had no detectable leak. One unit had a small leak between the water and gas injection channels. The leaking unit was discarded. Three of these units were subsequently machined, with one unit used as a pathfinder for the machining process, and two units delivered for testing.

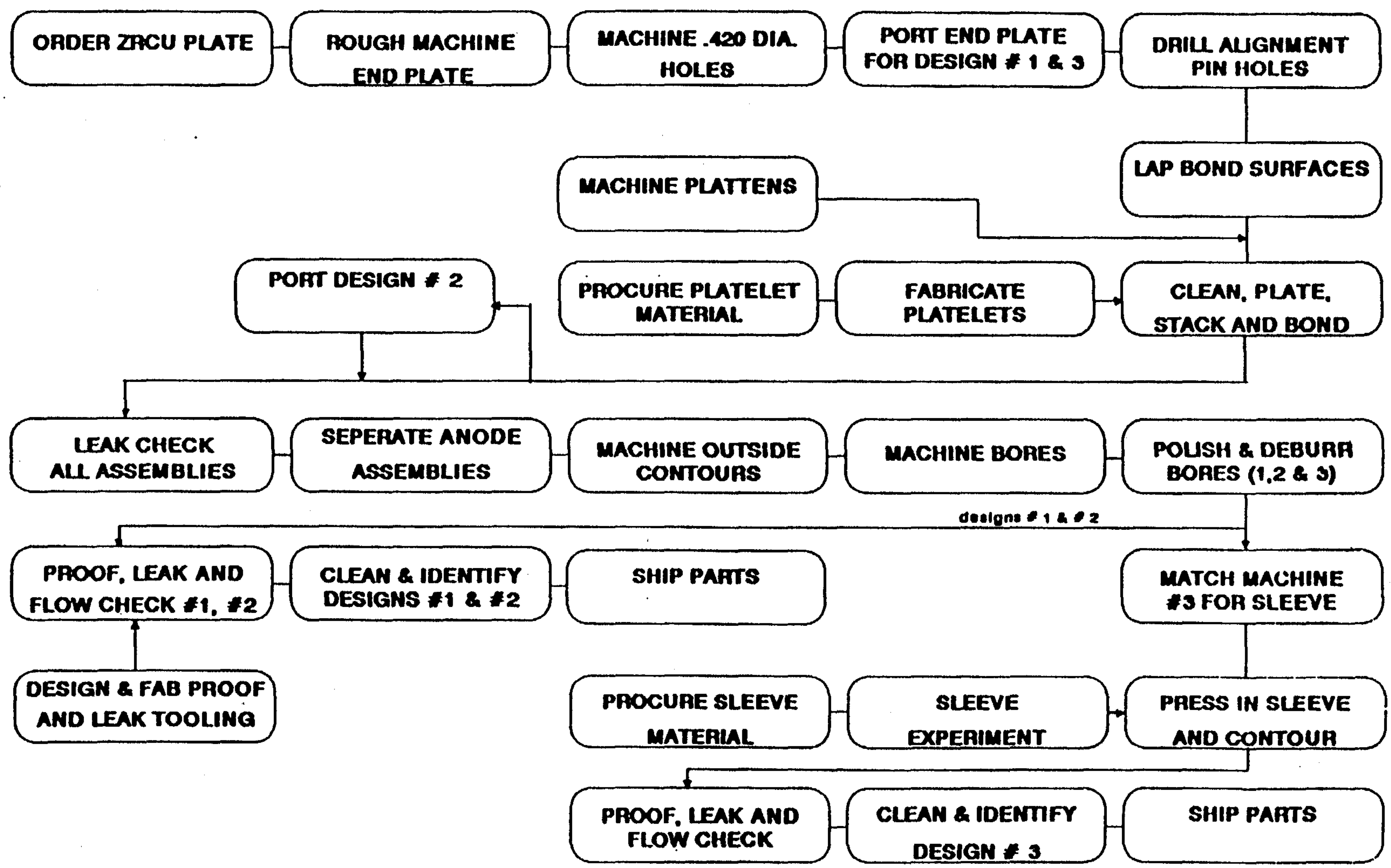
Following leak check the units were put through a second bond procedure in a hot isostatic press (HIP) furnace to restore material properties. Following HIP the units were final machined to obtain the outer contour. Each electrode followed a different process to finish the inner diameter. Design no. 1 units were machined on the inner diameter. Design no. 2 units were electrostatic discharge machined (EDM) on the inner surface to open the gas injection slots without smearing them. Design no. 3 units were machined on the inner diameter then fitted with iridium sleeves. Additional details of the fabrication are provided below.

Design no. 1

Three of these units were built without incident. The third unit was built as a spare in case something happened to the two deliverable units. Cold flow results are listed below.

Table 7. AJ1 Cold Flow Data Summary @ 50 psig

S/N	kw	wdot gpm	velocity fps
1	.085	4.32	36.4
2	.081	4.12	34.7
3	.084	4.27	36.0



PAT 2 2-15-94

Figure 13. Fabrication Process Chart

Cold flows were performed in Aerojet "A" area using a flow tool fixture built specifically for these electrodes. Water inlet pressure was measured with a dial gage connected at the flow tool fitting inlet. Flow rate was measured using a flow meter with +/- 1/2 percent accuracy. Flow rates were set by adjusting a hand turned regulator while reading the flow meter spin frequency. The flow rate range was 1.8 to 4.5 gpm. Corresponding inlet pressures were 8-60 psig. The calibration constant for the flow meter was 1443.43 cycles per lb/s.

Visual inspection of the spray patterns at the water outlet slots showed that S/N 1 and S/N 3 units had flow good distribution. S/N 2 had two slots out of fifty-six that appeared to have slightly weak jets. This seems to corroborate with S/N 2 having a lower total flow rate and KW. Subsequent recleaning of this unit did not improve the KW.

Design no. 2

A problem with this design was discovered after machining the outer diameters. A generous flow of air was observed to issue from each of the six water manifold slots directly downstream from the gas injection channels when the argon inlet was pressurized. A subsequent check of the platelet stacking sequence revealed an inadvertent error in the design which allowed interconnection between the water and gas channels. This is an unacceptable arrangement since it allows water to backflow into the torch and quench the plasma. For the units to be usable, those slots had to be closed off.

The six water manifold slots were successfully filled with a Nioro braze alloy. The units were then pressurized to 200 psi and no leak was detected between the water and gas manifolds. Thus the braze operation was deemed a success and the units were then sent out for final machining and EDM of the inside diameter to open the slots.

The flow rates and KW's for the gas injection electrodes were as follows.

Table 8. AJ2 Cold Flow Data Summary @ 50 psig

S/N	kw	wdot gpm	velocity fps
1	.057	2.97	24.4
2	.056	2.85	24.0

There was no specific water flow requirement for the -2 design. It was felt that the lower flow rate would be acceptable if the gas injection was able to improve the arc foot rotation. The kw is about 33 percent lower than the -1 or -3 anodes owing to (1) fewer channels, 50 instead of 56; (2) longer high velocity flow path, 1.1 versus 0.6 inches; and (3) higher velocity inlet and turn. There are only 50 water channels because six were removed to make room for the gas injection passages.

Design no. 3

Johnson-Mathy supplied three iridium sleeves. The iridium sleeves as received were smooth on the outer diameter, but weld seams were visible on the inner diameter. The seams were about 1/8 inch wide and appeared rough enough to cause concern over possible arc foot "sticking". To eliminate the seam, the sleeves were taken to a vendor to grind both inner and outer diameters. Following grinding the inner wall appeared acceptably smooth.

The sleeve was next assembled to the body. First, a .02 inch deep groove was cut in the electrode inner wall. The sleeve was then frozen while the body was heated and the sleeve was dropped into the groove. After both parts returned to room temperature the estimated interference was estimated to be approximately .001 inch. The sleeve was then final machined at the open end to obtain a smooth contour.

Cold flow rates and kW's for the iridium sleeve units were as follows:

Table 9. AJ3 Cold Flow Data Summary @ 50 psig

S/N	kw	wdot gpm	velocity fps
1	.085	4.32	36.4
2	.083	4.17	35.5

These flow rates meet the requirement of flowing 4-5 gpm. Both electrodes exhibited good water flow patterns and flowed about 4.2 gpm at 50 psi pressure drop. This is the same flow rate as the design no. 1 units, indicating good manufacturing repeatability.

5.5 Test Planning

A copy of the test plan is provided in Appendix A. The purpose of the test plan was to identify the tests and procedures to be followed during the tests at Retech. The test schedule is reproduced in Figure 14. Initially, one Retech electrode was to be tested for up to five days, or to failure, whichever came

Test No.	Day	Duration	Comment
Retech Anode			
1	1	10 minutes	Baseline test
2		30 minutes	
3		2 hours	
4-7	2-5	8 hours	
Aerojet Design No. 1			
8	6	10 minutes	Water Cooled
9		30 minutes	
10		2 hours	
11-14	7-10	8 hours	
Aerojet Design No. 3			
15	11	10 minutes	Iridium sleeve
16		30 minutes	
17		2 hours	
18-21	12-15	8 hours	
Aerojet Design No. 2			
22	16	10 minutes	Water cooling with Argon injection
23		30 minutes	
24		2 hours	
25-28	17-20	8 hours	
Aerojet Design TBD			
29-42	21-44	8 hours	Extended duration testing

Figure 14. Test Matrix

first. The objective of this test was to establish the life of the reference electrode. Next, each of the three platelet electrodes were to be tested. On the first day of testing there were to be three test durations: 10 minutes, 30 minutes, and 2 hours. The electrode would be inspected after each of these tests. The reason for the short duration tests on the first day was to ensure that the installation was correct and that the arc was attaching properly. On second and later days the test duration was to be 8 hours. Testing was limited to 8 hours per day during normal operating hours when the power generator was normally available. Following the tests of the three electrodes, one would be chosen for extended duration testing up to about 100 hours.

During testing Retech agreed to data log crucial operating parameters, including torch voltage and current, and coolant water temperatures. The operator was also required to maintain a log of comments.

During test plan preparation and evaluation, it was decided to attempt to install an Aerojet owned optical detection system on the torch tank to look for electrode erosion products. The equipment had been in use the prior year at NASA Marshall in Huntsville, Alabama where it was used to evaluate rocket plumes. It was believed that the timing of the copper erosion, if detectable, might yield some clues concerning the erosion mechanism. For example, if the detected material signal strength was observed to increase during a voltage spike, it might be concluded that the primary erosion mechanism was due to anomalous events occurring in the torch rather than steady, normal operation. It was also speculated that the optical system would provide a semi-quantitative measurement of electrode material loss rate which might indicate the onset of failure, or could be used to establish a life prediction methodology.

A schematic of the optical system is shown in Figure 15. The system consisted of a fiber optic probe, a detector, a signal processor and a personal computer with data control software. It was determined that the system could accomplish the task subject to the following uncertainties: (1) the ppm sensitivity of the detector; (2) the affect of background radiation on detection accuracy; (3) the availability of a viewport.

A meeting was held at with Rob Haun at Retech on 21 April which led to a decision to install the optical system. The system was first returned from Huntsville to Aerojet in Sacramento for calibration. At the same time Retech prepared a viewing port by installing a view port on the torch tank wall consisting of a flange with a 4 inch long, 1.5 inch diameter pipe fitting. The optical probe was inserted in a 4 inch long, 1 inch diameter pipe nipple and affixed to the tank coupling by a bushing. Dry gaseous nitrogen was purged through the pipe to protect the lens. The pipe nipple was protected from heating by wrapping it with copper pipe and flowing water through the pipe. This arrangement

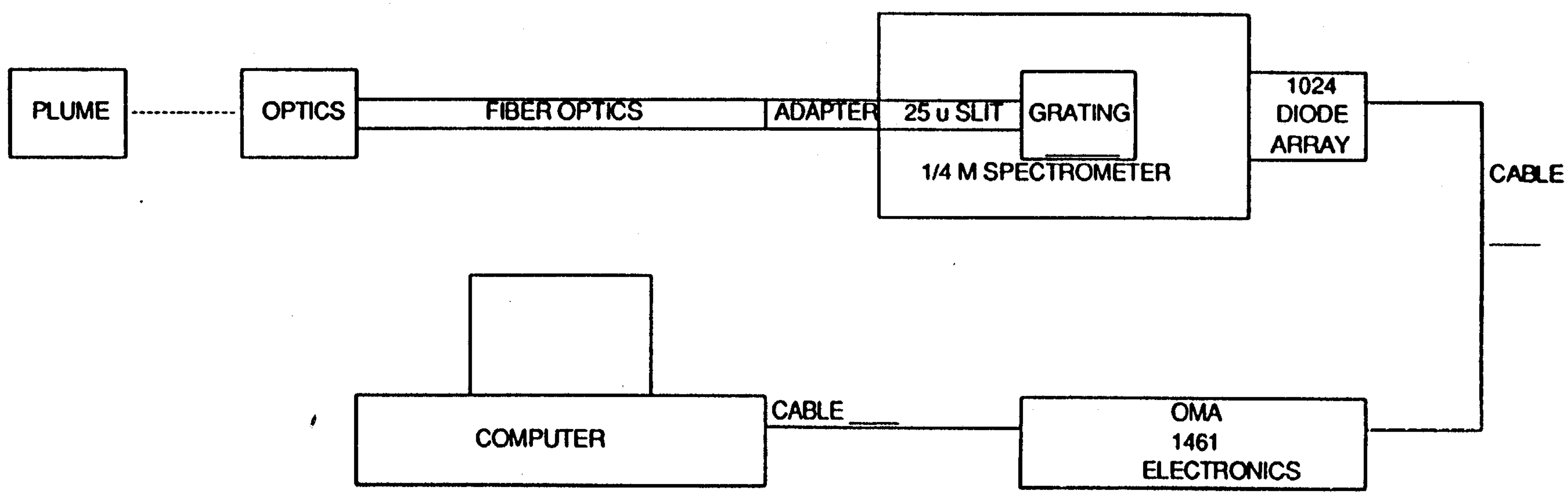


Figure 15. Optical System Schematic

provided an adequate view of the plasma while protecting the probe from heating and lens contamination.

During operation of the 75T its three-axis torch is regularly moved by the operator to keep the material in the crucible uniformly heated. This creates a problem for the optical system which is focused on a fixed position. It was decided that the optical probe could be aimed at a known position, and that the torch could be periodically returned to a position which would place the plasma in view of the probe. Thus, optical measurements would be periodic, but not continuous.

Section 6

Results and Conclusions

Testing occurred between June and September 1994. Table 10 gives the test hardware designations.

Table 10. Test Hardware Designations

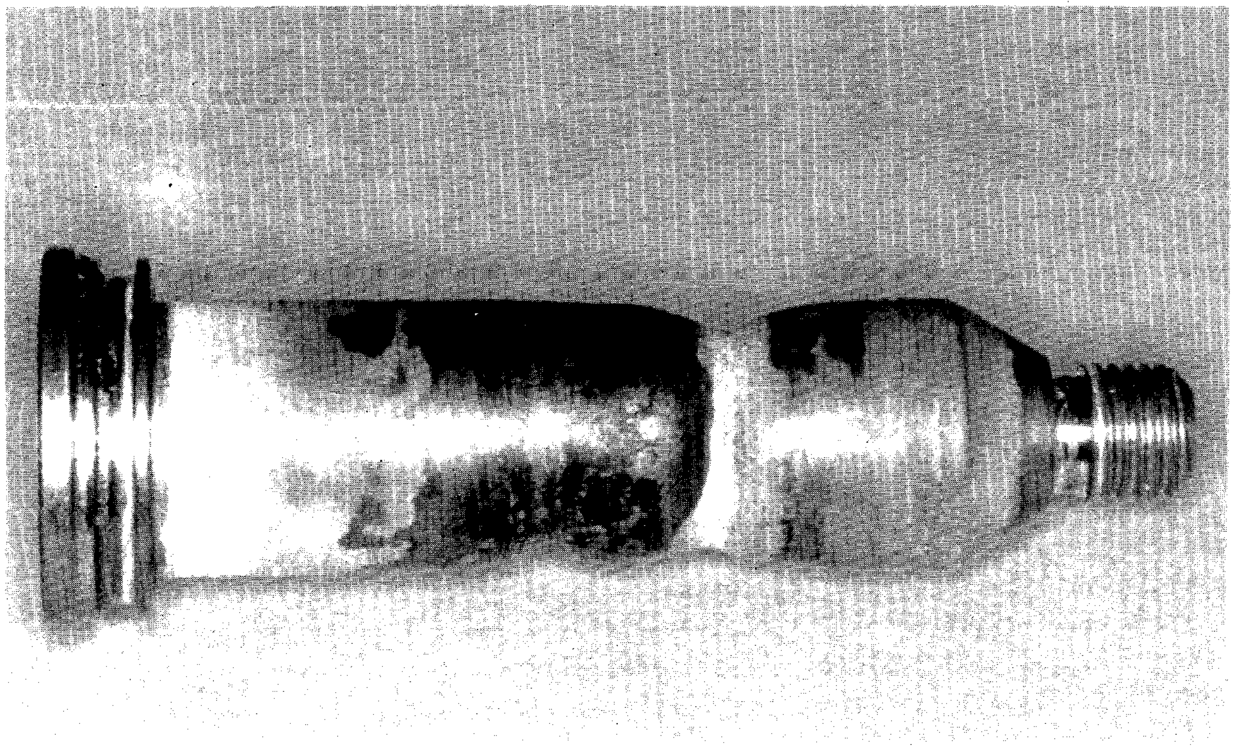
Electrode Designation	Electrode Type
R-1 to R-6	Retech water-cooled electrode
AJ1-1, AJ1-2	Aerojet all-copper, water cooled
AJ2-1, AJ2-2	Aerojet all copper, water cooled with gas injection
AJ3-1, AJ3-2	Aerojet copper body with iridium sleeve

The three designations AJ1, AJ2 and AJ3 identify the three different Aerojet platelet electrode designs. Dash numbers indicate serial numbers.

6.1 Test Results

The first Retech reference electrode, R-1, was tested on 7 June. Failure occurred after 87 minutes operating with 2.1 scfm nitrogen as the torch gas. A concern arose when inspection of the electrode revealed a prominent necked area approximately 1 3/4 inch from the open end. A small dimple, possibly a pinhole leak, was also observed 1 1/4 inch from the open end. Post-test photos of the electrode are shown in Figure 16. The location of the necked area was a potential concern for the platelet electrodes whose cooling channels were located over the first 1 inch from the open end. Retech addressed this concern by proposing to move the attachment point toward the open end by lowering the torch gas flow rate.

The first Aerojet electrode, AJ1-1, was tested on 15 July. Initial test durations were 10 and 30 minutes. After the last test the electrode was removed from the assembly and a dimple on its outer diameter 1.7 inches from the open end was observed. This dimple indicated an arc attachment location in about the same location as the reference electrode and about 3/4 inch beyond the platelet cooling channels. For the next test on 25 July a two-hole injection ring was substituted and the torch gas flow rate was reduced to 1.5 scfm in an attempt to move the arc attachment point forward. Failure occurred after 19 minutes. Post test inspection revealed erosion of the anode flange face indicating that the arc was improperly attaching at the flange. Post-test photos of the AJ1-1 electrode are shown in Figure 17.



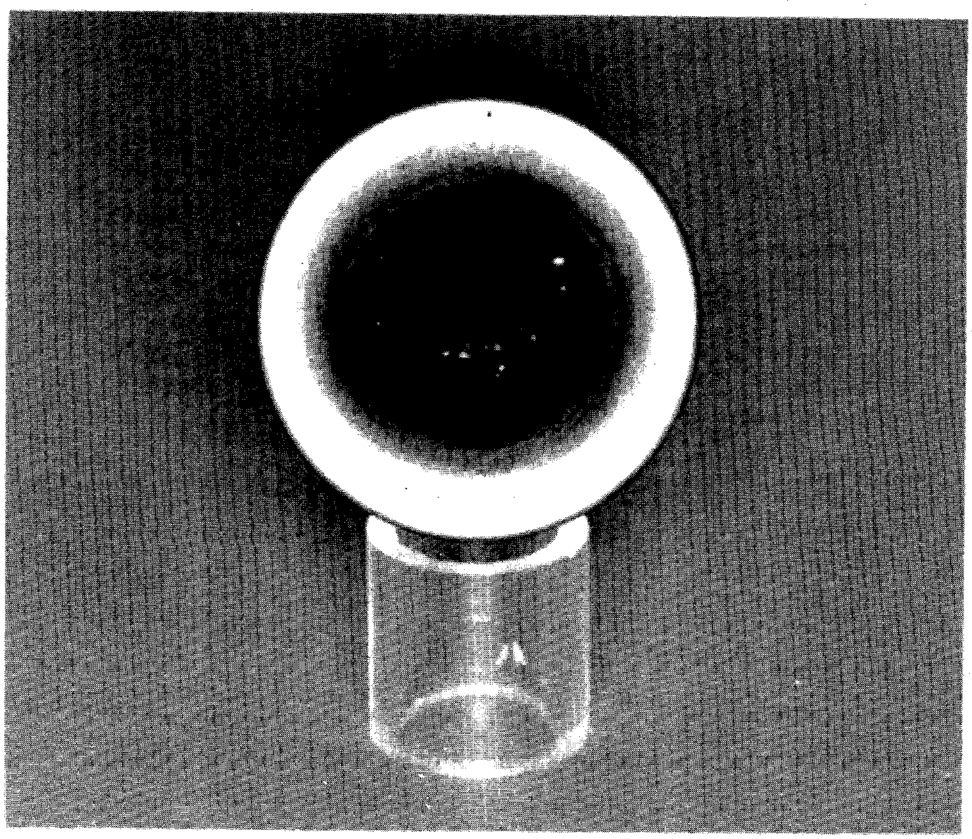


Figure 16. Post-Test Photograph of Electrode R-1

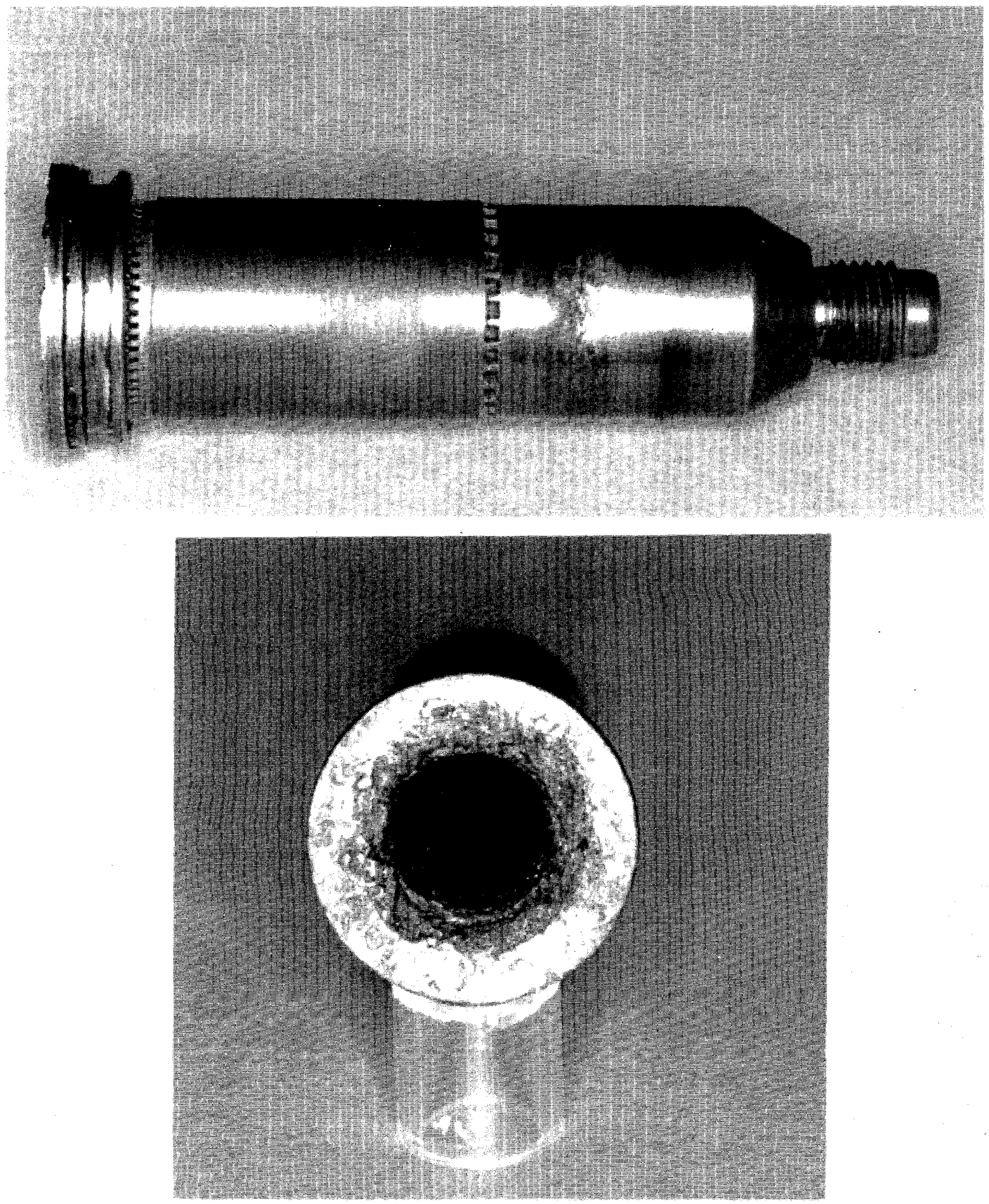


Figure 17. Post-Test Photograph of Electrode AJ1-1

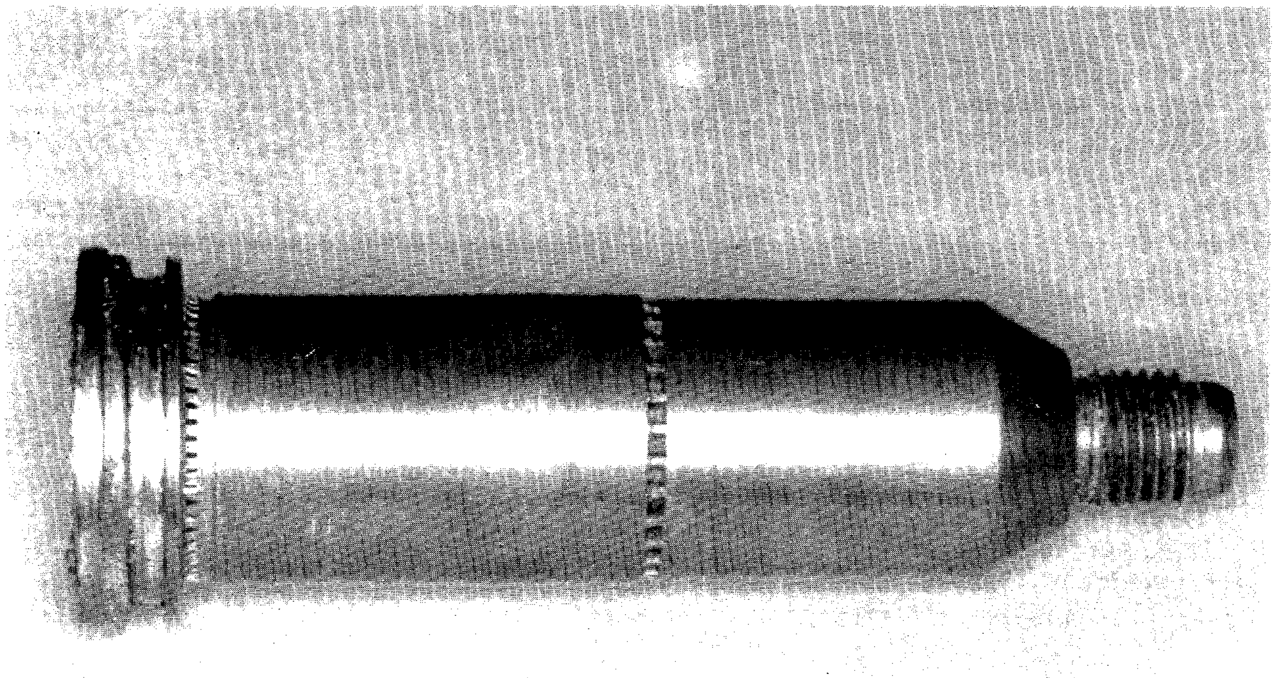
To correct the improper attachment of the arc, the nitrogen flow rate was increased to 1.7 scfm on the same day for the testing of AJ3-1, a water cooled platelet electrode with an iridium sleeve. After the initial ten minute test some melting and resolidification of the iridium was observed. Testing was resumed and failure occurred after 16 additional minutes. Post-test photos of the AJ3-1 electrode are shown in Figure 18. Arc attachment again appeared to be located on the flange face and some damage to other torch hardware was observed.

Because of the circumstances surrounding the failure of the two platelet electrodes, it was decided to firmly establish the arc attachment location and its repeatability by testing three Retech reference electrodes, R-2, R-3 and R-4, to failure. These tests were accomplished on 3-8 August. The torch gas flow rate was 1.2 scfm and arc attachment induced failures occurred 7/8, 3/4 and 3/4 inch from the front end as evidenced by necking on the outer diameter. Post-test photos of these three electrodes are shown in Figures 19-21. These tests demonstrated repeatability of the arc attachment location for the reference design and also provided more reference life data. These reference electrodes failed after 4, 4.5 and 8 hours.

A new water cooled platelet electrode, AJ1-2, was tested on 9 August. After the first test the arc appeared to be attaching 1 inch from the open end. After the second test there appeared to be some erosion further into the electrode indicating a second arc attachment location. The torch shut itself down during the third test after a cumulative duration of 62 minutes. Electrode failure was adjudged imminent based on post-test appearance, so no further tests were performed. Post-test photos of the AJ1-2 electrode are shown in Figure 22. Subsequent dissection of this electrode suggests that the arc was probably attaching beyond the platelet channels.

A platelet electrode with both water cooling and argon injection, AJ2-1, was tested from 11-23 August. The argon gas flow rate through the anode was 1.0 scfm. The nitrogen flow rate through the gas injection ring was maintained at 1.2 scfm. After the first few tests the electrode inner diameter retained a shiny new appearance. Tests continued until 40 hours test duration was accumulated. The electrode still showed no erosion but the internal diameter began to show a darker and duller appearance and there were four red marks on the outer diameter at the locations of the torch body water manifolds.

The success AJ2-1 promoted considerable discussion among Aerojet and Retech engineers. It was concluded that the torch power level, gas composition and gas flow rate were independent variables which should be held constant to put to rest any uncertainties about the influence on operating conditions between the platelet and reference electrodes.



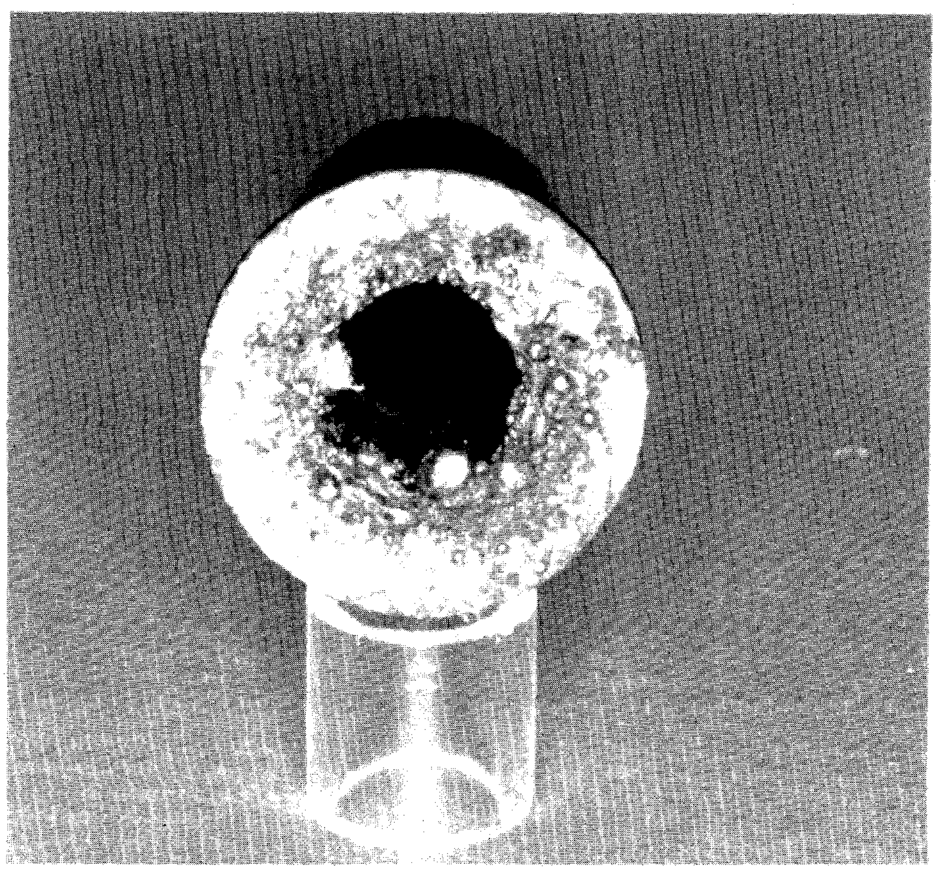


Figure 18. Post-Test Photograph of Electrode AJ3-1

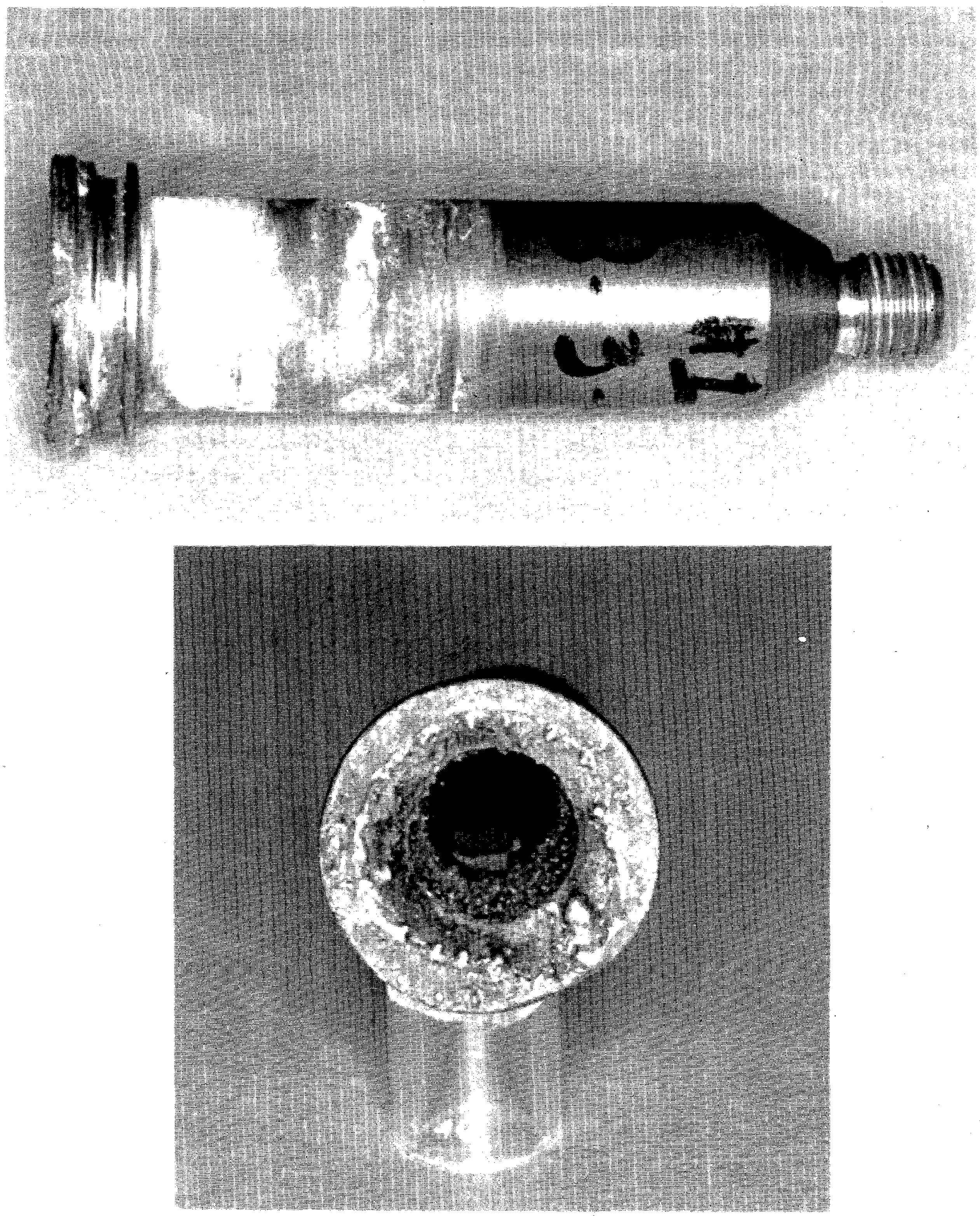


Figure 19. Post-Test Photograph of Electrode R-2

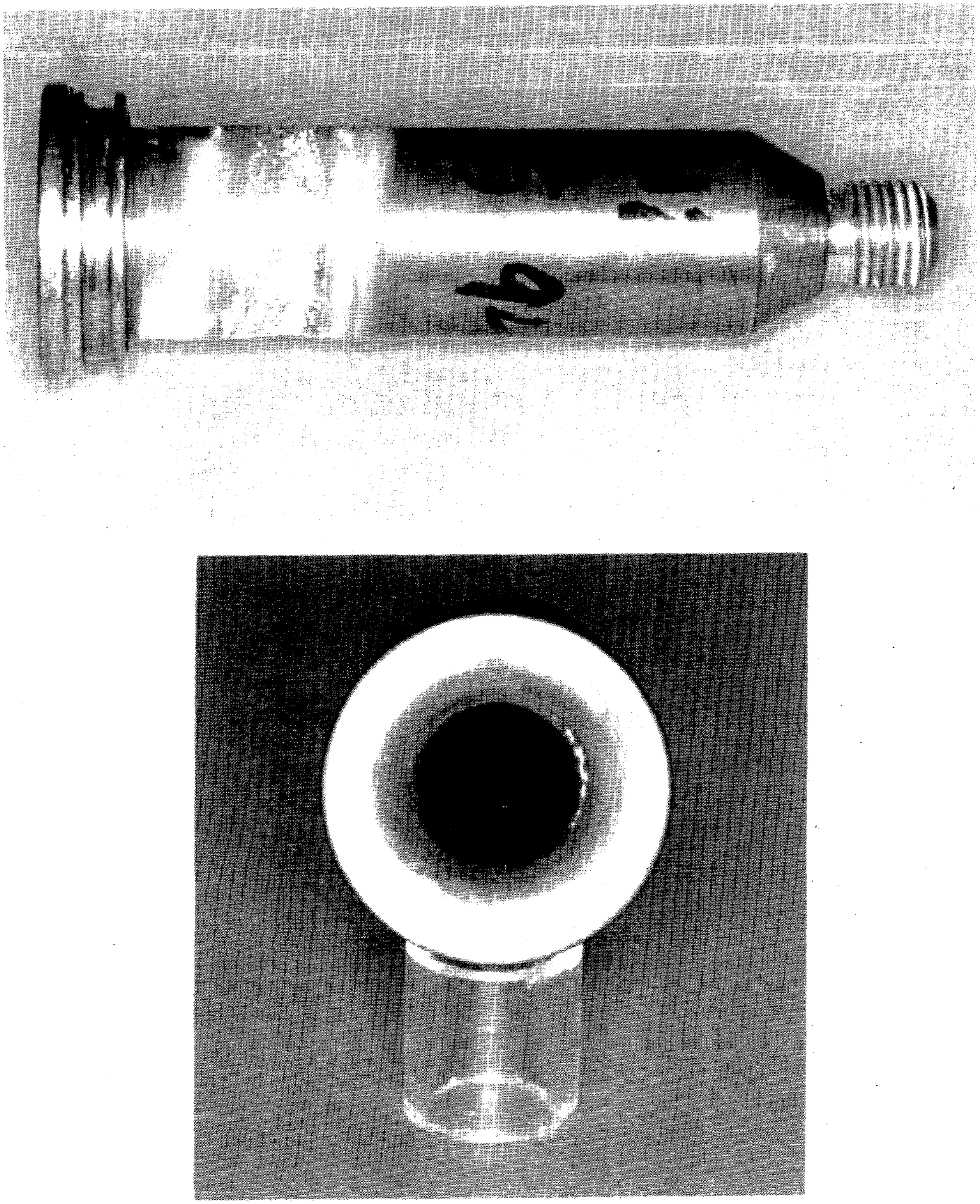


Figure 20. Post-Test Photograph of Electrode R-3

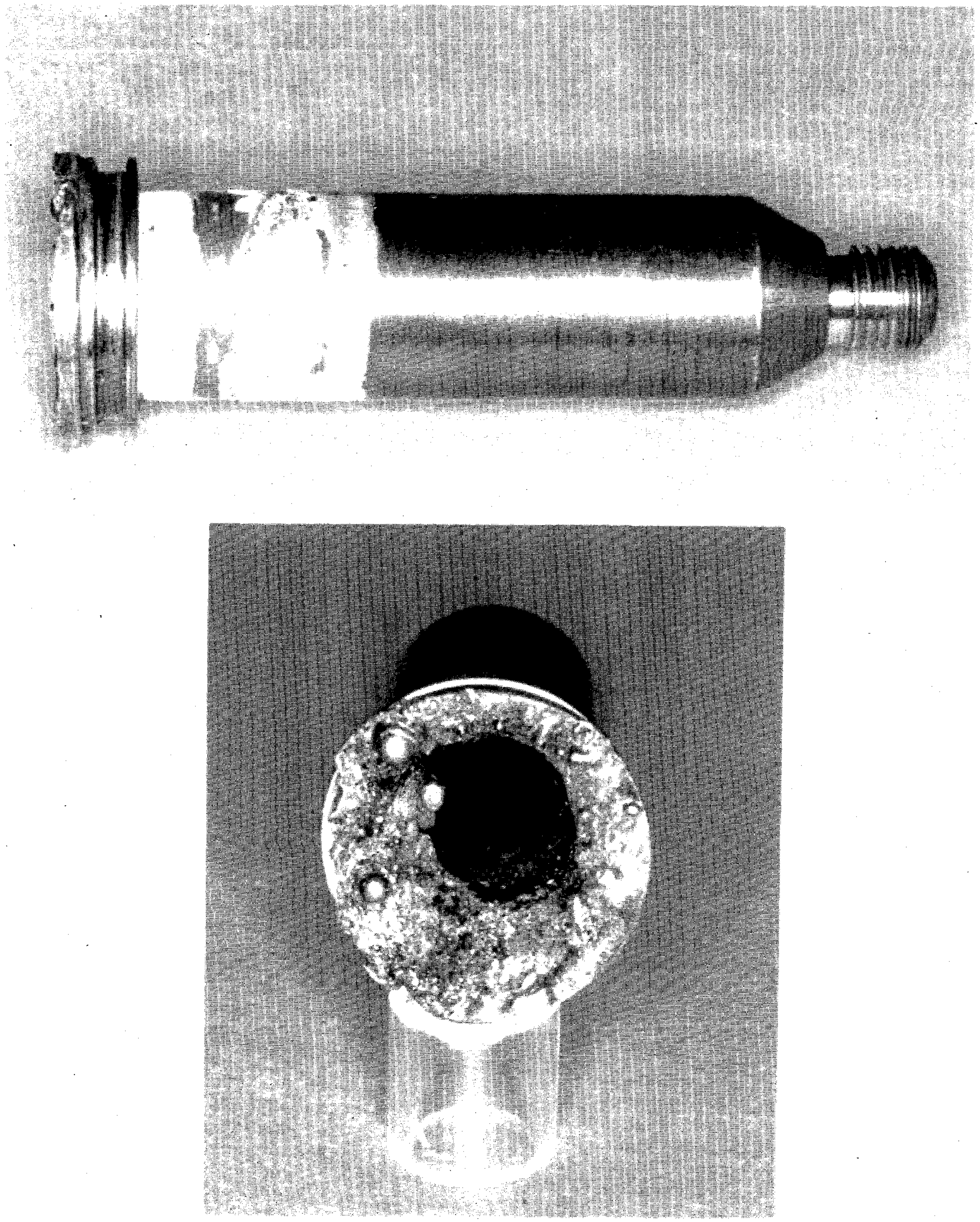


Figure 21. Post-Test Photograph of Electrode R-4

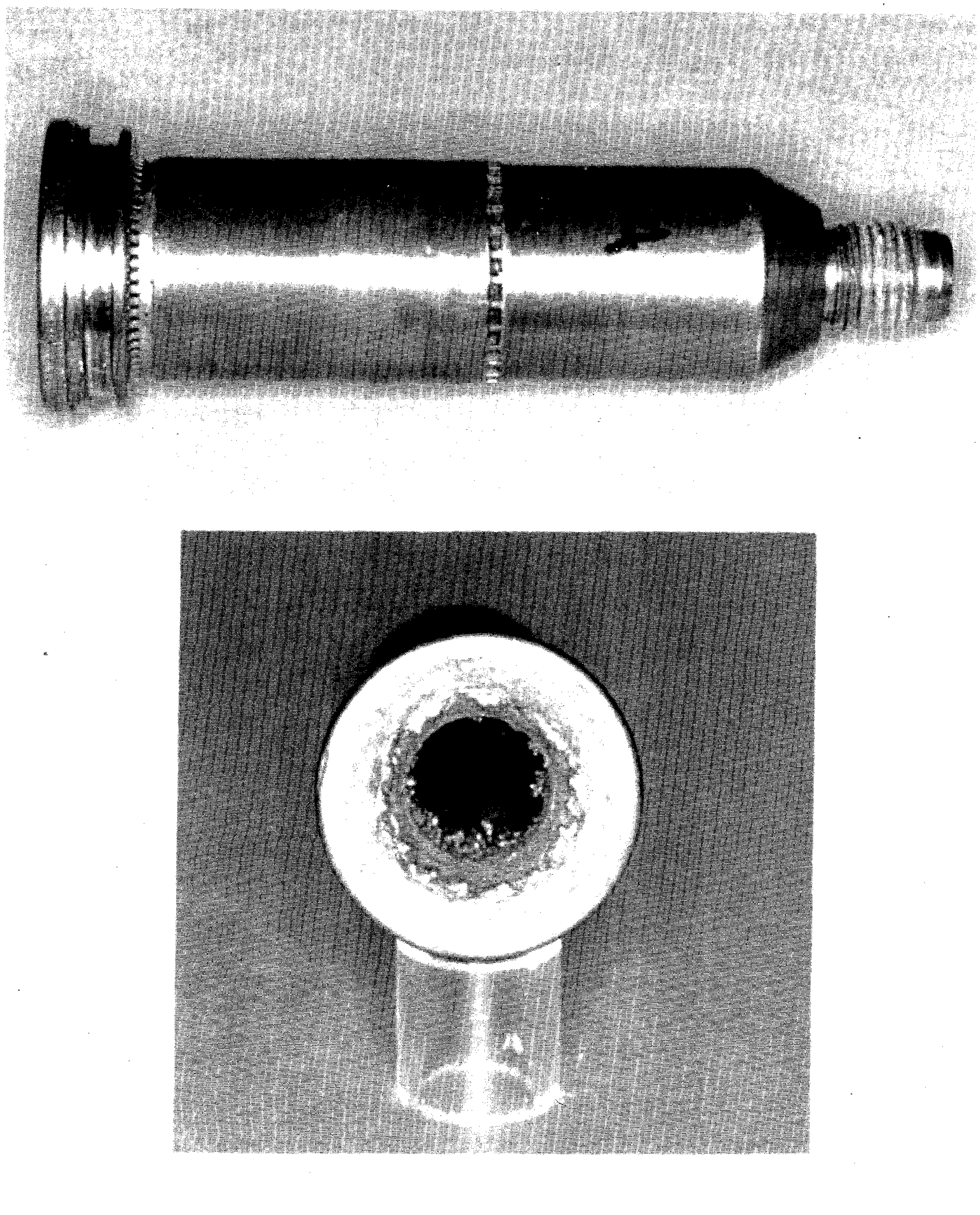


Figure 22. Post-Test Photograph of Electrode AJ1-2

Reference electrode R-5 was tested on 25 August using mixture of 1.2 scfm nitrogen and 1.0 scfm argon injected through the two-hole gas injection ring to simulate the same overall gas composition as used for AJ2-1. Failure occurred after 5 hours and 37 minutes. Post-test photos of the R-5 electrode are shown in Figure 23. The power level for this test was 77 kW. This test shows that simply adding argon via the injection ring produced no measurable life increase for the reference electrode.

In the next test a reference electrode R-6 was tested at 59 kW with 1.2 scfm nitrogen and 1.0 scfm argon injected at the torch gas injection ring. The electrode failed after 82 minutes. Post-test photos of the electrode are shown in Figure 24. This test shows that even at the same total power level and gas composition the reference electrodes have much shorter life than the Aerojet electrodes with gas injection. Conversely, the increase in life for the Aerojet electrode is not caused simply by the slightly different power level or the gas composition.

On the next test Aerojet electrode AJ3-2 with an iridium sleeve was tested. This test was performed as a repeat of an earlier test performed on 25 July where results were in question because of possible faulty arc operation. The electrode was tested for about five minutes, then removed. Post-test photos of the AJ3-2 electrode are shown in Figure 25. Beads of iridium metal on the electrode inner wall indicate that at least some portions of the iridium sleeve had melted and resolidified. This is consistent with the earlier test where the iridium sleeve appeared to have disappeared during the first ten minute test segment. The very rapid melting suggests a high probability that the failure mechanism is inadequate thermal contact between the iridium sleeve and the copper body.

In the next test segment the second platelet electrode with gas injection, AJ2-2, was tested. The gas injected through the platelet was 1.0 scfm nitrogen rather than argon as injected for AJ2-1. This electrode ran 19 hours without failure and was in good shape post test. Post-test photos of the electrode are shown in Figure 26. This result indicates that improved electrode life can be achieved with either nitrogen or argon as the injected gas. Furthermore, the fact that the life is enhanced using either gas suggests that gas swirl induced arc foot rotation may be the primary life increase mechanism. Whether argon or nitrogen is better cannot be decided without a conclusive test to failure for both electrodes.

In the final test segment, the AJ2-1 electrode, which had already logged 40 hours, was tested for an additional 24 hours, bringing its total duration to 64 hours. The appearance of the electrode was still good at the end of the 64 hours and Retech torch operators estimated from its appearance that it could run as long as 100 hours. Post-test photos of the electrode are shown in Figure 27.

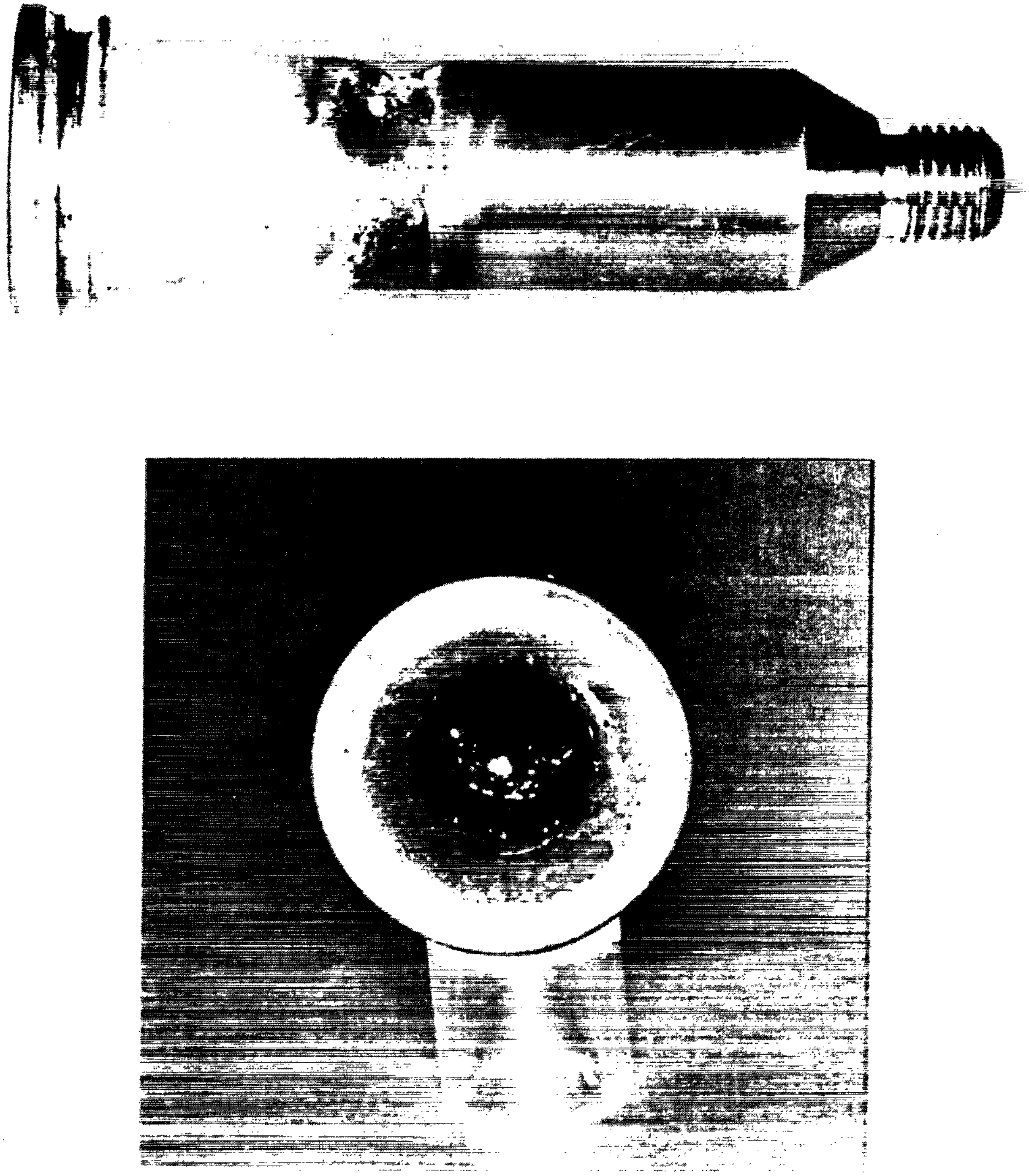


Figure 23. Post-Test Photograph of Electrode R-5

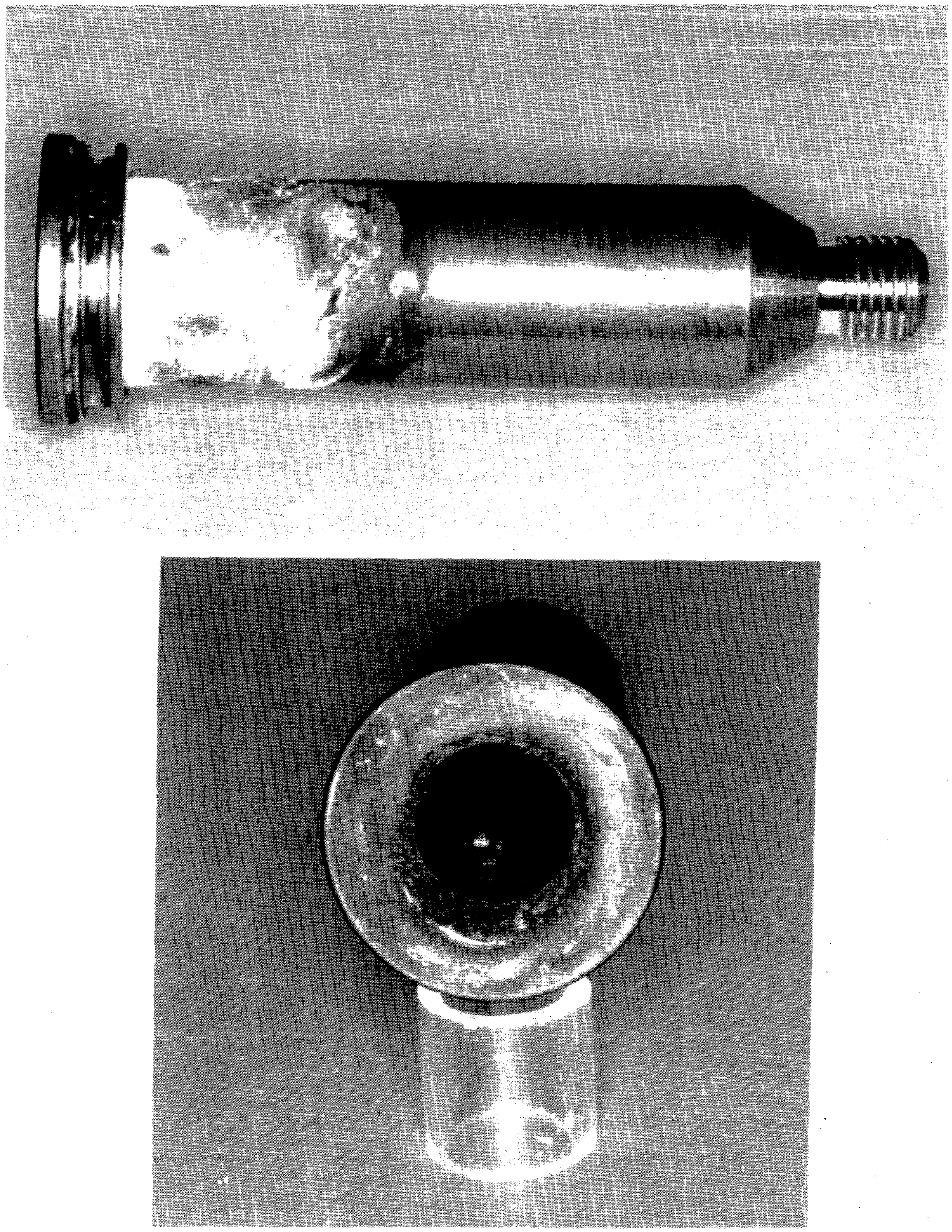


Figure 24. Post-Test Photograph of Electrode R-6

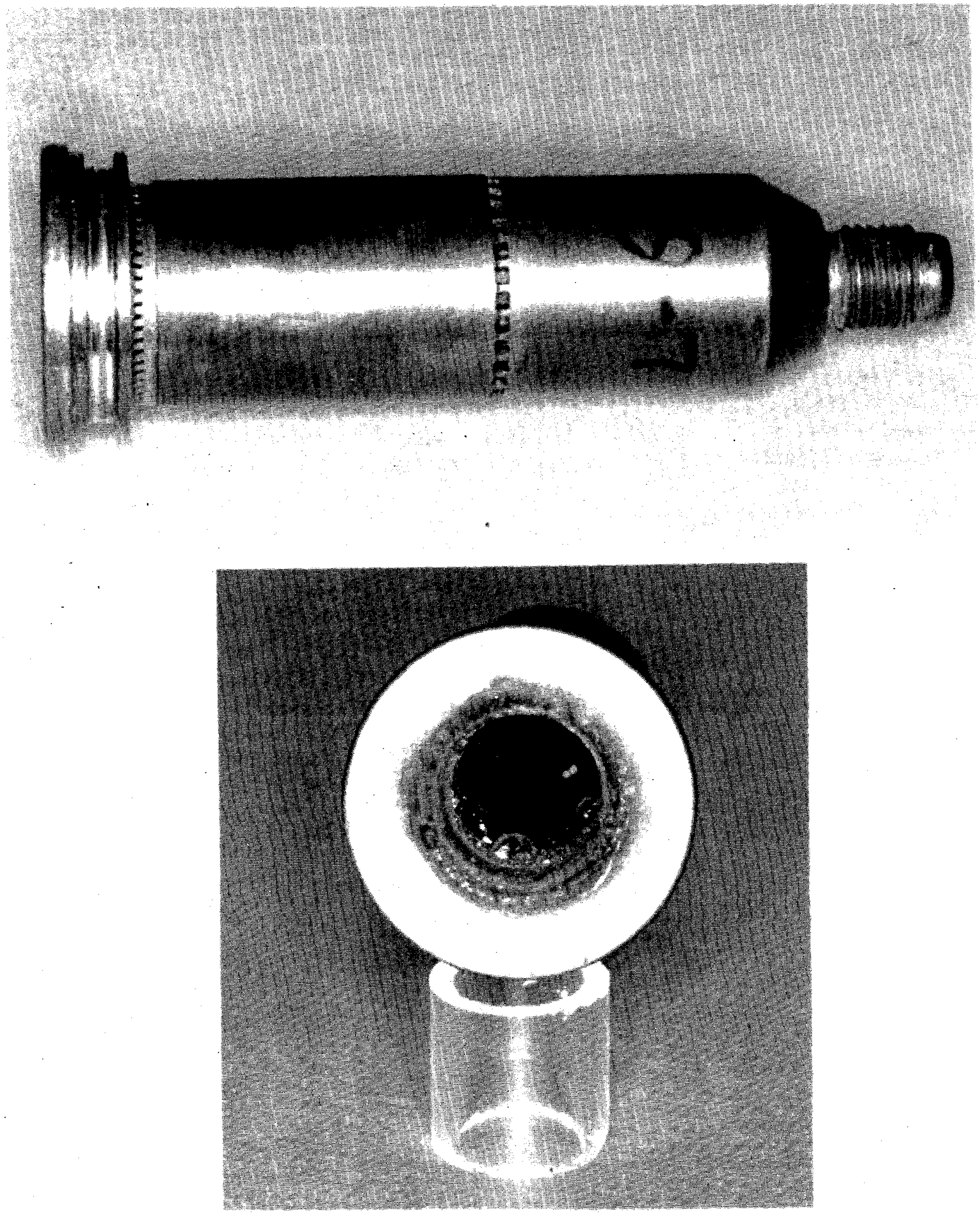


Figure 25. Post-Test Photograph of Electrode AJ3-2

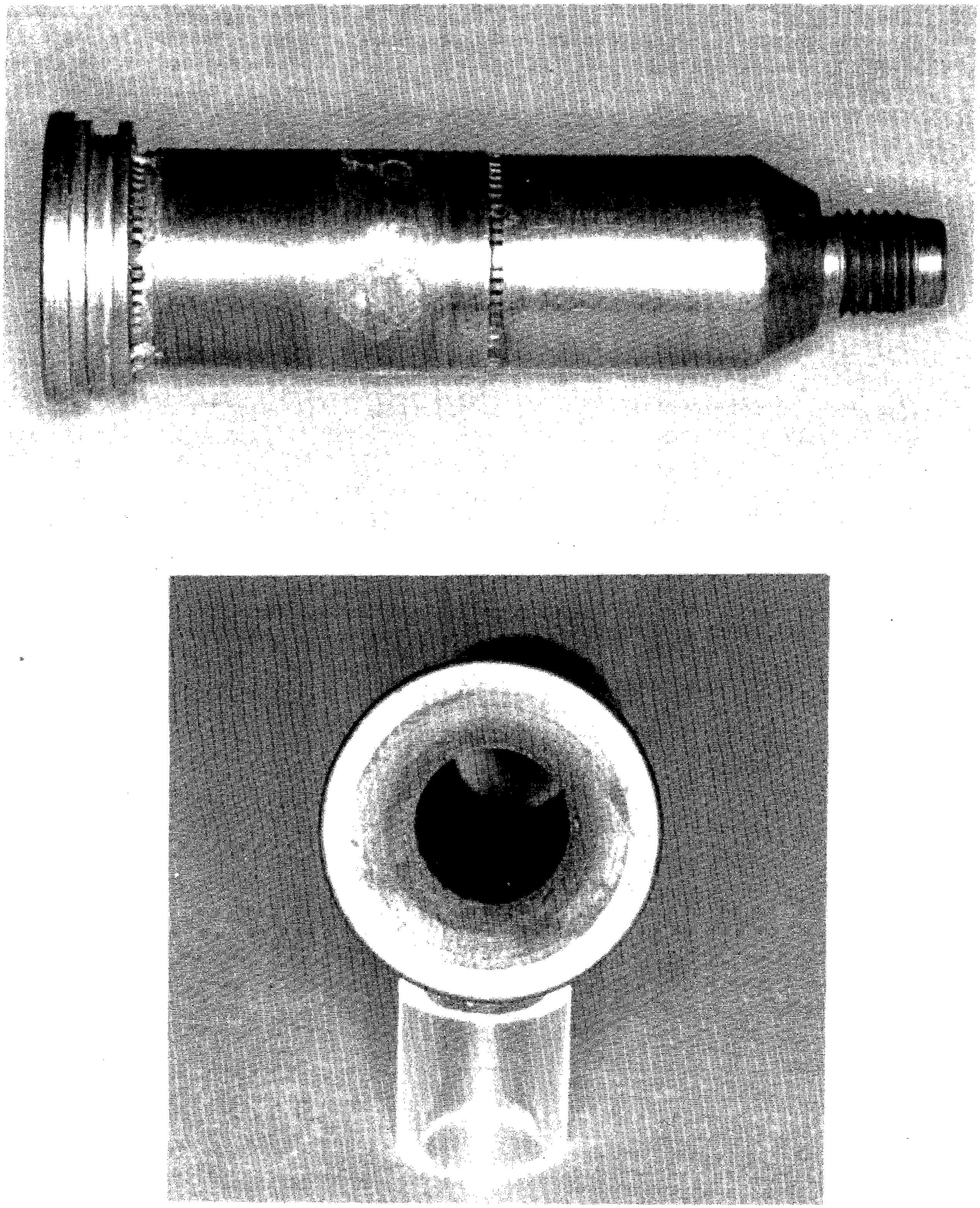


Figure 26. Post-Test Photograph of Electrode AJ2-2

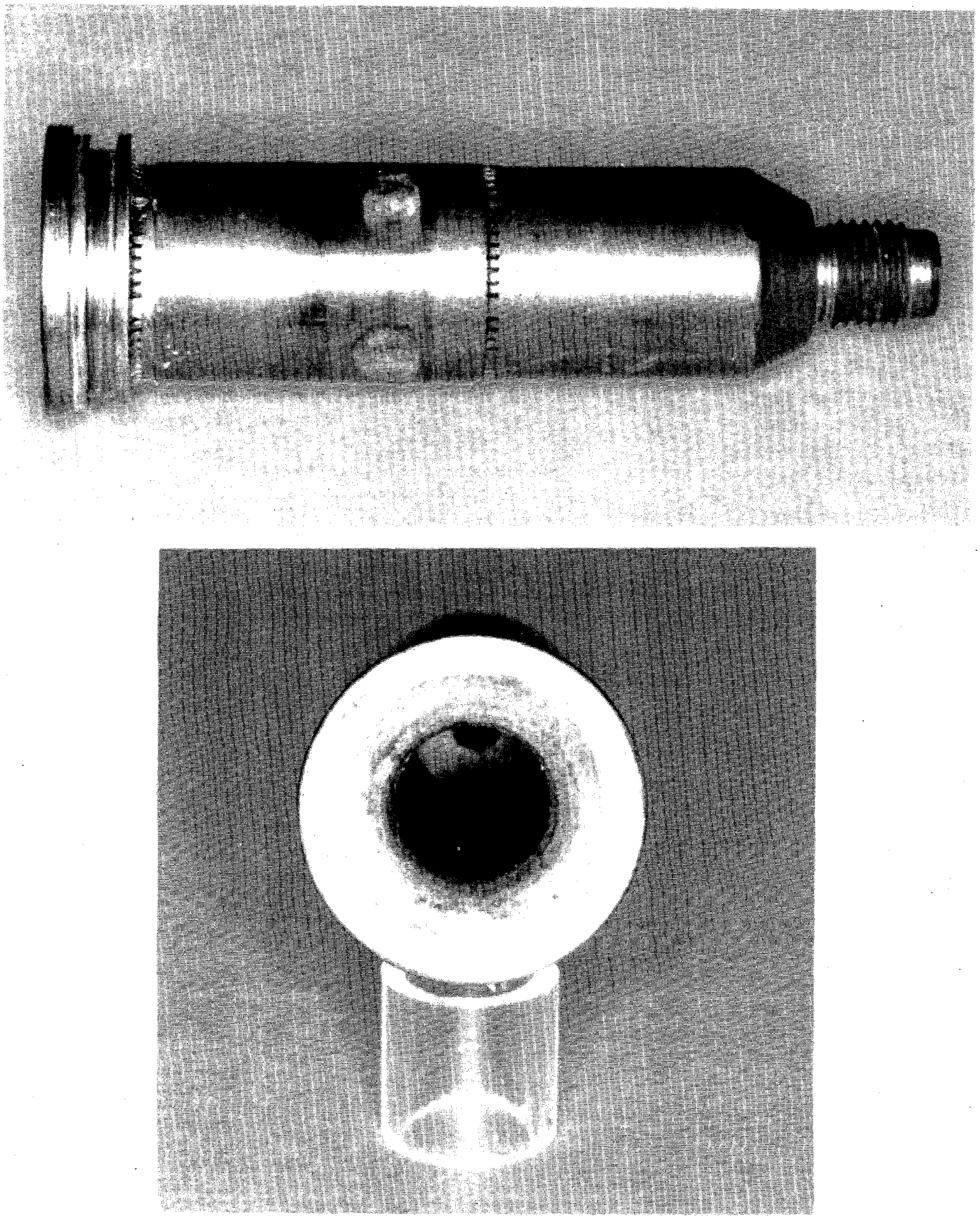


Figure 27. Post-Test Photograph of Electrode AJ2-1

The test program followed the test plan in general, but there were several changes which occurred. First, current rather than power was held constant. Because the work piece is a tub of rotating waste material, the arc length and electrical resistance is constantly changing, and so, consequently, the voltage also changes. Second, test durations were shorter than planned. The reference electrodes failed after 1.5 to 8 hours, rather than after 10-30 hours as originally estimated by Retech. The reason for the difference was that the arc had to be attached on the front end of the electrode. This provides the proper simulation of the arc attachment mechanism for the 1 MW electrodes which also attach the arc on the side wall.

As a result of the shorter test times, it was not possible to perform daily measurement, weighing or photography, since only the two AJ2 electrodes lasted more than eight hours. Electrodes were inspected after 10 and 30 minutes, but typically they looked fairly new until failure occurred. No weight loss was ever detected, even after failure, suggesting that material was melting but remaining on the electrode.

6.2 Test Data Analysis

The primary data produced by this program was the measured electrode life. Table 11 summarizes this data.

Table 11. Summary of Electrode Life

Electrode	Life	Comment
R-1	87 minutes	Reference electrodes
R-2	4 hours, 24 minutes	
R-3	8 hours	
R-4	4 hours, 39 minutes	
R-5	5 hours, 37 minutes	
R-6	82 minutes	
AJ1-1	59 minutes	Questionable arc attachment location
AJ1-2	62 minutes	
AJ1-3	not tested	
AJ2-1	> 64 hours	Argon injection
AJ2-2	> 19 hours	Nitrogen injection
AJ3-1	26 minutes	Sleeve melted
AJ3-2	5 minutes	Sleeve melted

The average life of the six Retech reference water cooled electrodes was 4.25 hours. The platelet electrodes with gas injection ran for 64 hours and 19 hours, respectively, without failure. At 64 hours, the life of the platelet electrode with argon injection is approximately fifteen times longer than the average life of the reference electrodes, or between eight and forty-seven times the minimum and maximum life.

The very short lives of the AJ1 and AJ3 electrodes most likely indicates a problem in design, or an operational deficiency. The most likely cause for the failure of the AJ1 electrodes were the short channel lengths, only 0.67 inch long. It is speculated that failure may have been caused by arc attachment beyond the coolant channels. A lesson learned is that precise placement of the arc attachment point is difficult, and coolant channels probably need to extend the entire length of the electrode.

The very rapid failure of the AJ3 electrodes suggests inadequate thermal contact between the sleeve and electrode body. Adding a braze material between the sleeve and the body might be one method to improve this contact. However, differential thermal expansion between the body and sleeve could also lead to a failure of the braze joint.

The increase in life of the AJ2 electrodes is most likely due to gas injection. However, the increased length of the water coolant channels to 1.17 inch must also be considered. It is possible that the extra 0.67 inch length was long enough that the arc was attaching over a coolant channels, and that water cooling may have contributed to the life increase.

It is the opinion of the authors that the remarkable increase in life of the AJ2 electrodes is produced primarily by gas injection, and not by the length of the coolant channels. Rarely does a researcher see an order of magnitude increase in any performance parameter, and when it does occur it is usually due to a major change in the operational approach, in this case the gas injection. The effect of arc foot rotational frequency on wall temperature reported in the literature [21] is very dramatic. Also arc foot rotation is known to be associated with torch gas swirl [10]. Finally non-radial gas injection is known to produce gas swirl in axial flows and it would almost certainly increase the swirl of any already established gas swirl. Whether argon or nitrogen is better cannot be determined without conclusive test to failure for both electrodes.

Other post test data analysis consisted of collecting operator comment sheets, printing and plotting pertinent electrical data, and calculating electrode cooling efficiencies. Torch and cooling power levels are plotted in Appendix B. The power levels show large fluctuations due to changes in arc length caused by tub rotation. These fluctuations are normal for this type of torch. Operator comments are found in Appendix C.

Electrical data is summarized in Table 12. This data shows that the torch power level was 85 kW for electrodes with water cooling only and nitrogen as the torch gas. When 1.0 scfm was added to the torch gas the torch power level was reduced slightly to 78 kW.

Table 12. Electrical Data Summary

Test Date	Electrode	Ave. Voltage volts	Ave. Power kW	Torch Flow Rate scfm	Electrode Gas Flow Rate scfm	Electrode Water Flow Rate gpm	Electrode Water Power Loss kW	Eff
7 June	R-1	260	78	2.1	n/a	5	n/d	
25 July	AJ1-1	260	78	1.5	n/a	4.2	18	0.23
25 July	AJ3-1	260	78	1.7	n/a	4.2	15.5-17	0.21
3 Aug	R-2	260	78	1.2	n/a	5	n/d	
5 Aug	R-3	260	78	1.2	n/a	5	n/d	
8 Aug	R-4	260	78	1.2	n/a	5	n/d	
9 Aug	AJ1-2	260	78	1.2	n/a	4.2	14-16	0.19
11-23 Aug	AJ2-1	197	59	1.2 1.0 argon	1.0 argon	3.5	9.5-11	0.17
25 Aug	R-5	260	78	1.2 1.0 argon	n/a	5	13.5	0.17
6 Sept	R-6	197	59	1.2	n/a	5		
7 Sept	AJ1-2	260	78	1.2	n/a	4.2		
7-12 Sept	AJ2-2	197	59	1.2	1.0 nitrogen	3.5	9	0.15
13-19 Sept	AJ2-1	197	59	1.2	1.0 argon	3.5	11-13	0.20

R-# = Retech conventional water cooled electrode
AJ-# = Aerojet platelet electrode

With the AJ2 electrode, where the argon was injected through the electrode, the torch power level was 59 kW. The differences in torch power level may be due to different electrical resistivity at the arc attachment point and in the arc column caused by differences in gas composition. Since the electric current was constant at 300 amps for all tests, and since resistance heating in the waste material is dependent only on current, it is possible that using the platelet electrode with argon gas injection provides the same heat into the waste material at a 31 percent lower torch power consumption.

Water cooling efficiencies for the platelet electrode, defined as water power loss divided by torch power input, ranged from 15 to 23 percent. Retech provided data from their historic data base showing that the cooling water power loss for their electrodes is about 14 percent of torch power input. This data suggests that the platelet electrodes may have a slightly higher cooling efficiency than the reference electrodes.

During the 64 hours testing with the AJ2-2 electrode the arc started easily and operated smoothly with no instabilities. It was not necessary to perturb the operation other than to start the argon flow and monitor its flow rate level periodically. The electrode survived numerous torch starts and stops, frequent exposure to contamination during inspection, and several insertions and removals from the torch where the insertion tool rubbed on the slotted surface. The electrode ran at 59 kW, down from 85 kW when running with nitrogen only.

The optical system was unable to detect any copper in the plasma. An experienced user of the system who operated the system on its first use offered the opinion that the arc background might be too bright and variable to allow detection of the copper signal even if there was copper present.

Based on the observed 75T electrode life increase, it is reasonable to expect that the life of a 1 MW platelet electrode with gas injection could also be increased. The reported life of the 1 MW electrode is approximately 200 hours. If the same magnitude of life increase were to occur for the 1 MW electrode as was observed for the 75T electrode, the 1 MW electrode would operate without failure for approximately 2000 hours. On the other hand, the fact that the 1 MW electrode already has a longer life than the 75T electrode suggests that 1 MW electrode heat flux may be lower, and so gas injection might not produce as dramatic an effect. Since there is no reliable heat transfer or life model for either electrode, this conclusion cannot be reached through analysis. The most logical method to determine the life of a 1 MW platelet electrode with gas injection would be by testing.

6.3 Conclusions

The conclusions of this program are summarized below.

1. Argon gas injection increases the life of the electrode more than tenfold, producing economic and safety benefits.

2. Nitrogen gas injection also provides life improvement.

3. Argon injection reduces power at set current, improving torch efficiency, an economic benefit.

4. The plasma torch operates smoothly and without instabilities with the platelet electrodes.

5. A 1 MW platelet electrode with gas injection would be expected to have increased life compared to a conventional electrode, but the amount of the increase can only be determined by test.

6.4 Recommendations

Recommendations from this program are summarized below.

1. Since the two platelet electrodes with gas injection did not fail during the test program, continued testing until failure occurs is recommended.

2. A follow on program to fabricate and test a 1 MW size electrode with gas injection is recommended.

Author's postscript:

Following the planned test program, Retech was authorized to perform additional in-service testing through 18 November. During this period the AJ2-2 electrode with nitrogen gas injection was tested for eleven additional hours. This testing increased the total duration for that electrode to thirty hours.

At some time during the last hours of testing, the nitrogen bottle ran out of gas and the electrode ran for an unknown period of time without gas injection. As a result, the electrode was eroded at the open end. After buffing the eroded areas with an emery cloth, the electrode was reinstalled but was determined to be leaking, and so testing could not be continued. This failure was clearly caused by operator error, and not by an electrode design deficiency, and therefore does not represent a true life failure data point. This incident further proves the importance of gas injection as the crucial mechanism for life increase.

References

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Appendix A

Test Plan

Test Plan

May 22, 1994

Platelet-Cooled Plasma Arc Torch

Table of Contents

1.0 Introduction

As part of the Platelet Cooled Plasma Arc Torch program, contract DE-AR21-93MC30361, Aerojet will test three different platelet anode designs in a Retech 75T torch. The tests will be conducted at Retech in Ukiah, California, as specified by Aerojet purchase order number 824707. Increase in torch life without loss of electrical power efficiency or arc stability is the goal of the program. The objective of the tests is to demonstrate at least a twofold increase in anode life capability compared to the existing backside water cooled anode currently in use on the 75T.

This program is part of the Mixed Waste Integrated Program where the intended application is plasma torch vitrification of mixed waste into earth storable forms. Plasma arc torch life is currently limited by anode failure. The need to repeatedly break into the arc to replace the anode may make that application impractical for mixed waste handling.

In the 75T plasma arc, an electric current passes between the anode and a cathode target material. A very high heat flux on the order of 1500 BTU/in2-s occurs where the arc foot attaches on the anode. Typically the arc gas is swirled to keep the arc foot rotating. Failure of the anode occurs when, after numerous passes by the arc foot, sufficient material is eroded to cause a water leak which quenches the arc. Water cooling is needed to prevent bulk heating of the anode, and it can also be effective in reducing the surface temperature and erosion rate under certain conditions [1].

The plasma gas heating environment is not well defined or understood, so the program emphasizes testing, rather than prediction, to define anode life. The strategy for technical success, i. e., at least two-fold increase in anode life, is to build and test three different platelet anode designs with increasingly sophisticated cooling techniques.

Design no. 1 is a copper, water cooled anode. This design improves on the existing backside-cooled anode by using platelet channels to increase the cooling surface area by a factor of four.

Design no. 2 retains the water cooling from design no. 1 then adds argon swirl injection at the wall to reduce the heating rate and create an inert gas barrier.

Design no. 3 is water cooled and has a .020 inch thick iridium sleeve in the arc attach zone. Iridium is a high melting point, high thermal conductivity material which may have a lower erosion rate than copper.

Aerojet will deliver six anodes for testing, two anodes of each of the three designs. One anode from each pair will be tested and the other will be reserved as a backup. Each anode will be initially tested for a period up to 5 days, or 35 hours. At the end of these tests the anode having the least erosion will be tested for up to 24 additional days, or 192 hours.

Platelet cooling is a proven technology developed by Aerojet over the last 30 years and implemented in a number of products, including rocket chambers, heat exchangers, and missile structural components. Additional information on platelets is provided in the Management Plan [2] for this program.

2.0 Test Objective

The objective of the testing is to determine the life and operating characteristics of three different platelet-cooled anodes through actual operational testing in a plasma arc torch. The life of the anodes will be measured by firing the 75T plasma arc and measuring the amount of anode erosion at specific time intervals, up to the point of failure. The testing will also measure cooling power requirements and heat loss, plus arc efficiency and stability characteristics. If the platelet anodes do not fail within the test period, life will be estimated by extrapolating on the measured material loss rate.

3.0 Equipment and Experimental Setup

Testing will be performed at Retech in Ukiah, California. Retech is currently involved in research into mixed waste processing by plasma arc torch. The test equipment will consist of a 75T plasma arc torch, plus a data logger system, and possibly some optical instruments for plasma plume measurement. Nominal power is 90 kW. Power for the arc is provided by an on-site diesel generator. Controls include voltage and current regulators. The plasma gas is nitrogen and the flow rate is approximately 5 scfm at 1 atm pressure. Coolant water is available at pressures up to 180 psig and flow rates up to 5 lb/s.

Figure 1 shows a sketch of the system. The anode is installed at the top where the electrical power input is indicated. The plasma is directed into a tub located about 3 feet below the anode. During testing the tub will be filled with uncontaminated dirt. A viewing port is located just above the tub enabling the operator to view the plasma by means of a pinhole camera.

Figure 2 shows a diagram of the torch coolant water delivery system. It is a closed system containing two 4-5 gpm Grundfos pumps, a filter housing and filter, a Modine tube-in-shell heat exchanger, and a five gallon supply tank The water goes first to the anode, then to the torch nozzle.

A separate system will be set up to supply argon to the torch. This system will consist of a six-pack of K-bottles, a regulator, a rotameter and a pressure gage. The argon supply temperature will be not be measured, but will be assumed to be the same as the measured ambient temperature. The argon flow rate will be 1 scfm.

Use of an Aerojet owned optical system to detect copper and iridium in the plasma gas is being considered. This system has been successfully used to detect metals in rocket exhaust plumes. The system would provide a means for detecting the erosion of anode material prior to coolant water breech, and when correlated with periodic anode weight measurements would provide a semi-quantitative material loss history. The system would consist of a fiber optic probe, a spectrometer and a high resolution detector, and would continuously monitor a narrow band of emissions centered on the peak emission wavelength for either copper or iridium.

4.0 Preparations and Procedures

Each anode will be flow checked at Aerojet and delivered to Retech with a flow data sheet. Prior to arc testing, Retech will install the anodes and perform water flow tests to ensure anode flow rates are consistent with the flow data sheets. The cooling water system will be configured to provide as high a water flow rate as possible to the anode without exceeding the 180 psi facility limit. Retech indicates that their anodes run between 2-5 lb/s.

The platelet anodes are intended to fit exactly as existing anodes, but two small modifications to the torch have been required: (1) an O-ring has been added on the anode housing inner diameter to prevent intermanifold water leaks; and (2) a tube and O-ring have been added at the threaded end to port Argon for design no. 2.

The two primary procedures which are followed are the start-up and shut down of the arc. These are standard procedures followed by Retech technicians. The arc is brought on-line slowly with Argon by increasing amperage until the operating power reaches 90 kW. The operator then switches to nitrogen and the arc is transferred from the nose cone to the bed. During operation the arc is current is maintained in the 300-400 amp range. On shut down the arc is simply turned off.

Cooling water pressure and flow rate will be monitored and the equipment shut down if they are out of range. Limits for flow rate and pressure will be established after the anodes are cold flowed.

Tests will be performed on daily work shifts. This schedule adds a number of starts and shut downs which would not occur in the field where plasma facilities will be run continuously. There may be some erosion effects associated with start transients. Never the less, the program still provides a one-to-one comparison between the tested anodes since they all experience the same duty cycle.

Each anode will be installed in the plasma arc and initially tested for up to 35 hours. The torch will be disassembled, inspected, and measured daily. If the optical system is installed, the anodes will also be removed and weighed to provide a correlation between the optical signal and metal loss rate. Photographs of the hardware will also be taken to document anode appearance. After 35 hours anode wear should be evident. The anode with the least wear will then be chosen by the principal investigator for an additional 192 hours testing. If all three anodes show comparable wear, then other characteristics, such as cooling power requirement, arc stability, electrical efficiency, cost, or technology advancement, may be used as "tie-breakers".

5.0 Test Matrix

Table 1 lists the test matrix. All tests will be conducted at the 90 kW power level. The initial test series for each anode will consist of five test days. On day one there will be several tests of increasing duration: 10 minutes, 30 minutes, then 2 hours. This procedure is recommended by Retech based on experience with their own electrodes. This approach shakes out any first order problems with the anode. The next four days the anodes are run eight hours in duration per day. This procedure will accumulate seven total tests (start, run and stop) and 35 hours of cumulative duration. One of the anodes will be tested for an additional 28 days, which is 192 hours additional testing.

6.0 Data Collection

Data will be recorded on a Macintosh computer over the entire period of testing. Monitored parameters will include voltage and current, plus possibly some optical measurements on the plasma plume. The measurements will be single datum sampling for long term stability measurement. In addition, at various intervals, intensive data sets measuring the short term behavior of these parameters will be obtained and analyzed. Arc stability will be measured quantitatively by a spectral density analysis of the arc voltage, current and power.

Cooling water inlet and outlet temperatures and pressures will be measured by periodic single datum sampling. This data will be used in conjunction with current and voltage measurements to derive an efficiency analysis.

Dimensional changes of the anode also constitutes data. Anodes will be measured and photographed on a daily basis. Retech will also keep a running log of operator comments regarding arc operation. Comments will include any anomalies in arc frequency, induced damage to power circuits or excessive noise in adjacent control and instrumentation circuits.

The primary output of the data will be a set of anode measurements versus time. Also there will be four life measurements, one for the existing anode, and three for the platelet anodes. If the platelet anodes do not fail within the test period, the life will estimated by extrapolating on the measured material loss rate.

7.0 Success Criteria

The objective of this program is to determine the useful life of a platelet-cooled anode for a plasma arc torch. The success criteria for the program is that it provide the data necessary to make this determination. The success criteria for the platelet-cooled anode design is that its useful life exceed that of a conventional anode by at least a factor of two.

The useful life of the anode is defined as the period of time it can operate without replacement while the arc operates within a specified range of electrical efficiency, stability and cooling power loss. The life of the anode is ended when either (1) it fails structurally due to excessive wear, or (2) it causes the arc to operate outside the specified set of conditions. During testing, the anodes will be inspected and measured every eight hours, while electrical efficiency, stability and cooling power loss will be continually monitored.

Electrical efficiency will be determined by measuring the total electrical power into the arc and the cooling power loss. Efficiency is then defined as electrical power, less cooling power loss, divided by electrical power, or

Efficiency= [Electrical Power-Cooling Power] / [Electrical Power]

Cooling power loss is defined by the bulk temperature rise of the water and its flow rate, plus any radiation or conduction losses from the hardware.

The required level of arc efficiency will be determined by the initial test with the Retech anode and by reviewing past operating characteristics of the 75T arc. Accurate measurement of the fluctuating arc current and voltage is required and caution is required in the interpretation of the data. Comparisons between two different arc configurations can be invalidated because of the effect of the differing wave forms on the measuring system.

Electrical stability is measured by spectral density analysis of the arc voltage, current or power. However, there are also practical and subjective measures of arc stability. If the arc starts and runs reliably; if the arc operates continually with very low frequency changes; if fluctuations in arc resistance do not induce damage to the power circuits or induce excessive noise in the adjacent control and instrumentation circuits, then the arc is stable.

8.0 Logic Tree Diagram

Figure 3 shows the logic tree for the test program. There is a planned decision point after the first three anodes are tested at which point the principal investigator will select one of the anodes based on its appearance after the initial testing. Possible decision points may arise during testing if anodes fail before the five day test period is completed. In this case the principal investigator will use available data to determine possible causes of failure. If the cause of the failure is traced to the set-up, for example a plugged filter in the coolant water line, then the fault will be corrected and the test series will continue with a backup unit. If the fault is traced to the anode, then testing will either continue with a backup unit, or proceed to the next design.

References

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2. Dick Johnson and Scott Sieger, Management Plan for Platelet Cooled Plasma Arc Torch Program, Contract DE-AR21-93M30361, October 29, 1993.

Table 1. Test Matrix

Test No.	Day	Duration	Comment
Retech Anode			
1	1	10 minutes	Baseline test
2		30 minutes	
3		2 hours	
4-7	2-5	8 hours	
Aerojet Design No. 1			
8	6	10 minutes	Water Cooled
9		30 minutes	
10		2 hours	
11-14	7-10	8 hours	
Aerojet Design No. 3			
15	11	10 minutes	Iridium sleeve
16		30 minutes	
17		2 hours	
18-21	12-15	8 hours	
Aerojet Design No. 2			
22	16	10 minutes	Water cooling with Argon injection
23		30 minutes	
24		2 hours	
25-28	17-20	8 hours	
Aerojet Design TBD			
29-42	21-44	8 hours	Extended duration testing

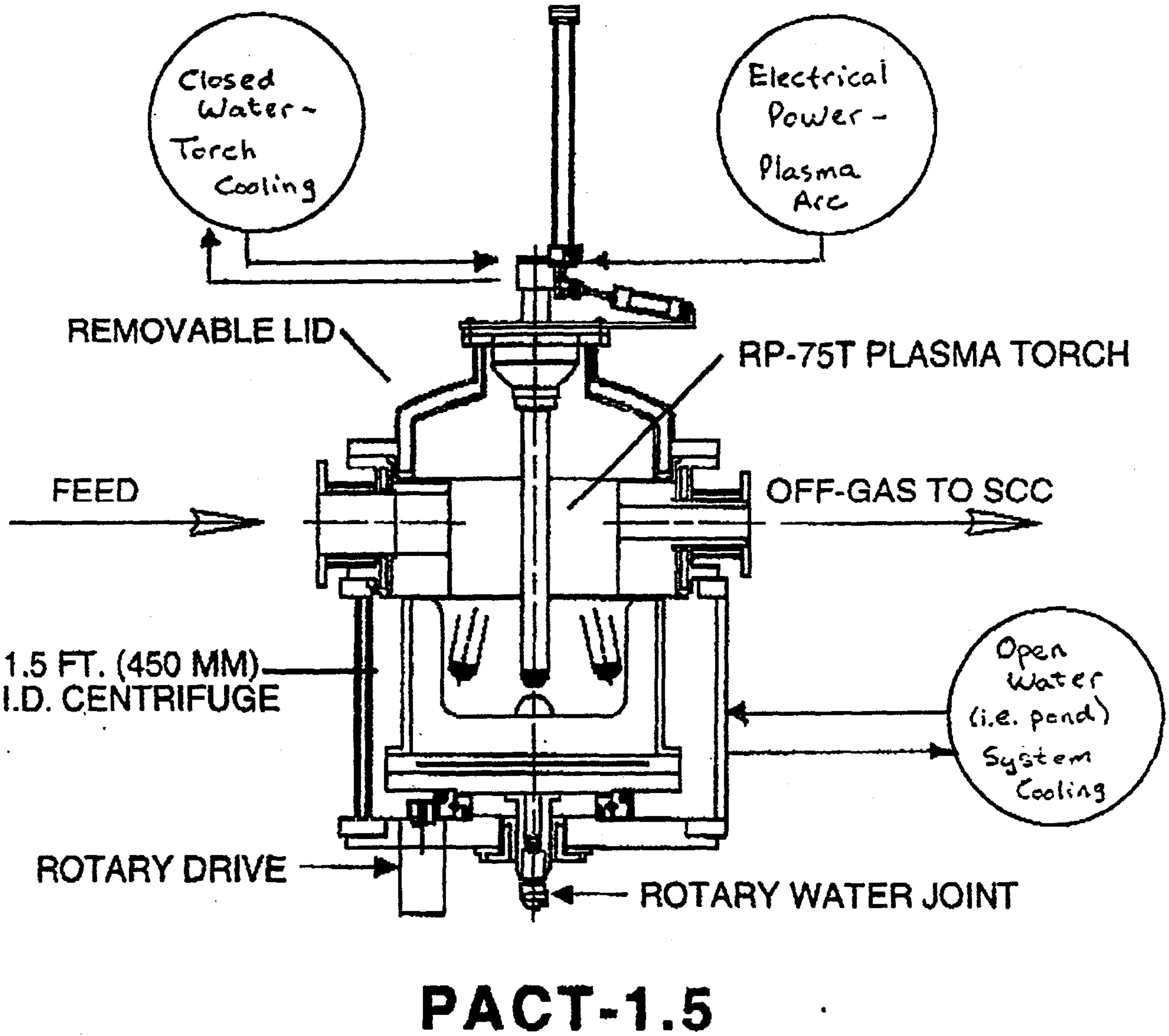

Figure 1 Retech RP-75T Plasma Torch

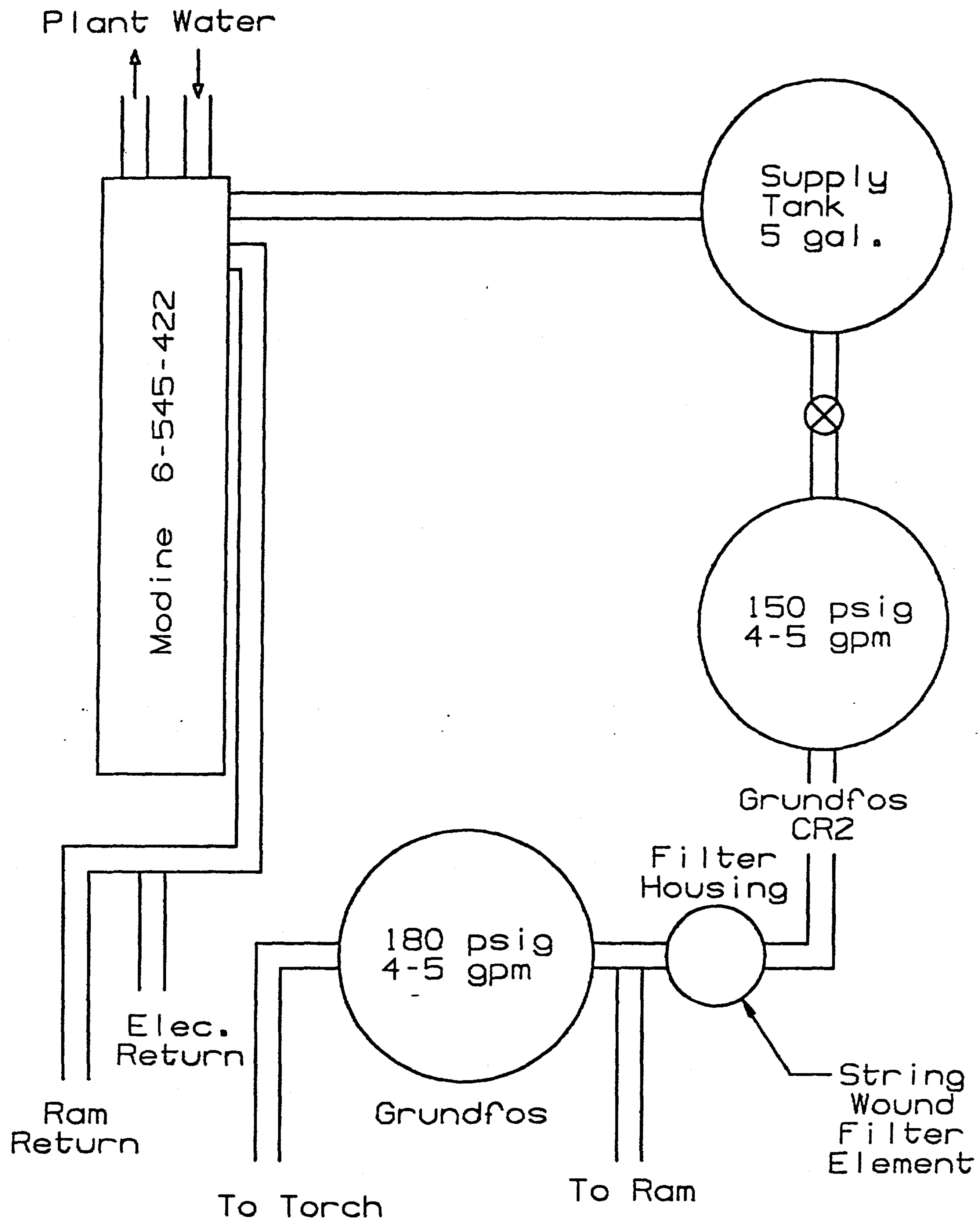

Figure 2 Closed Water Cooling System for Plasma Torch

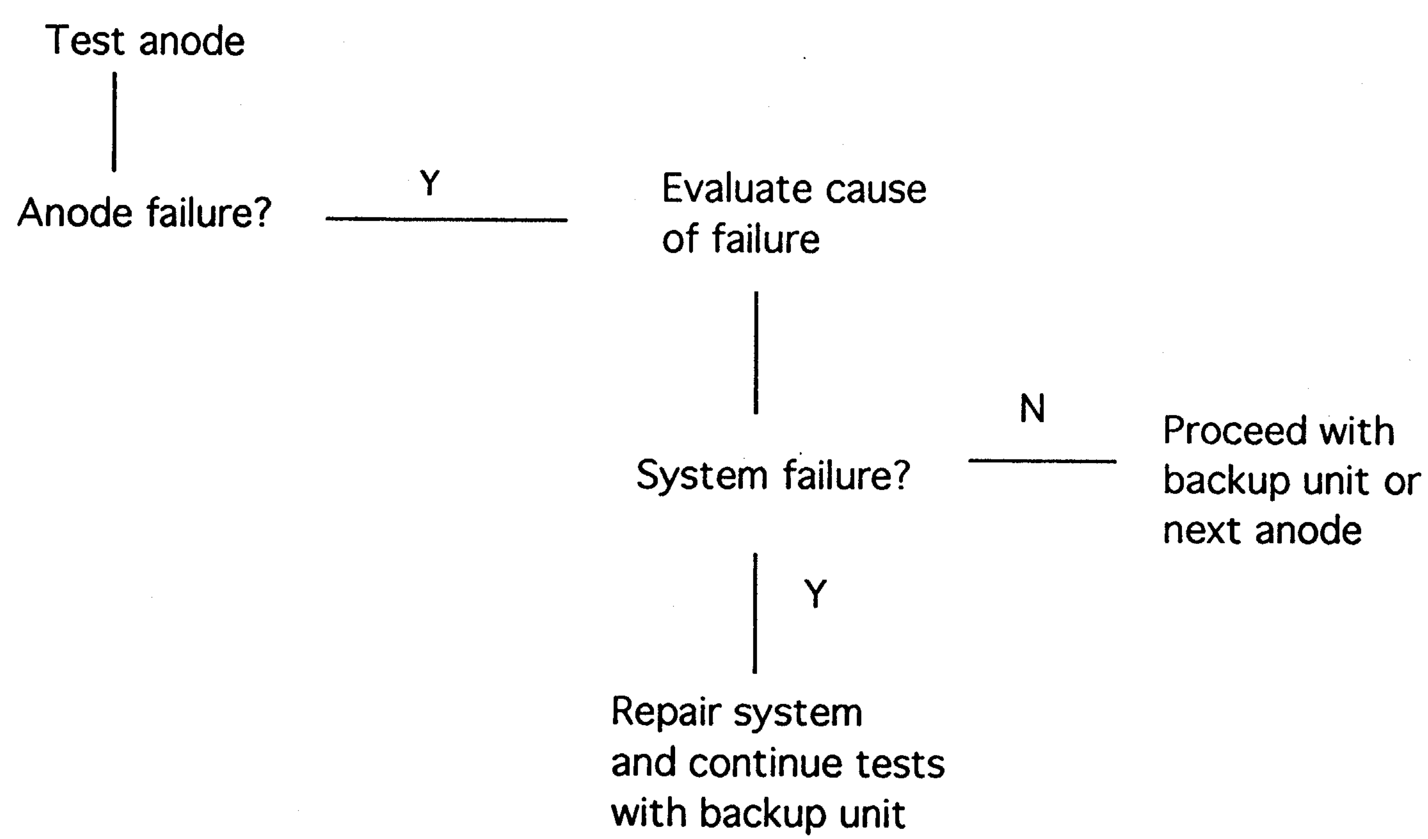

Figure 3. Logic Matrix

Test Plan

Rev. A

June 6, 1994

Platelet-Cooled Plasma Arc Torch

NOTE: Change Pages Only

1.0 Introduction

As part of the Platelet Cooled Plasma Arc Torch program, contract DE-AR21-93MC30361, Aerojet will test three different platelet anode designs in a Retech 75T torch. The tests will be conducted at Retech in Ukiah, California, as specified by Aerojet purchase order number 824707. Increase in torch life without loss of electrical power efficiency or arc stability is the goal of the program. The objective of the tests is to demonstrate at least a twofold increase in anode life capability compared to the existing backside water cooled anode currently in use on the 75T.

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> Design no. 1 is a copper, water cooled anode. This design improves on the existing backside-cooled anode by using platelet channels to increase the cooling surface area by a factor of four.
>
> Design no. 2 retains the water cooling from design no. 1 then adds argon swirl injection at the wall to reduce the heating rate and create an inert gas barrier.
>
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Aerojet will deliver six anodes for testing, two anodes of each of the three designs. One anode from each pair will be tested and the other will be reserved as a backup. Each anode will be initially tested for a period up to 5 days, or 35 hours. At the end of these tests the anode having the least wear without loss of electrical efficiency or arc stability will be tested for up to 24 additional days, or 192 hours.

Platelet cooling is a proven technology developed by Aerojet over the last 30 years and implemented in a number of products, including rocket chambers, heat exchangers, and missile structural components. Additional information on platelets is provided in the Management Plan [2] for this program.

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Figure 1 shows a sketch of the system. The anode is installed at the top where the electrical power input is indicated. The plasma is directed into a tub located about 3 feet below the anode. During testing the tub will be filled with uncontaminated dirt. A viewing port is located just above the tub enabling the operator to view the plasma by means of a pinhole camera.

Figure 2 shows a diagram of the torch coolant water delivery system. It is a closed system containing two 4-5 gpm Grundfos pumps, a filter housing and filter, a Modine tube-in-shell heat exchanger, and a five gallon supply tank The water goes first to the anode, then to the torch nozzle.

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Use of an Aerojet owned optical system to detect copper and iridium in the plasma gas will be employed if experimental conditions for viewing the plasma can be worked out. This system has been successfully used to detect metals in rocket exhaust plumes. The system would provide a means for characteristics, such as cooling power requirement, arc stability, electrical efficiency, cost, or technology advancement, may be used as "tie-breakers".

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7.0 Success Criteria

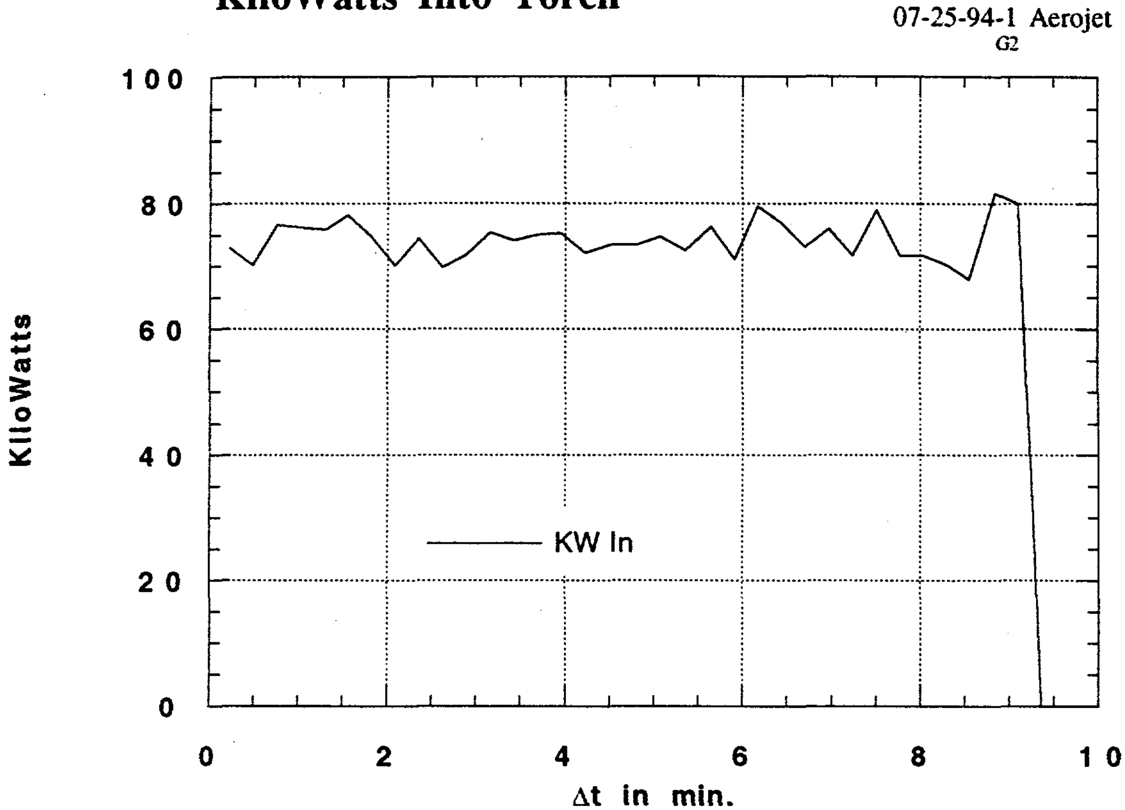
The objective of this program is to determine the useful life of a platelet-cooled anode for a plasma arc torch. The success criteria for the program is that it provide the data necessary to make this determination. The success

Appendix B

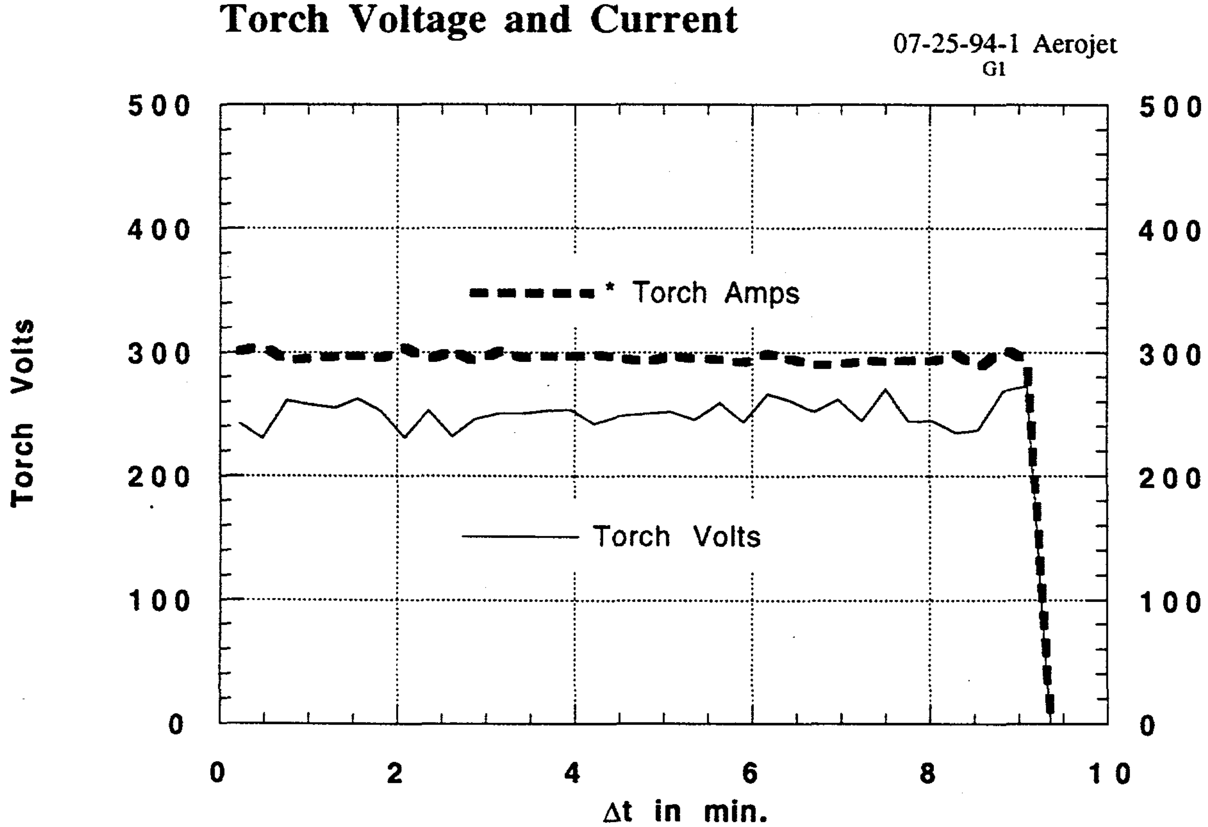
Test Data

1/4 Scale Data Summary		
	Run Date: 7/25/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: Concrete & Glass		Video Tape #: 7-25-94 Aerojet
Furnace Configuration: Rotary		Video Start: 0
Type of Feedstock: None		Supply Gas: N2
Estimated Electrode Hours: 0.6		Operators: PAG, REH
Remarks: A 10 min. test on Aerojet's Cu platelet electrode. We are trying to lower the arc termination. We have a two hole gas ring in the torch because the four hole ring at 32 psig caused the termination not to be on the platelet section.		Results: Ran for 10 min. Gas flow was 2.1 scfm.

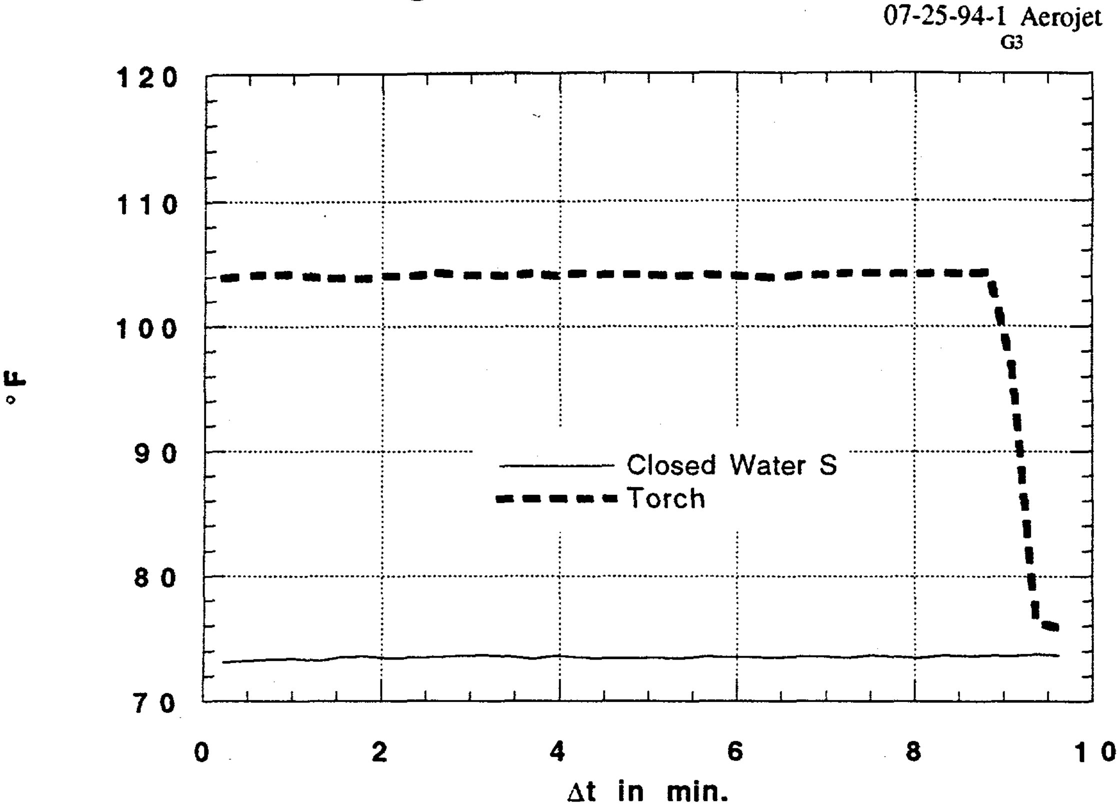
KiloWatts Into Torch



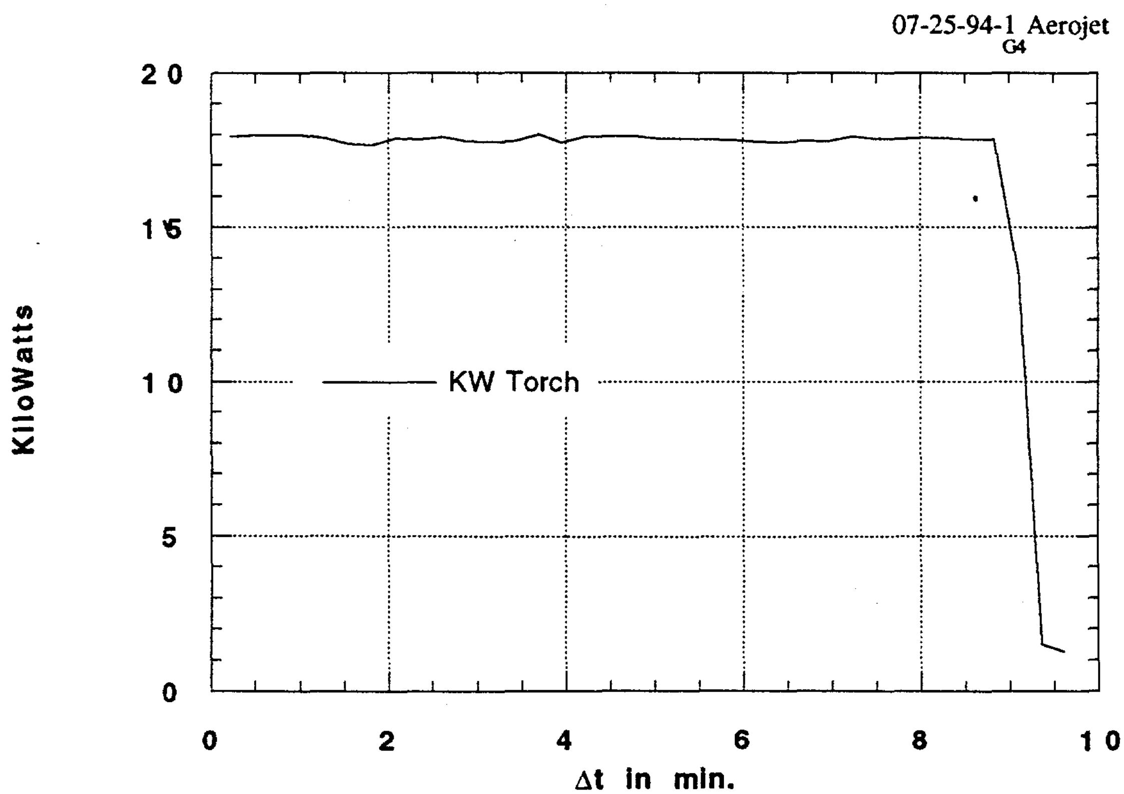
Torch Voltage and Current



Torch Cooling Circuit Temperature

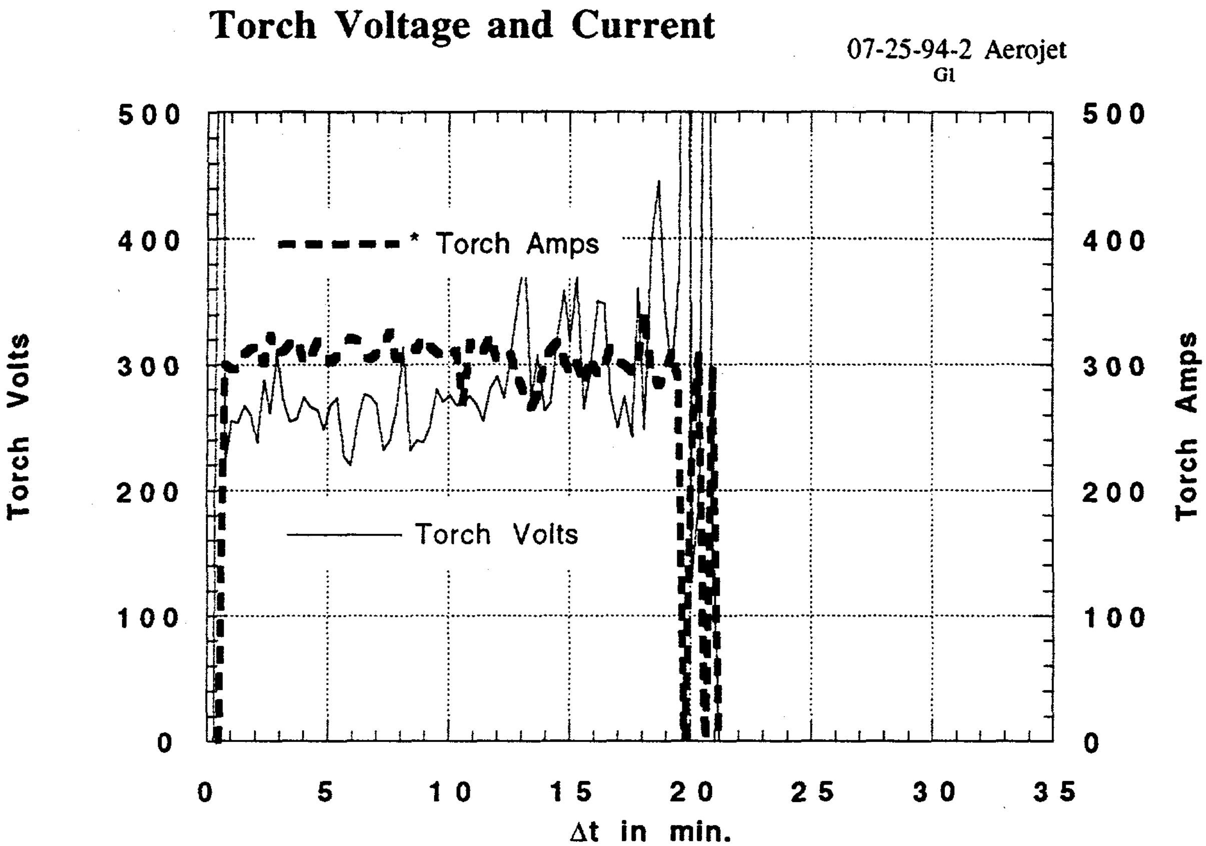


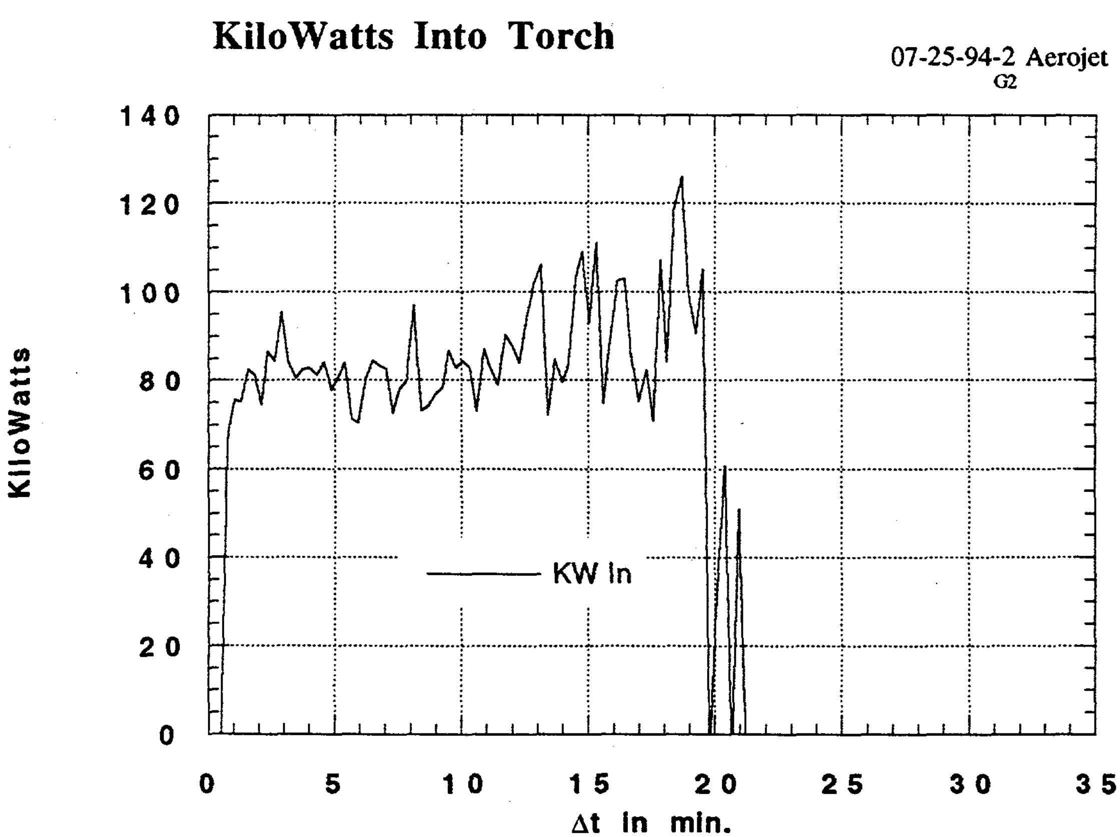
KiloWatts Removed by Torch Cooling Circuit



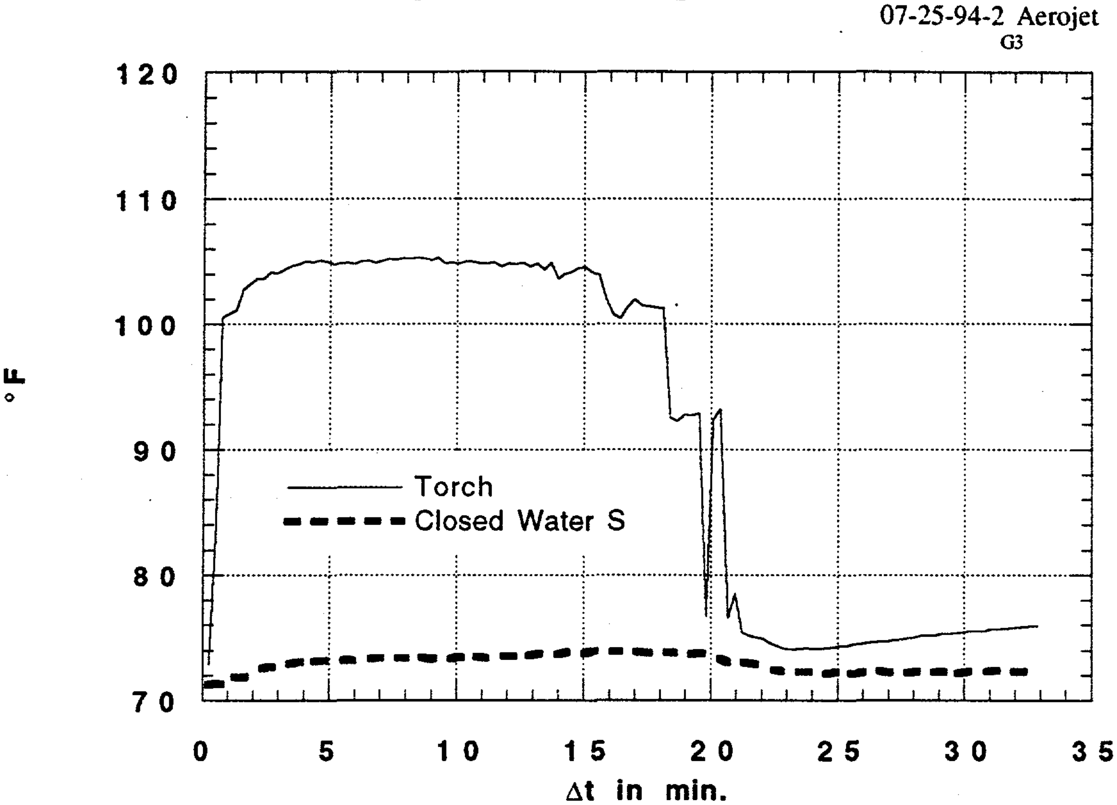
1/4 Scale Data Summary		
	Run Date: 7/25/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: Concrete & Glass		Video Tape #: 7-25-94 Aerojet
Furnace Configuration: Rotary		Video Start: 0
Type of Feedstock: None		Supply Gas: N2
Estimated Electrode Hours: .7		Operators: PAG, REH
Remarks: A 30 min. test on Aerojet's Cu platelet electrode. We are trying to lower the arc termination. We have a two hole gas ring in the torch. The torch supply pressure will be set at 35 psig.		Results: Ran for 20 min. and lost the electrode because the arc terminating just up inside the electrode. It
		was not on the fine section of the platelet cooling. The flow rate was 1.4 scfm N2 @ 35 psig torch
		supply. The 2.1 scfm @ 50 psig ran earlier terminated on the coarse section of the platelet
		So I think a flow rate of 1.7 scfm

will put the arc on the fine platelet cooled section.		

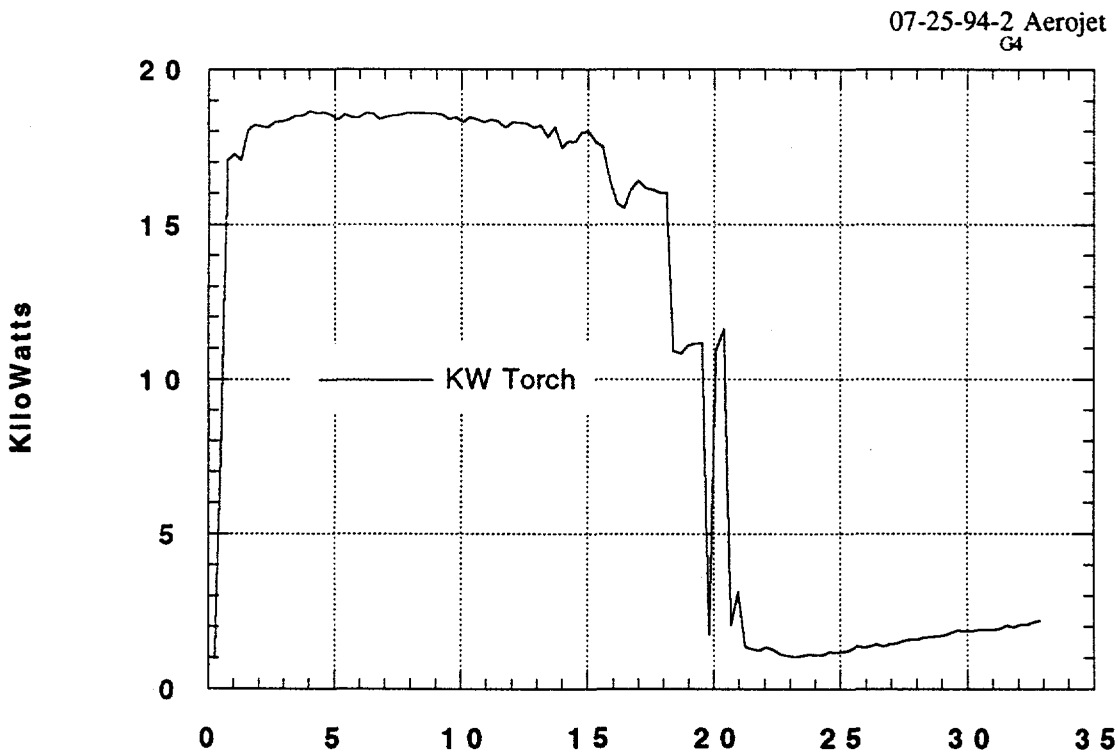

Torch Voltage and Current
07-25-94-2 Aerojet
G1
Torch Amps
Torch Volts
500
400
300
200
100
0
0 5 10 15 20 25 30 35
Δt in min.


KiloWatts Into Torch
07-25-94-2 Aerojet
G2
KiloWatts
KW In
140
120
100
80
60
40
20
0
0 5 10 15 20 25 30 35
Δt in min.

Torch Cooling Circuit Temperature



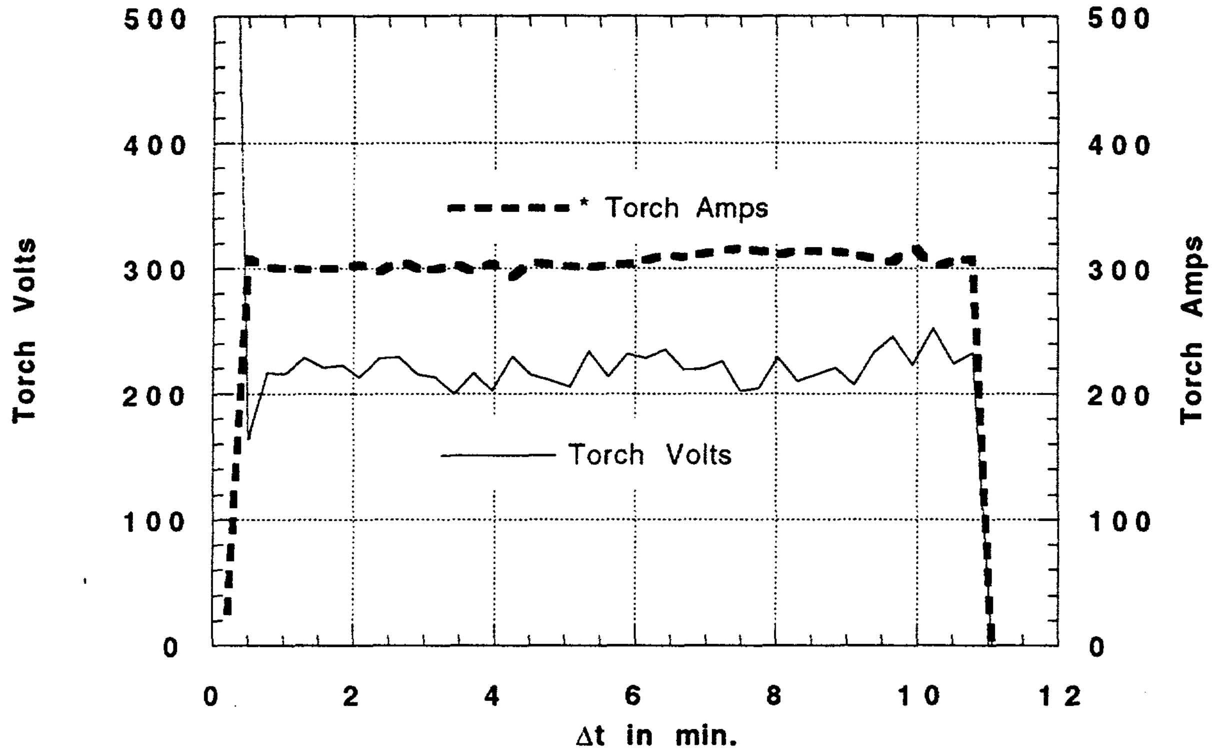
KiloWatts Removed by Torch Cooling Circuit



1/4 Scale Data Summary		
	Run Date: 7/25/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: Concrete & Glass		Video Tape #: 7-25-94 Aerojet
Furnace Configuration: Rotary		Video Start: 30 min.
Type of Feedstock: None		Supply Gas: N2
Estimated Electrode Hours: 0		Operators: PAG, REH
Remarks: A 10 min. test on Aerojet's Ir sleeve, Cu platelet electrode. We have a two hole gas ring in the torch. The torch supply pressure will be set at 42-43 psig.		Results: Got the arc termination up in the coarse platelet section again. The arc melted the Ir in this region.
		Randy wants to try it again anyway because the Cu looks to be in good shape.

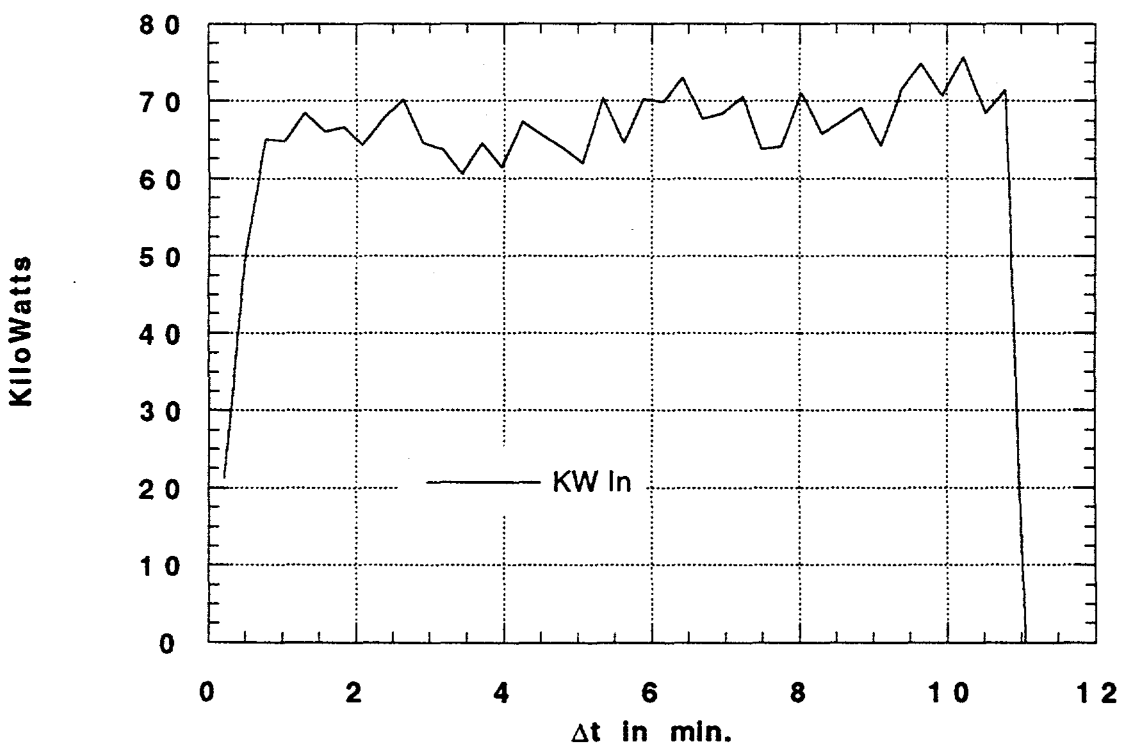
Torch Voltage and Current

07-25-94-3 Aerojet
G1

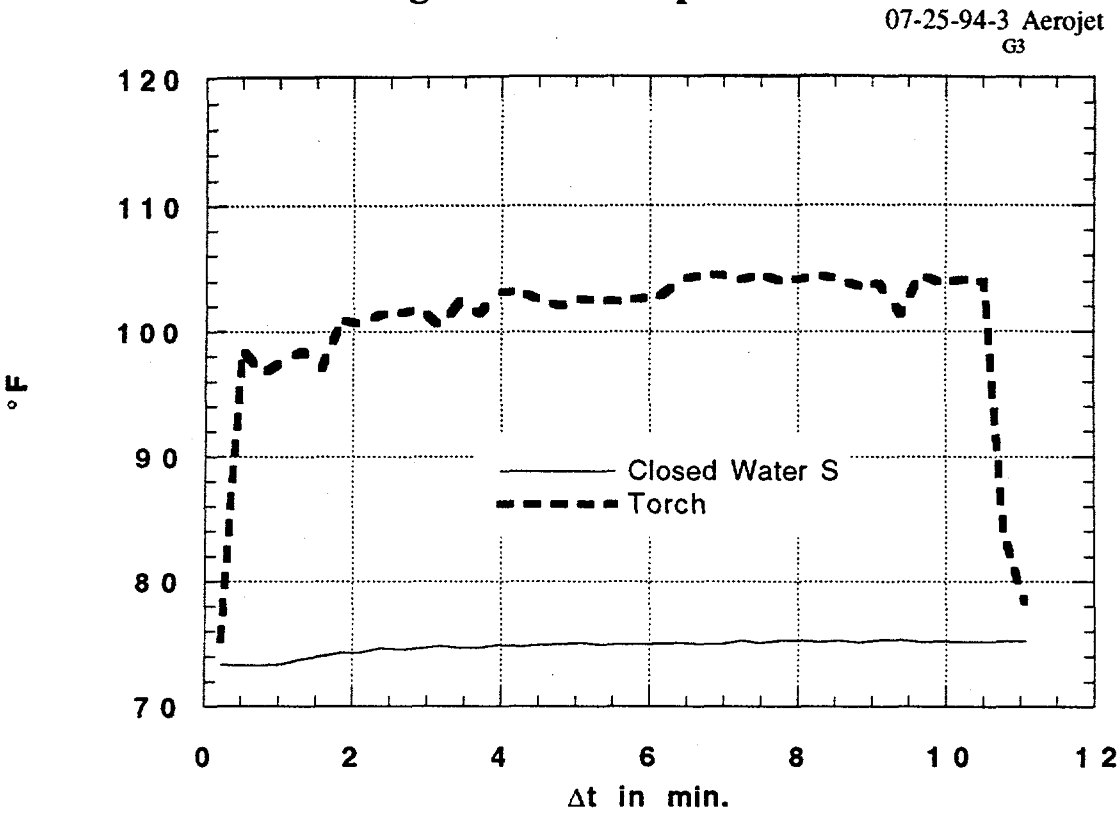


KiloWatts Into Torch

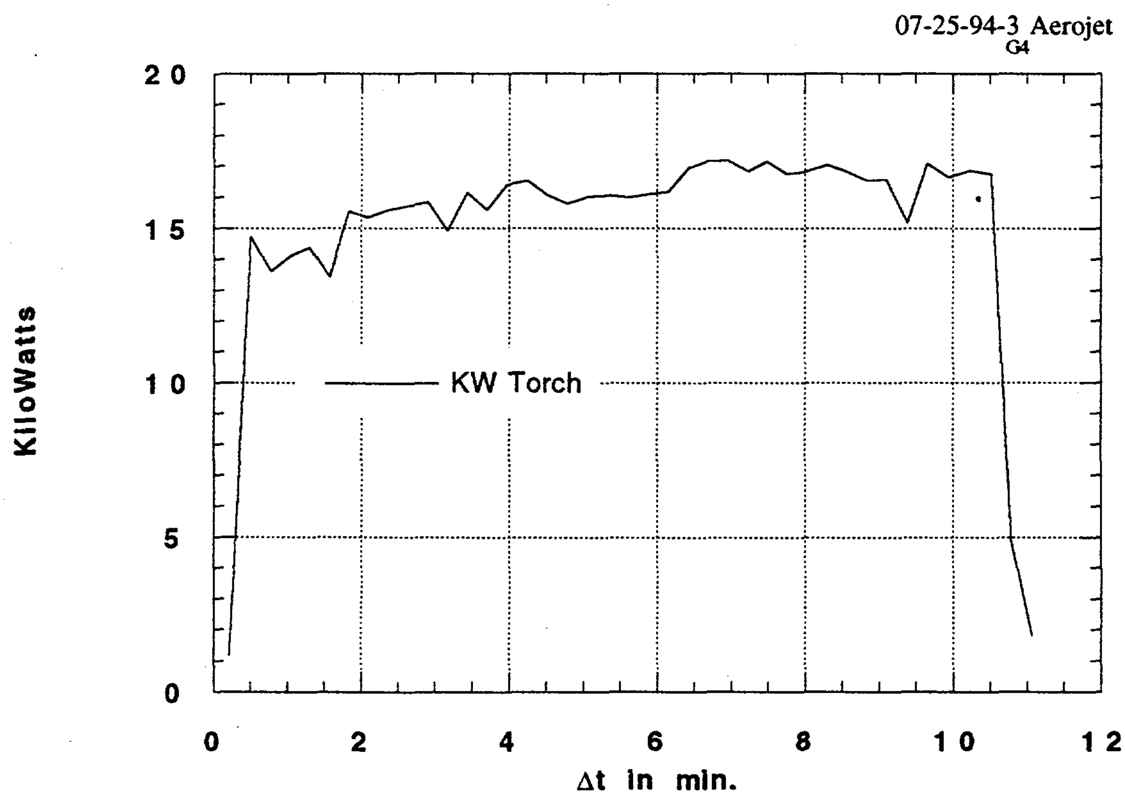
07-25-94-3 Aerojet
G2



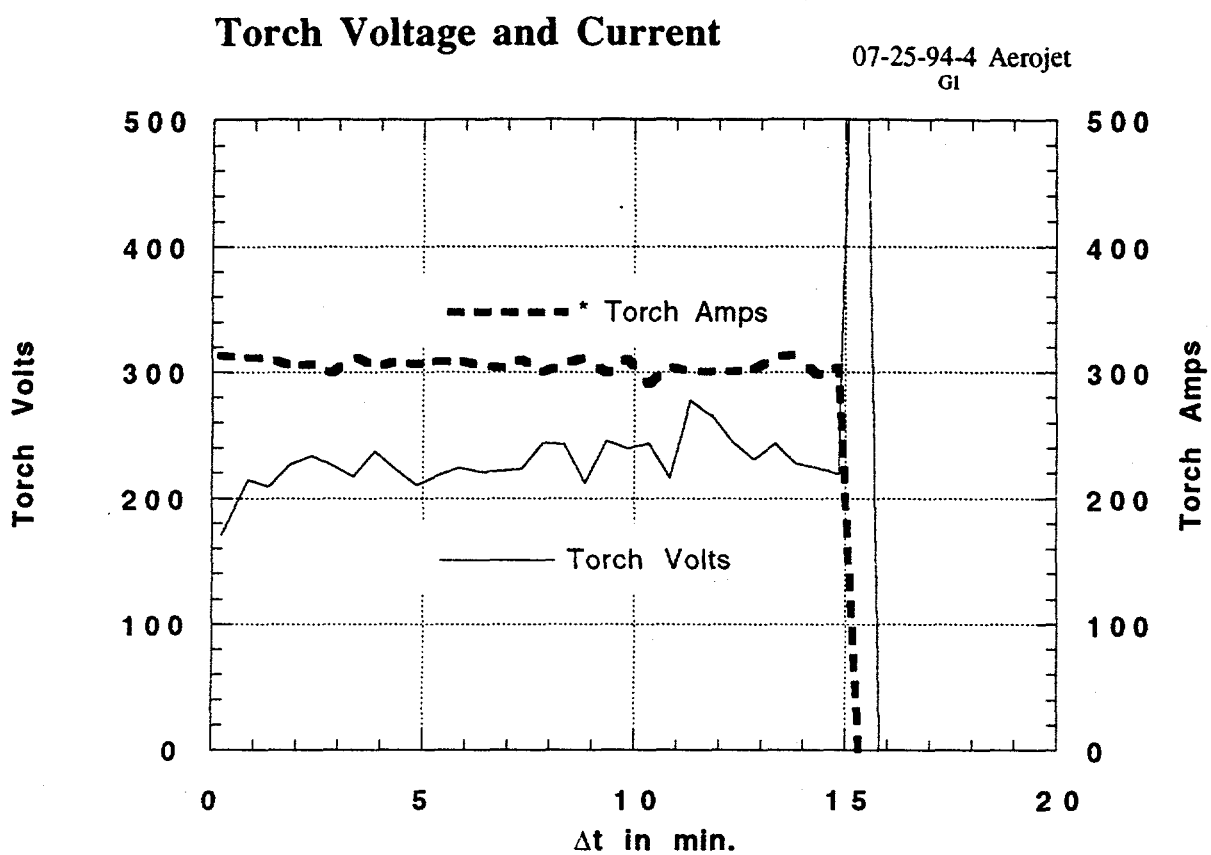
Torch Cooling Circuit Temperature

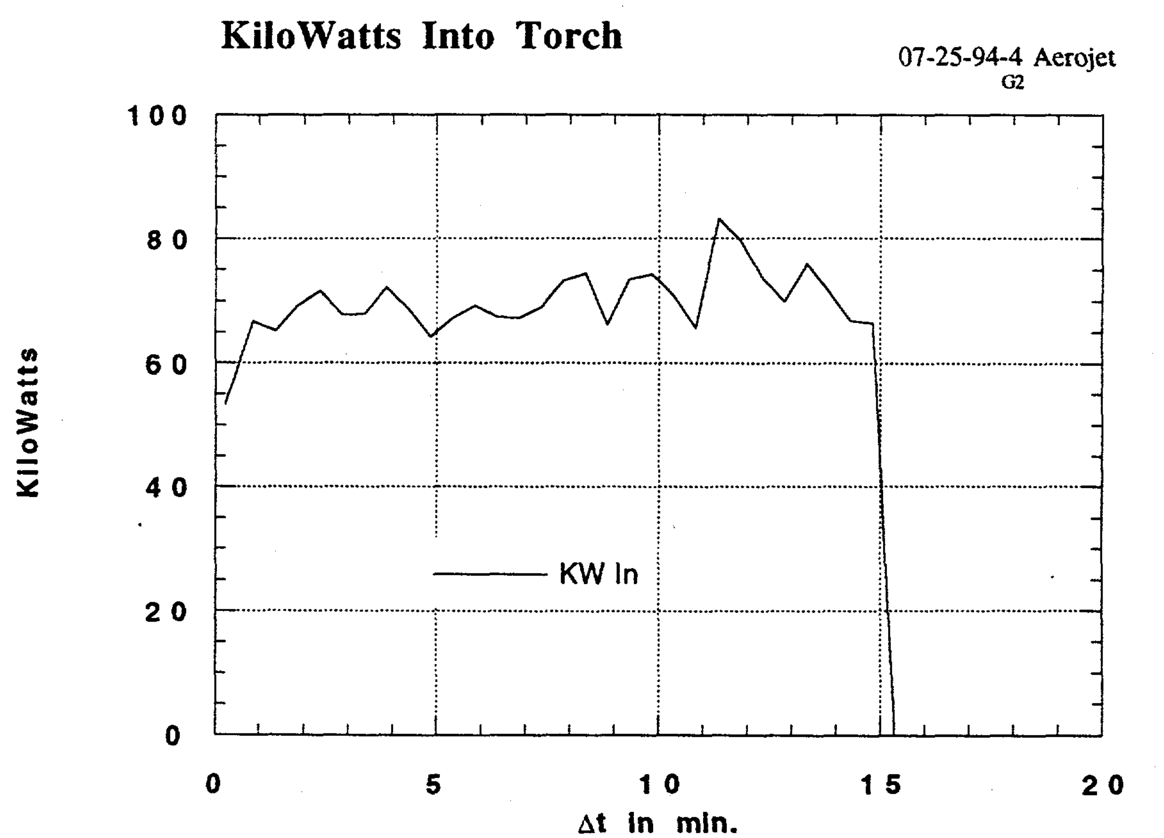


KiloWatts Removed by Torch Cooling Circuit



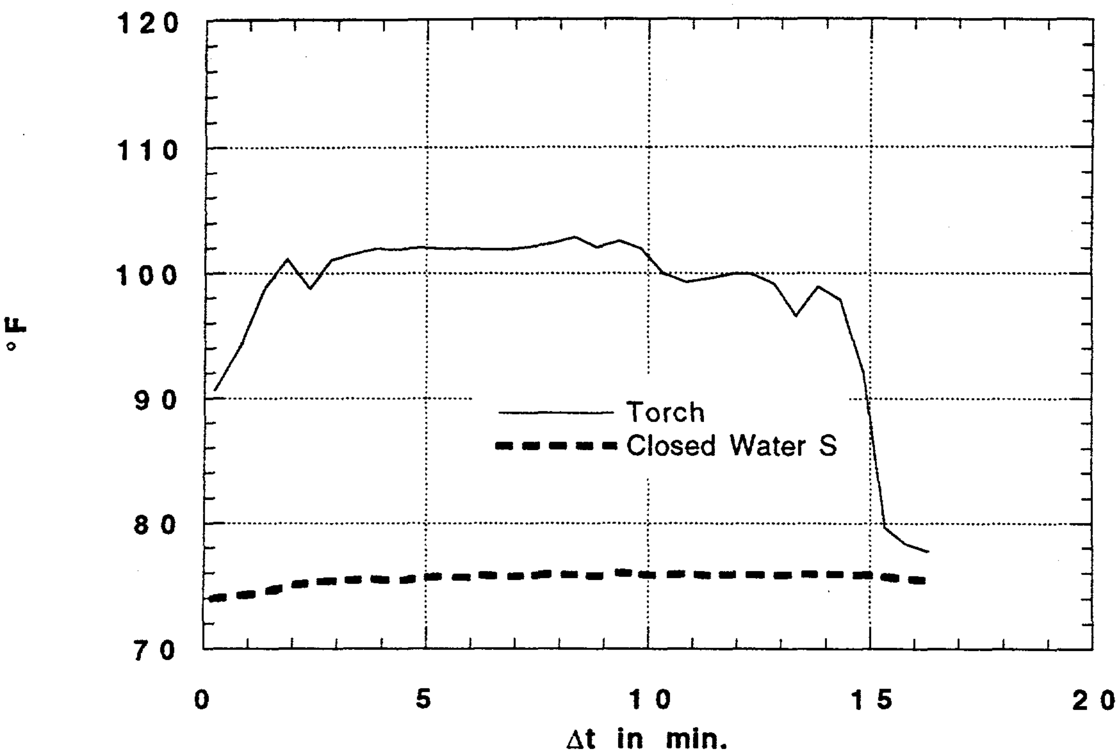
1/4 Scale Data Summary		
	Run Date: 7/25/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: Concrete & Glass		Video Tape #: 7-25-94 Aerojet
Furnace Configuration: Rotary		Video Start: 40 min.
Type of Feedstock: None		Supply Gas: N2
Estimated Electrode Hours: 0.167		Operators: PAG, REH
Remarks: A 30 min. test on Aerojet's Ir sleeve, Cu platelet electrode. We have a two hole gas ring in the torch. The torch supply pressure will be set at 40 psig. The Ir sleeve is melted out in a ring up in the coarse platelet section of electrode.		Results: Developed a water leak in the electrode and couldn't restart the torch. The ID of this electrode was
		pretty rough and the arc probably stuck in one spot. The Ir sleeve is completely gone.


Torch Voltage and Current
07-25-94-4 Aerojet
G1
Torch Volts
Torch Amps
* Torch Amps
Torch Volts
500
400
300
200
100
0
0
5
10
15
20
Δt in min.


KiloWatts Into Torch
07-25-94-4 Aerojet
G2
KiloWatts
KW In
100
80
60
40
20
0
0
5
10
15
20
Δt in min.

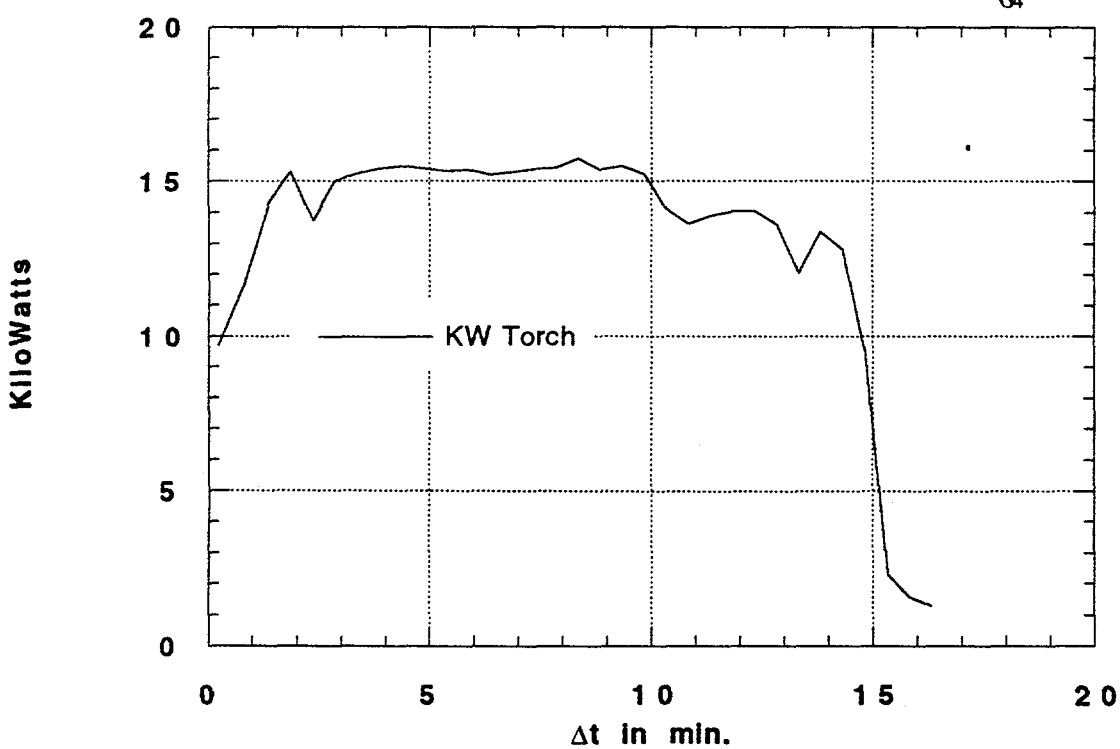
Torch Cooling Circuit Temperature

07-25-94-4 Aerojet
G3

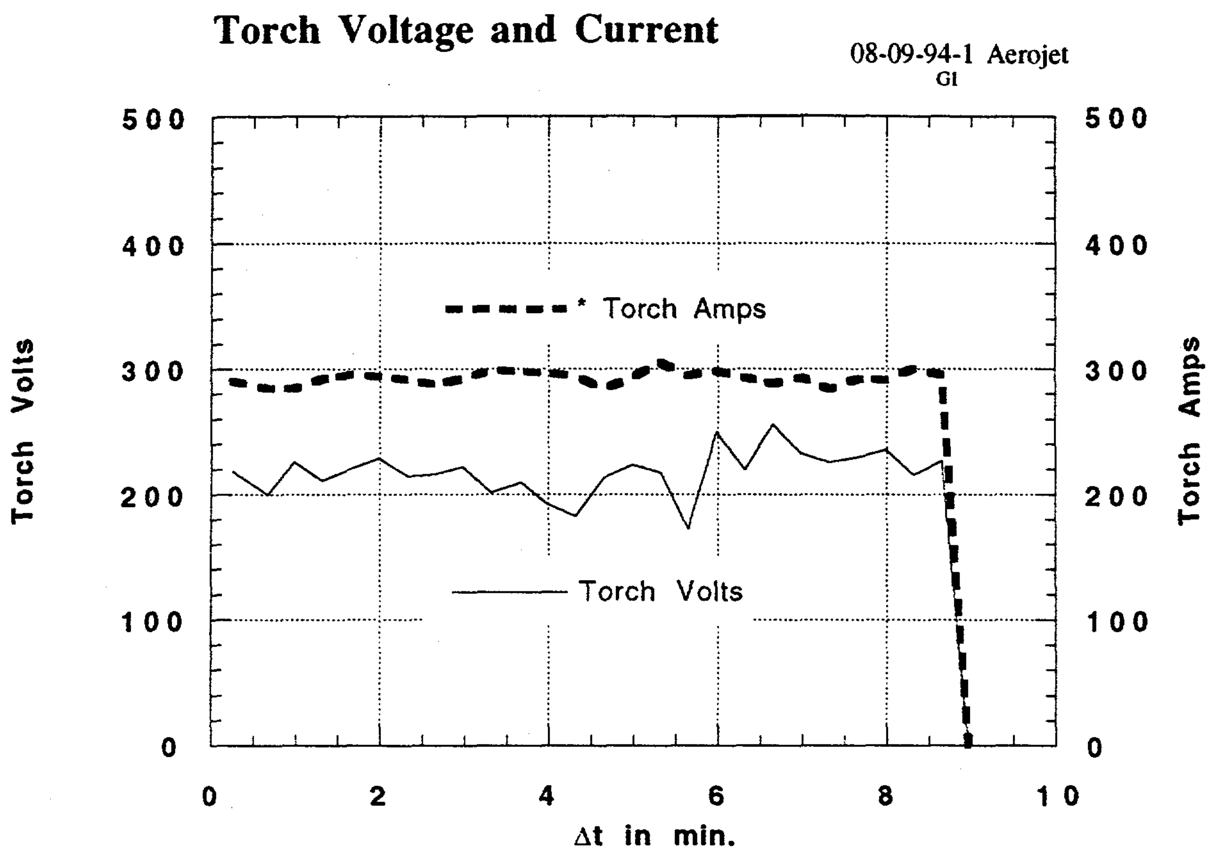


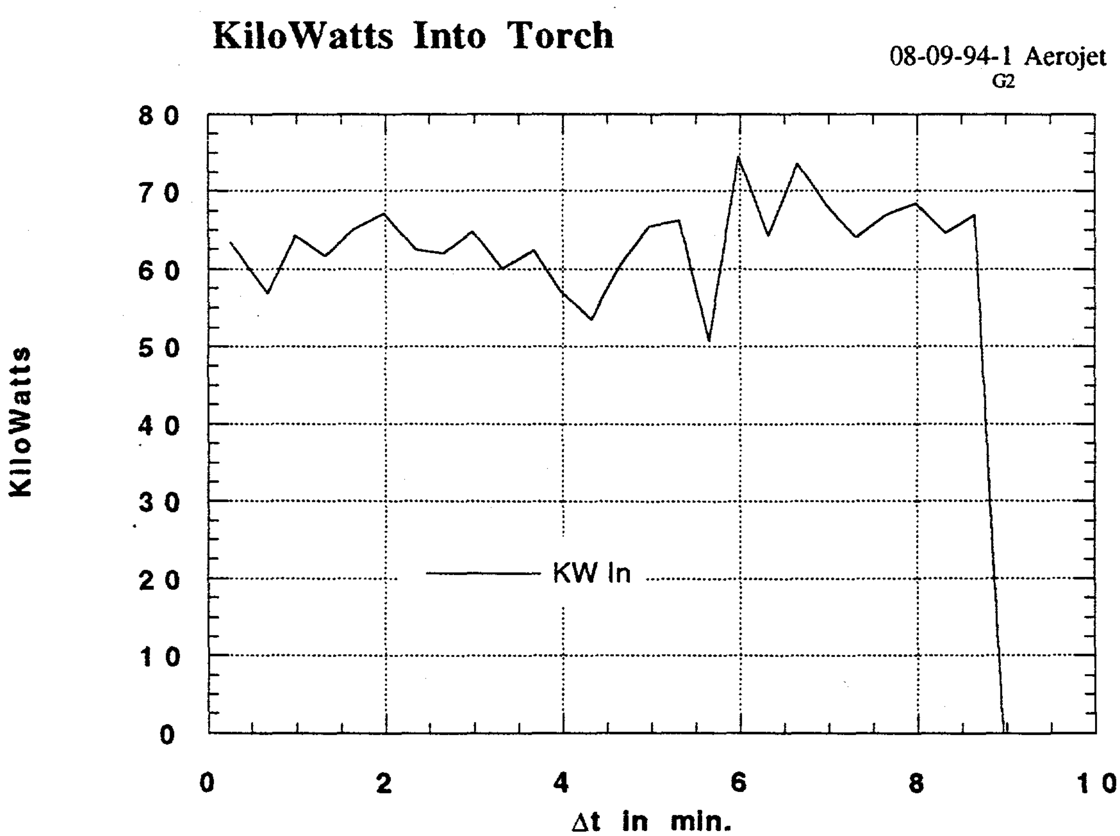
KiloWatts Removed by Torch Cooling Circuit

07-25-94-4 Aerojet
G4



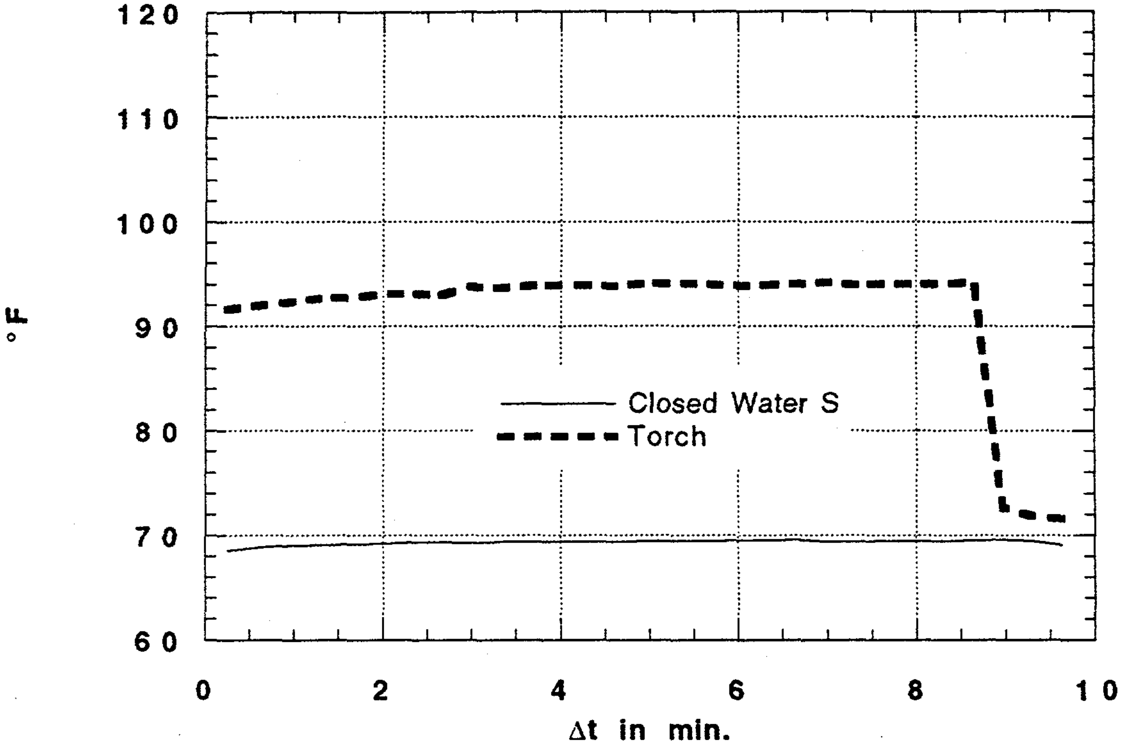
1/4 Scale Data Summary		
	Run Date: 8/9/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: concrete		Video Tape #: 7-25-94 Aerojet
Furnace Configuration: rotary		Video Start: about 1 1/2 hr
Type of Feedstock: none		Supply Gas: N2
Estimated Electrode Hours: 0		Operators: PSW, MAK
Remarks: "spare" Aerojet Cu platelet electrode. Electrode mass: 107.1g.		Results: Just a 10 minute initial run was done. The electrode was weighed (107.2 g) and the approximate arc
		termination was measured to be 1 inch. There was probably some water still in the passages of the electrode,
		so the weight is not exact.


Torch Voltage and Current
08-09-94-1 Aerojet
G1
Torch Volts
Torch Amps
* Torch Amps
Torch Volts
500
400
300
200
100
0
0
2
4
6
8
10
Δt in min.


KiloWatts Into Torch
08-09-94-1 Aerojet
G2
KiloWatts
KW In
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
Δt in min.

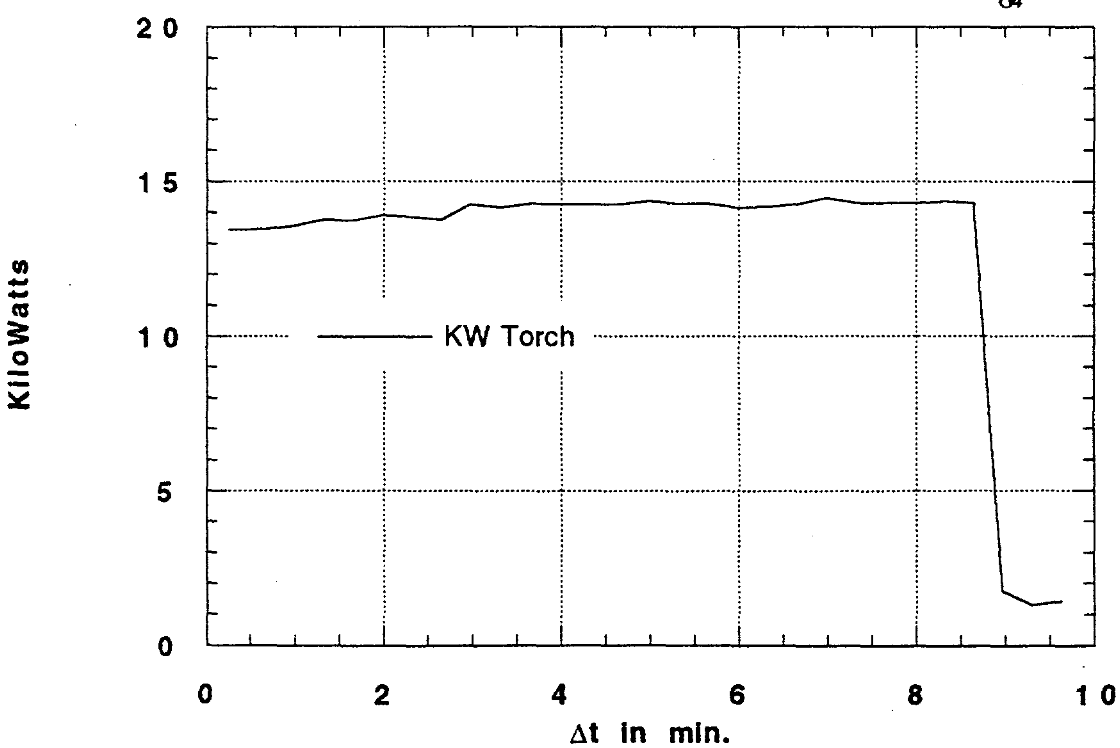
Torch Cooling Circuit Temperature

08-09-94-1 Aerojet
G3

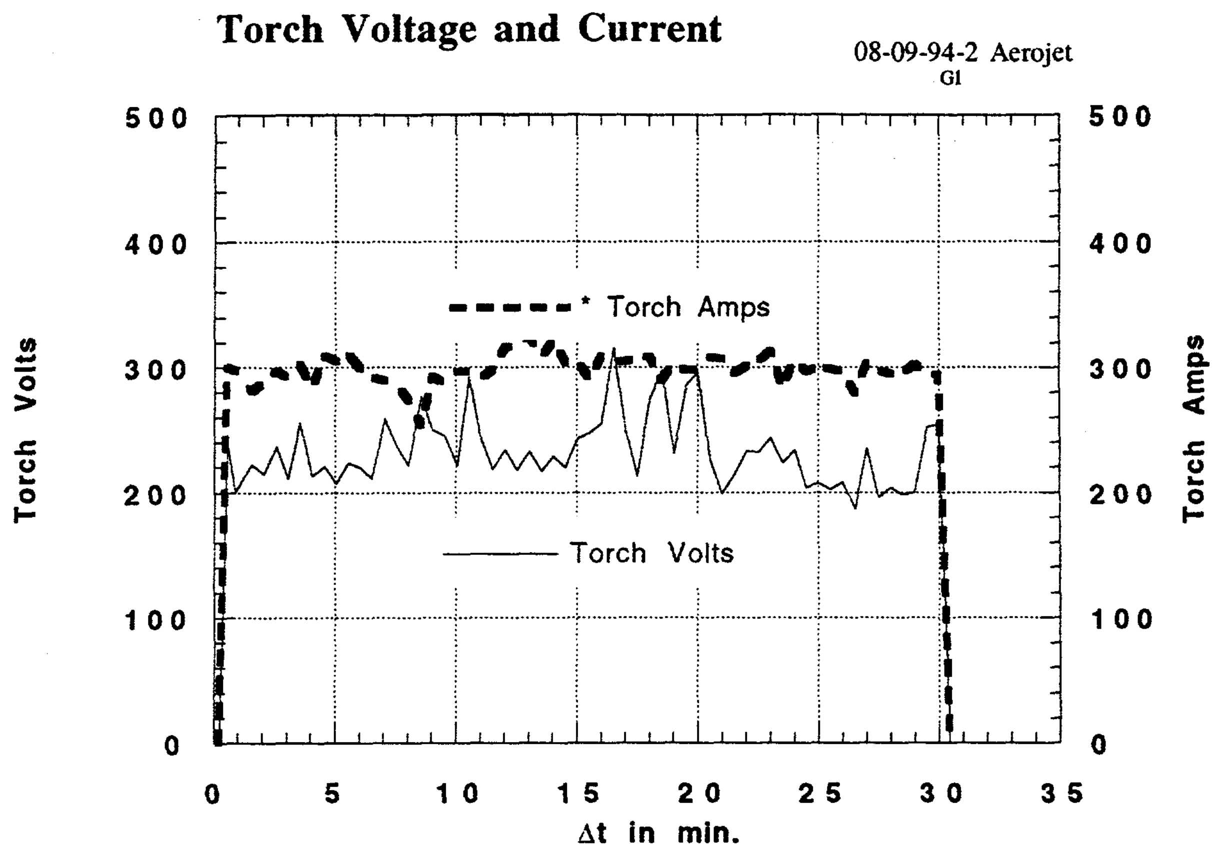


KiloWatts Removed by Torch Cooling Circuit

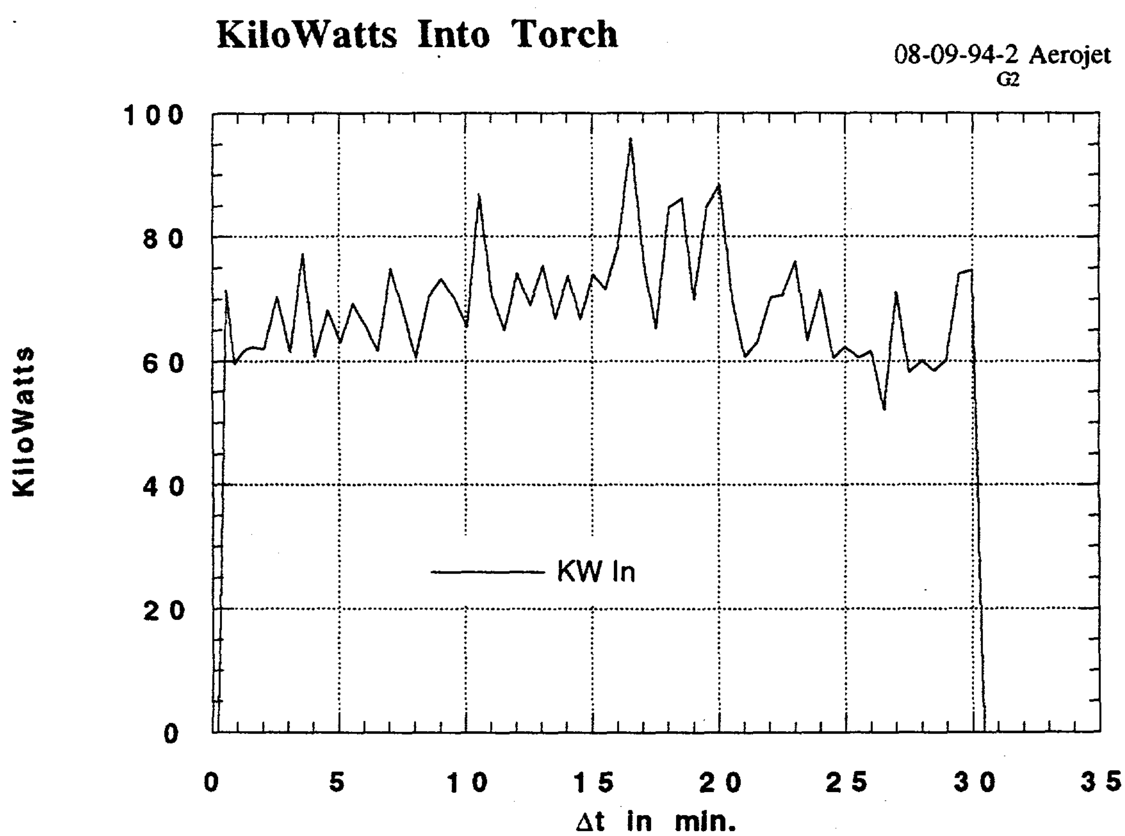
08-09-94-1 Aerojet
G4



1/4 Scale Data Summary		
	Run Date: 8/9/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: concrete		Video Tape #: 7-25-94 Aerojet
Furnace Configuration: rotary		Video Start: about 1 1/2 hr
Type of Feedstock: none		Supply Gas: N2
Estimated Electrode Hours: 0		Operators: PSW, MAK
Remarks: Follow up run of "spare" Aerojet Cu platelet electrode. Electrode mass: 107.2g (probably about a tenth of a gram of water left in the electrode.) 10 minutes already on the electrode.		Results: 40 minutes now on the electrode. By inspection it looks as if there were two arc termination points,
		one of which was just above the water-cooled passages. The next run will be until the electrode fails.



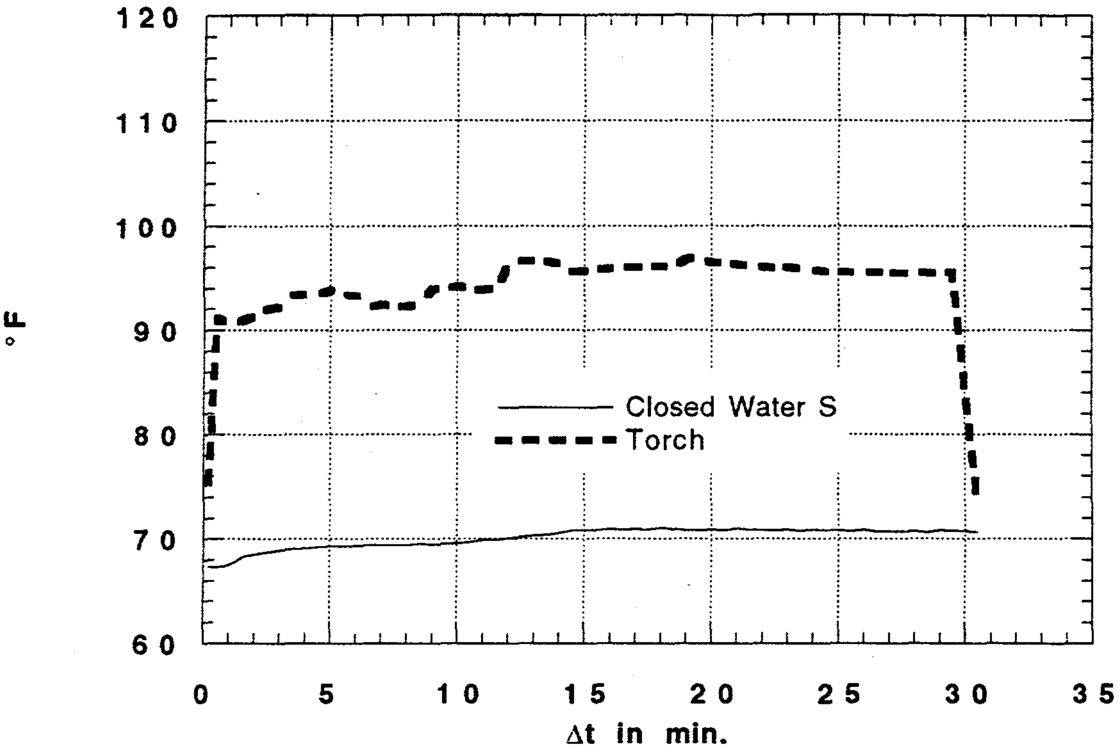
Torch Voltage and Current
08-09-94-2 Aerojet
G1
500
400
300
200
100
0
Torch Amps
Torch Volts
Torch Volts
Torch Amps
0
5
10
15
20
25
30
35
Δt in min.



KiloWatts Into Torch
08-09-94-2 Aerojet
G2
100
80
60
40
20
0
KW In
KiloWatts
0
5
10
15
20
25
30
35
Δt in min.

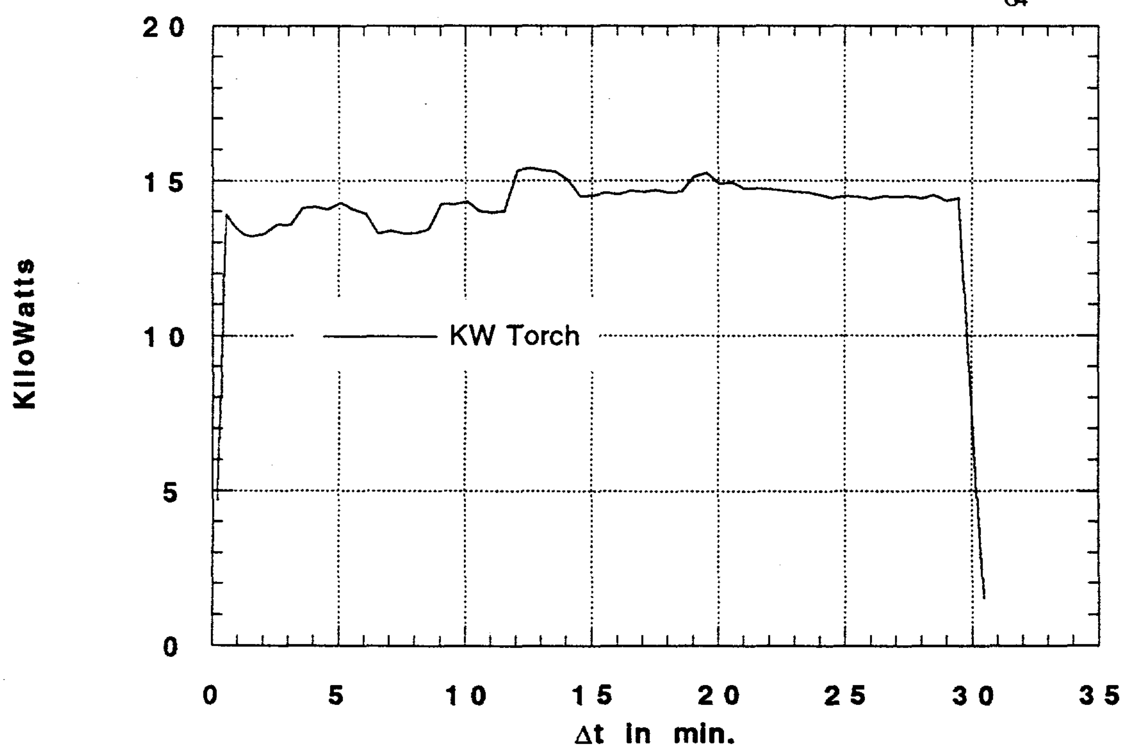
Torch Cooling Circuit Temperature

08-09-94-2 Aerojet G3



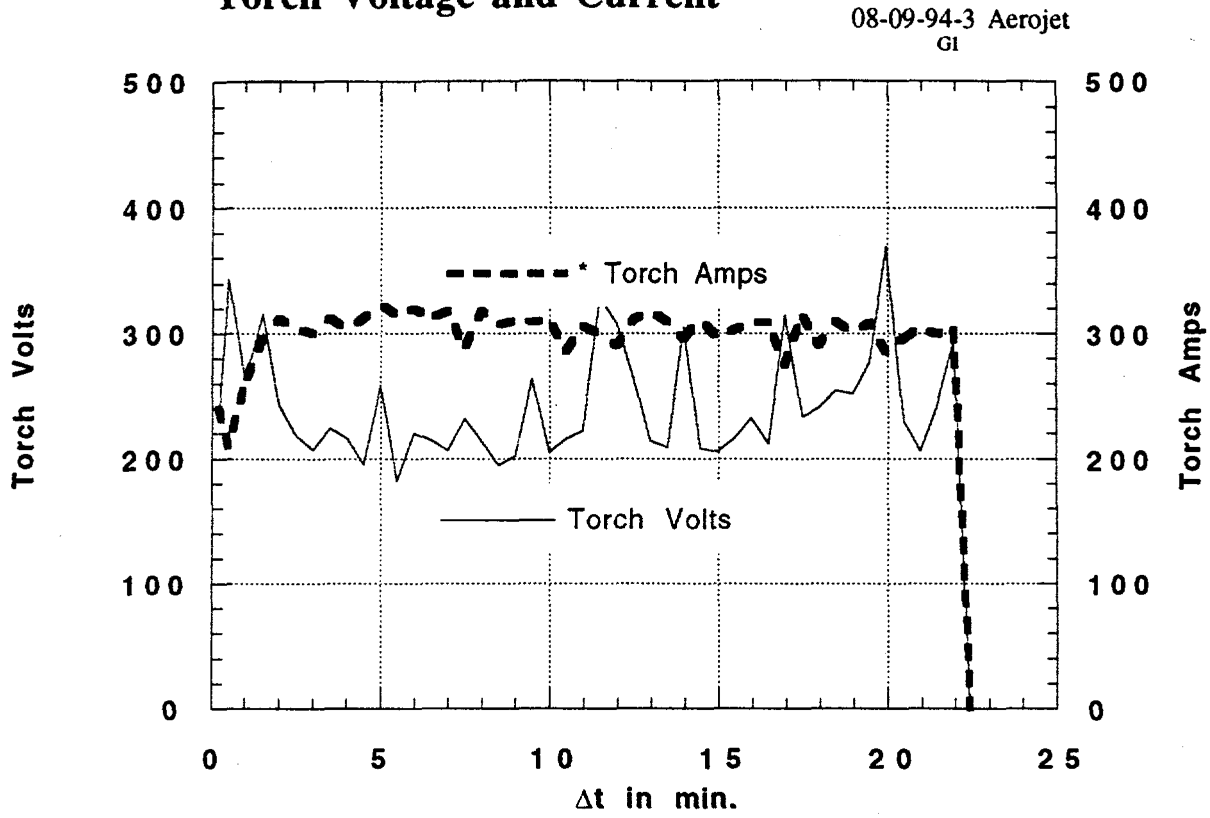
KiloWatts Removed by Torch Cooling Circuit

08-09-94-2 Aerojet G4

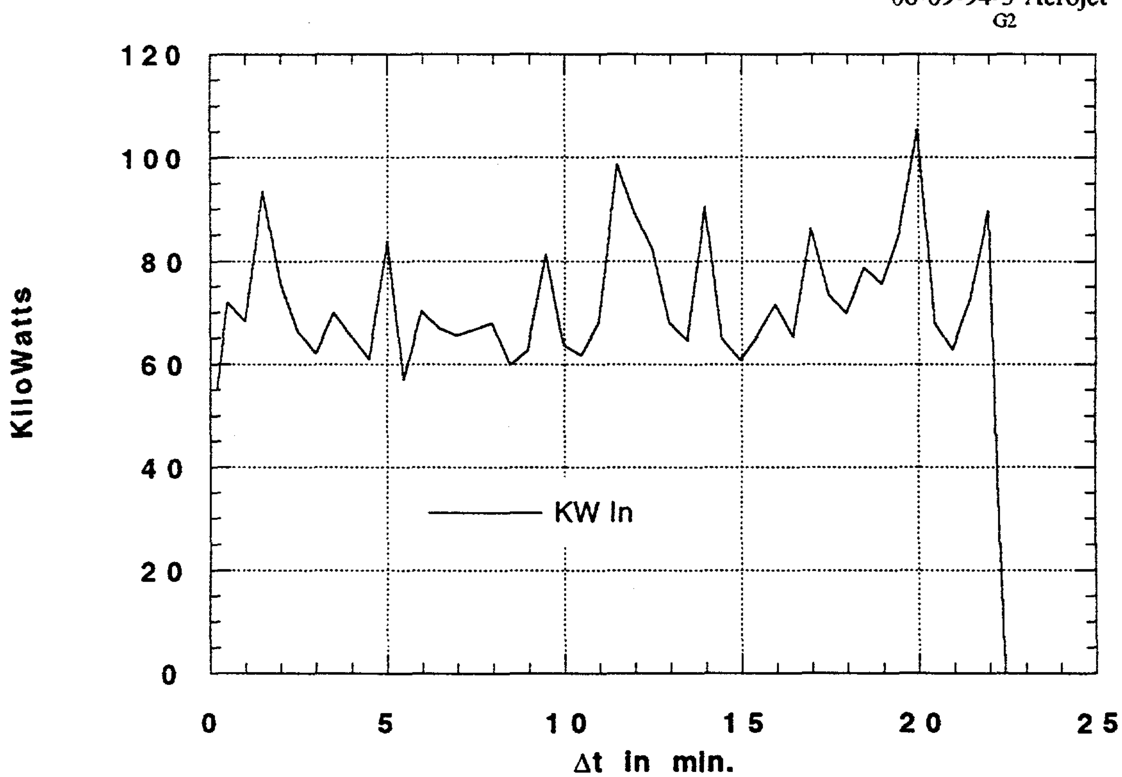


1/4 Scale Data Summary		
	Run Date: 8/9/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: concrete		Video Tape #: 7-25-94 Aerojet
Furnace Configuration: rotary		Video Start: about 2 hr
Type of Feedstock: none		Supply Gas: N2
Estimated Electrode Hours: 0		Operators: PSW, MAK
Remarks: Third run of "spare" Aerojet Cu platelet electrode. Forty minutes now on electrode.		Results: Arc out after 22 minutes of running and shut down. Took out electrode and found that it was badly eroded/partially
		melted. It has essentially failed.

Torch Voltage and Current

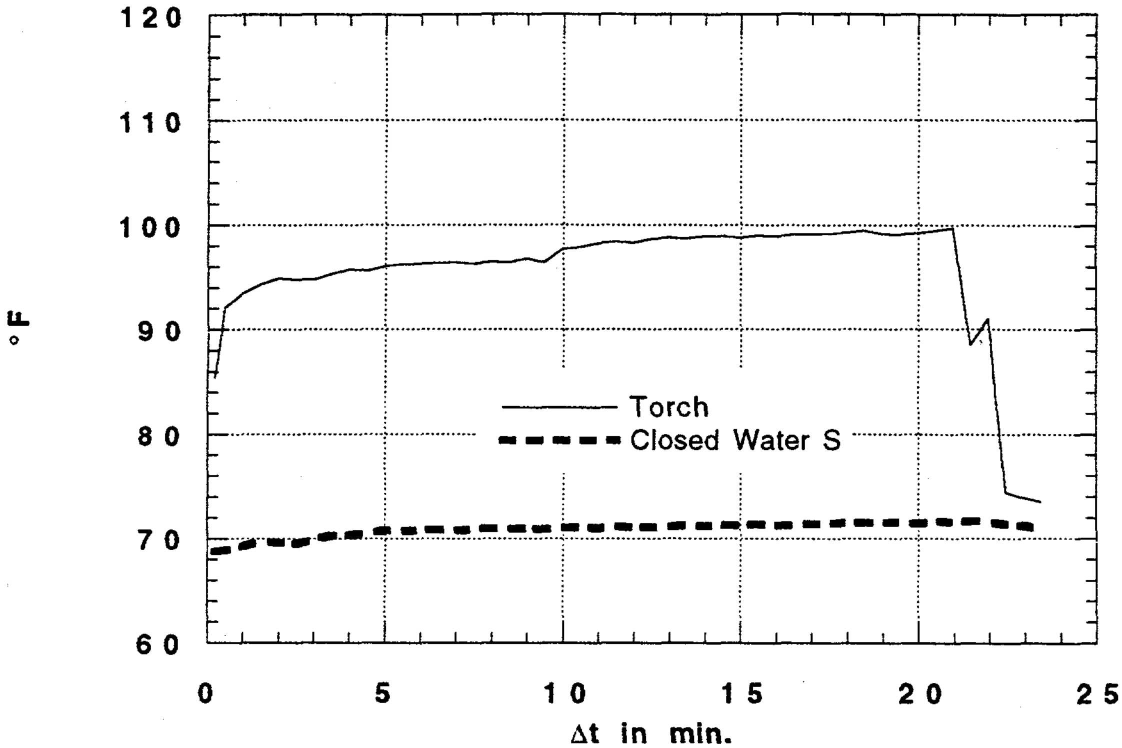


KiloWatts Into Torch



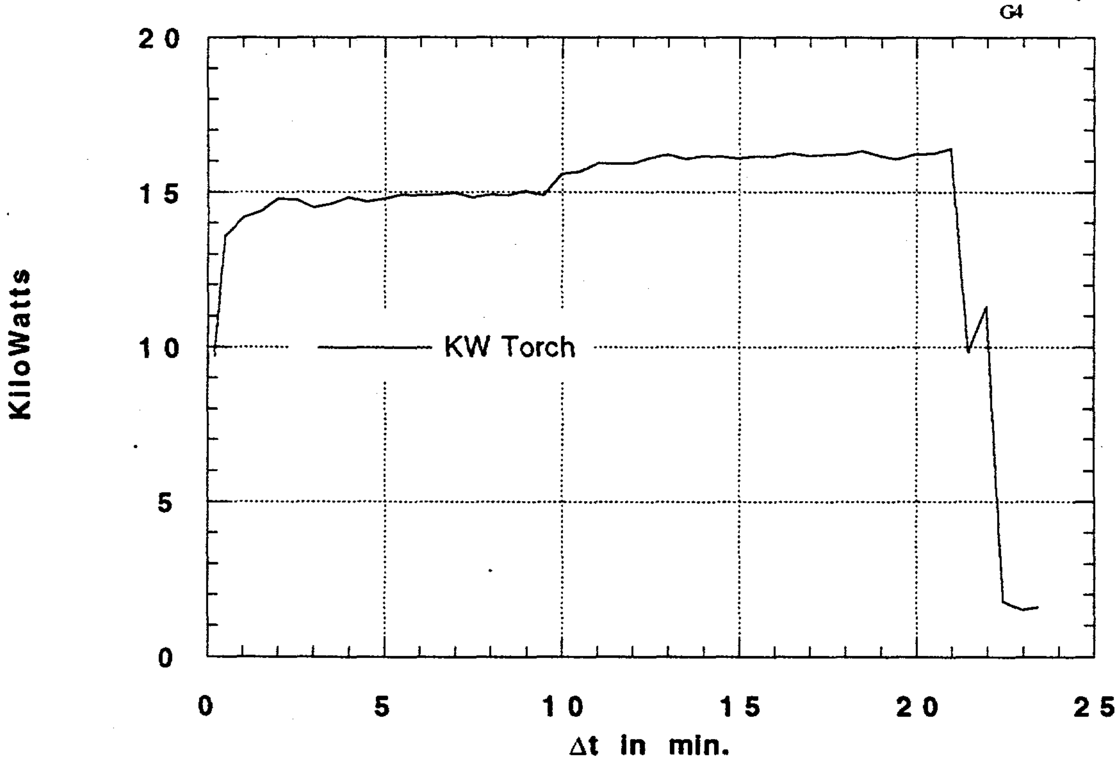
Torch Cooling Circuit Temperature

08-09-94-3 Aerojet
G3



KiloWatts Removed by Torch Cooling Circuit

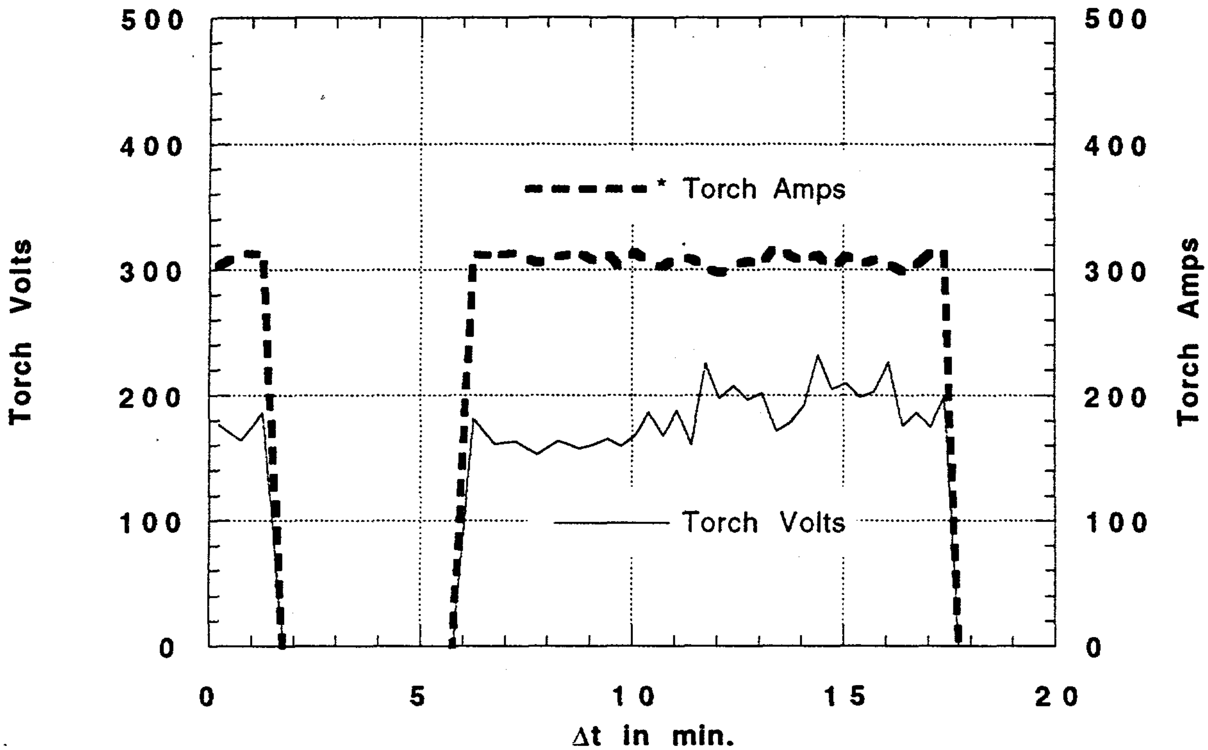
08-09-94-3 Aerojet
G4



1/4 Scale Data Summary		
	Run Date: 8/11/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: small amt steel grit		Video Tape #: 7-25-94 Aerojet
Furnace Configuration: rotary		Video Start: about 2 hr
Type of Feedstock: none		Supply Gas: N2
Estimated Electrode Hours: 0		Operators: PSW, MAK
Remarks: Run with Aerojet power tube assembly, and electrode with Argon going through it.		Results:

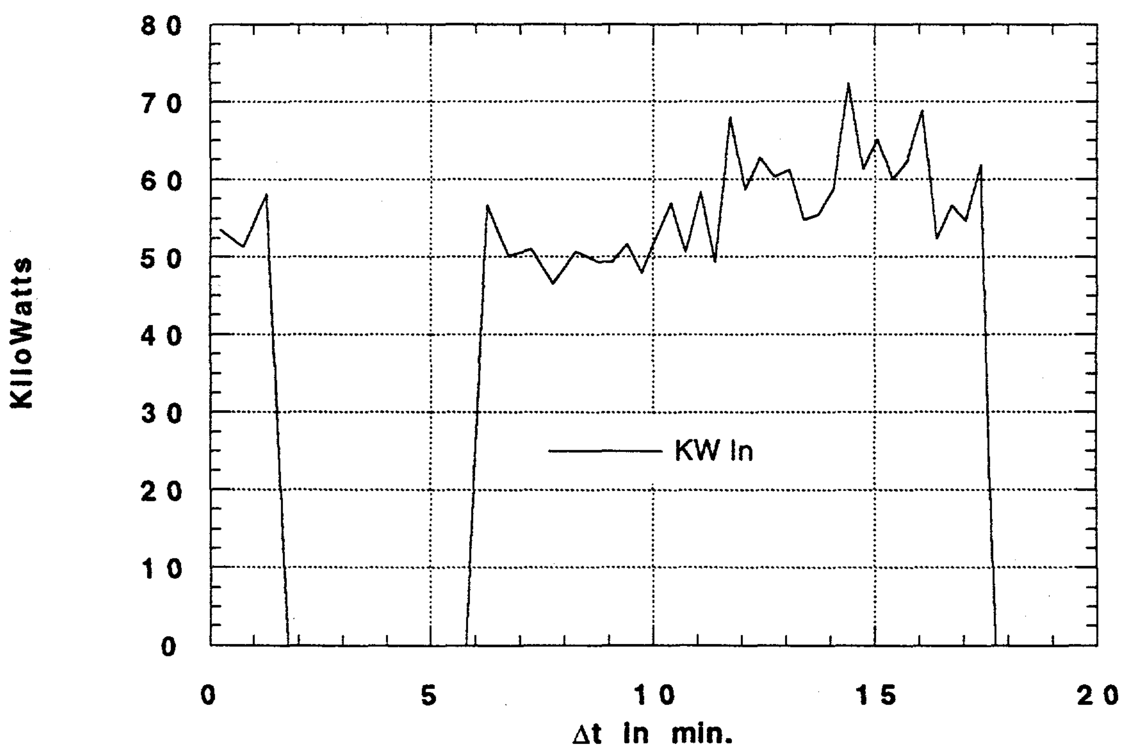
Torch Voltage and Current

08-11-94 Aerojet
G1

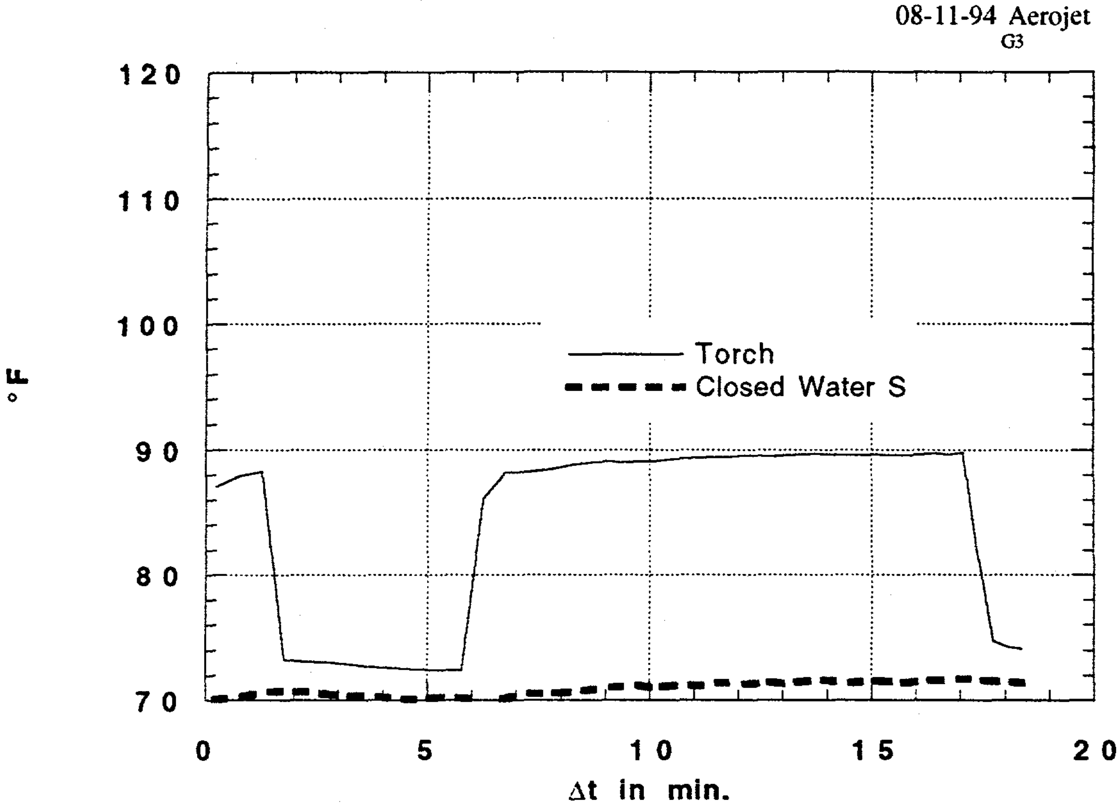


KiloWatts Into Torch

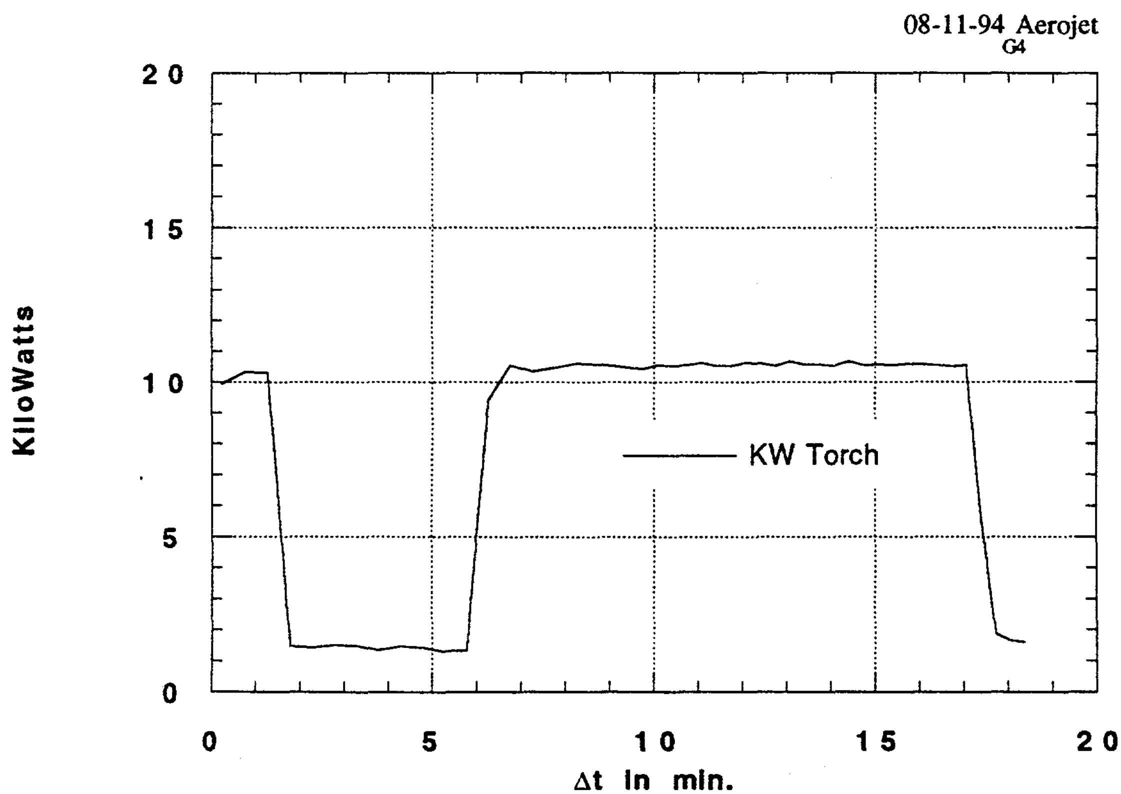
08-11-94 Aerojet
G2



Torch Cooling Circuit Temperature



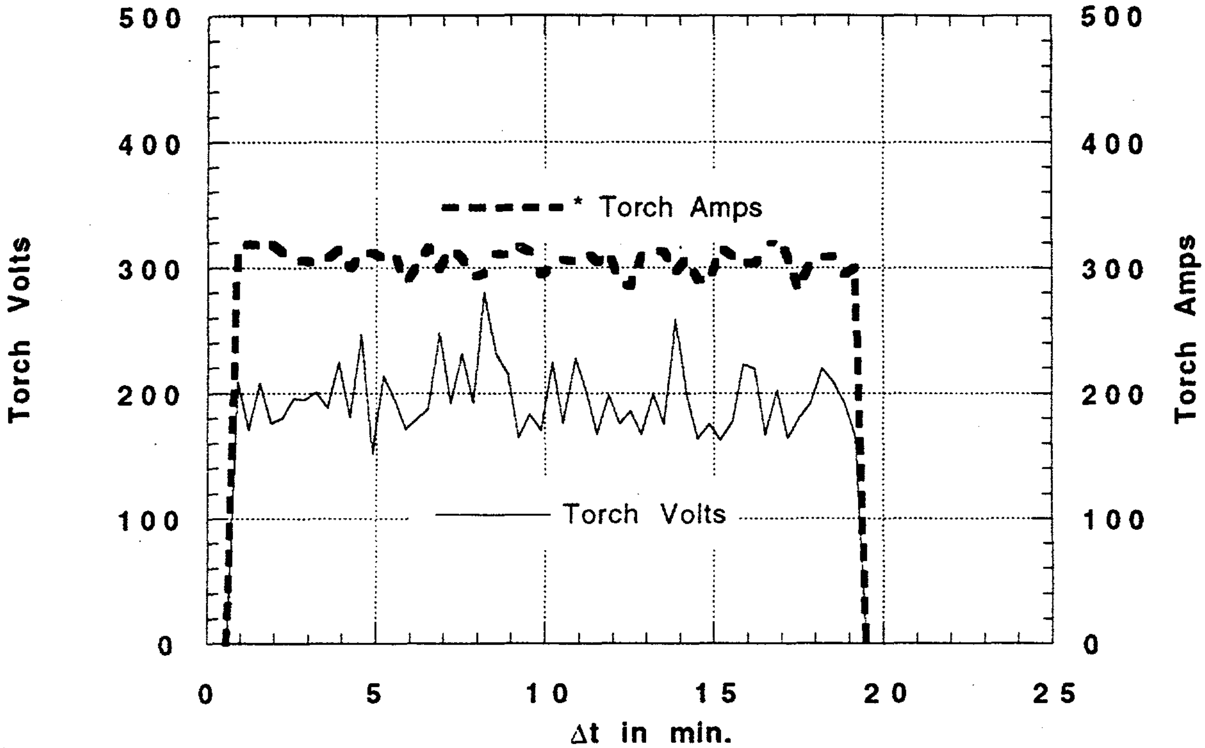
KiloWatts Removed by Torch Cooling Circuit



1/4 Scale Data Summary		
	Run Date: 8/11/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: small amt steel grit		Video Tape #: 7-25-94 Aerojet
Furnace Configuration: rotary		Video Start: about 2 hr
Type of Feedstock: none		Supply Gas: N2
Estimated Electrode Hours: 0		Operators: PSW, MAK
Remarks: Proceed with thirty minute run with Aerojet power tube assembly, and electrode.		Results:

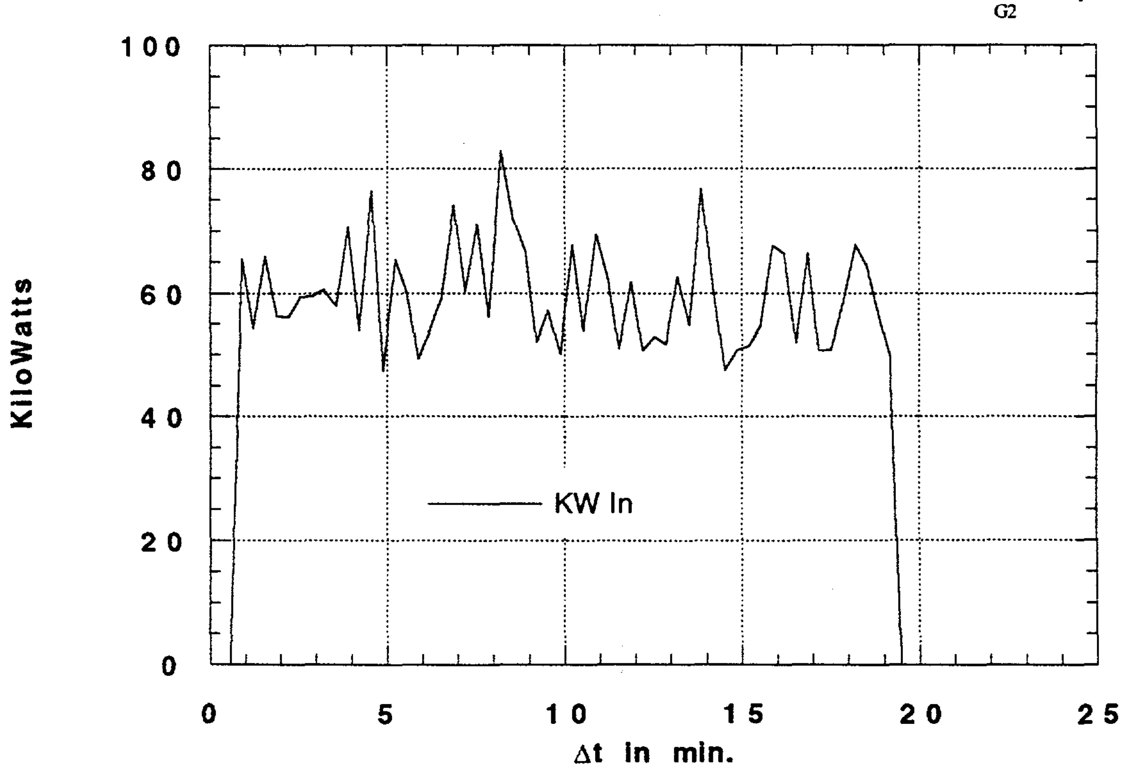
Torch Voltage and Current

08-10-94-2 Aerojet
G1

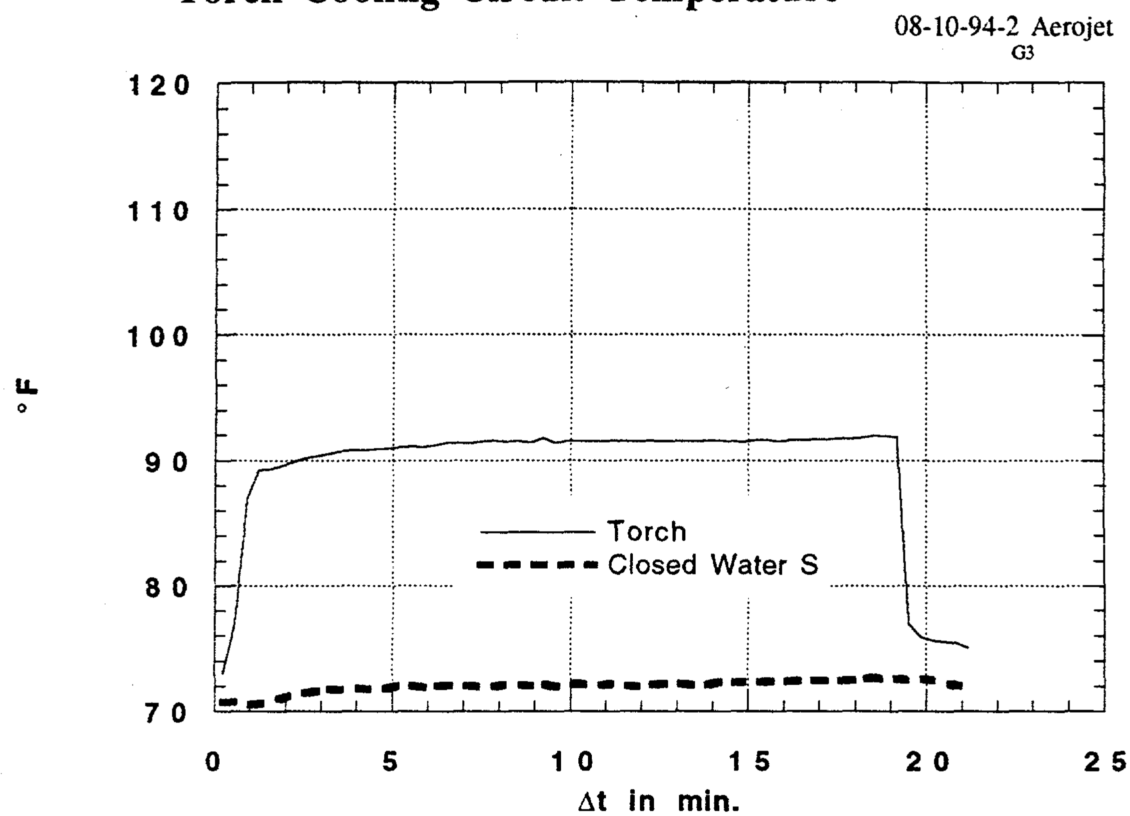


KiloWatts Into Torch

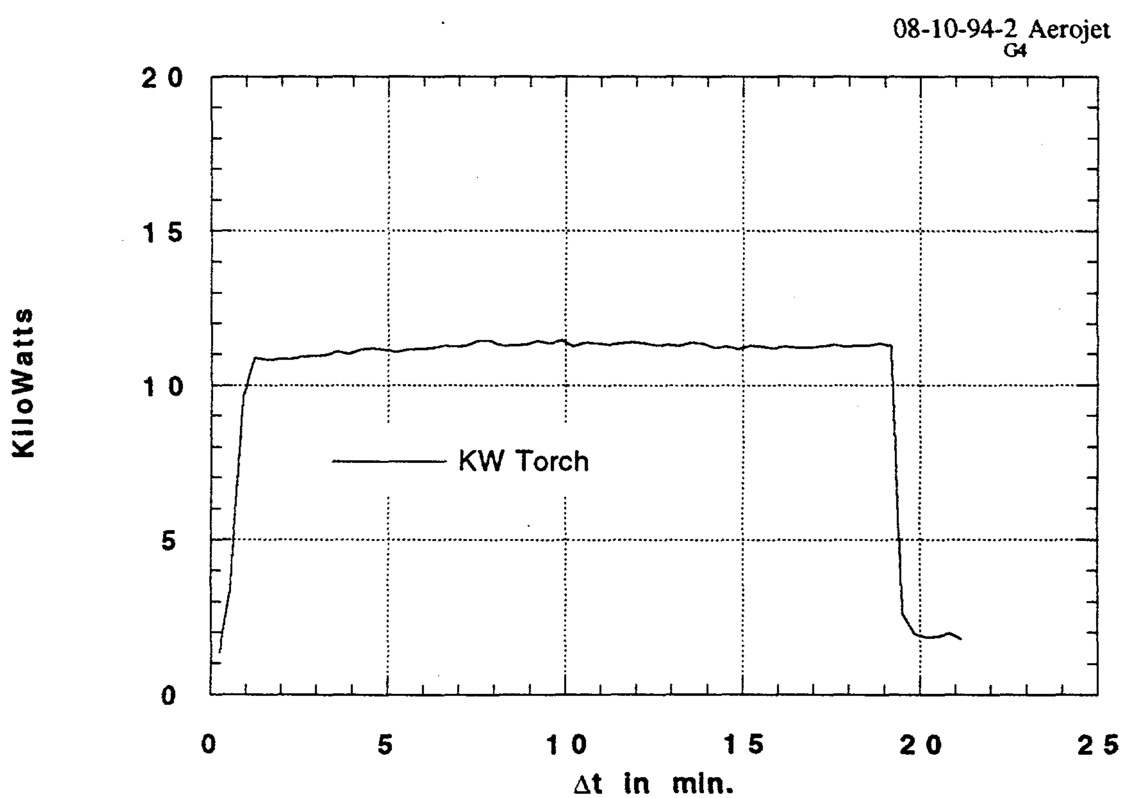
08-10-94-2 Aerojet
G2



Torch Cooling Circuit Temperature

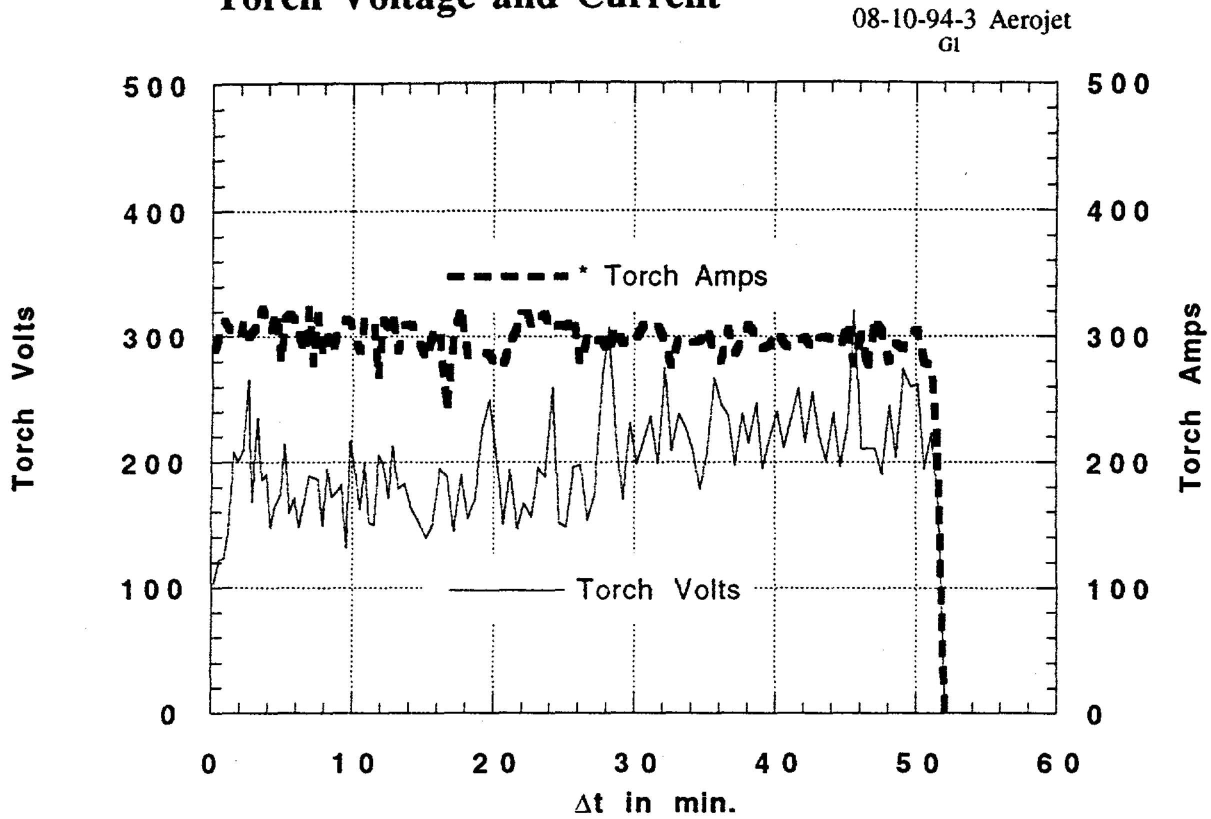


KiloWatts Removed by Torch Cooling Circuit

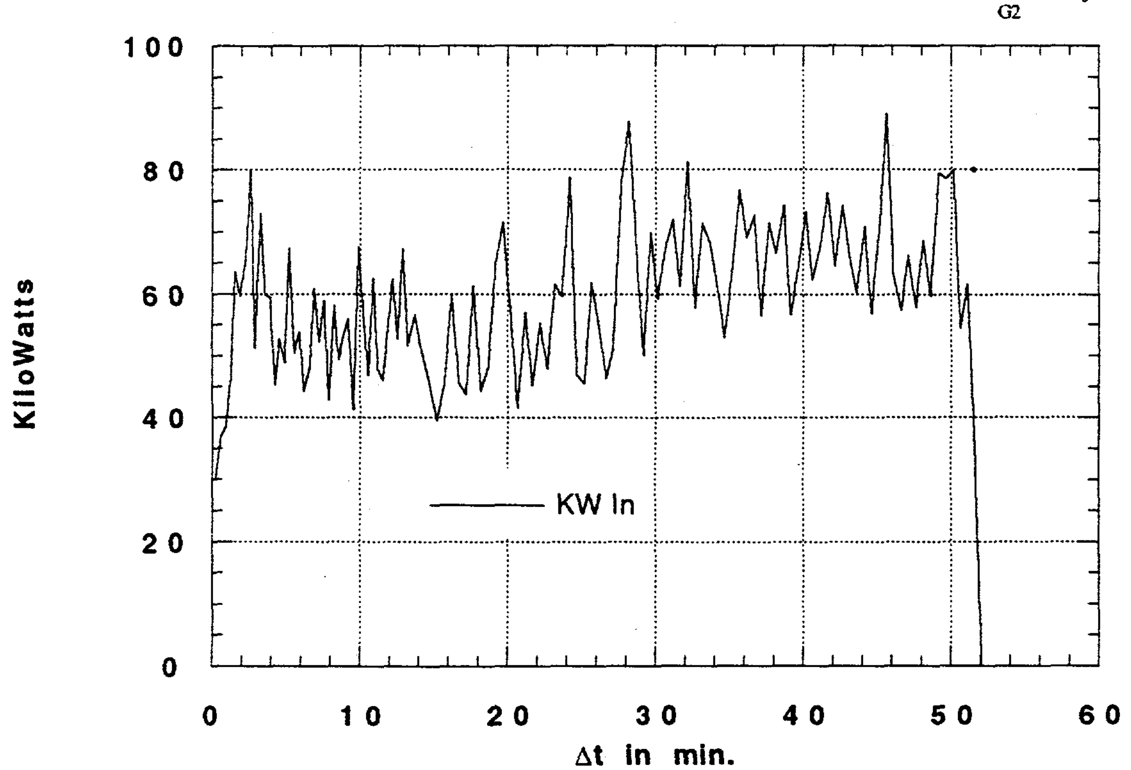


1/4 Scale Data Summary		
	Run Date: 8/11/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: small amt steel grit		Video Tape #: 7-25-94 Aerojet
Furnace Configuration: rotary		Video Start: about 2 hr
Type of Feedstock: none		Supply Gas: N2
Estimated Electrode Hours: 0		Operators: PSW, MAK
Remarks: Proceed with Aerojet power tube assembly, and electrode (until failure.)		Results: Shut down for the day after 47 min. of running. The electrode still looks in very good shape. The total
		run time today was about 75 minutes.

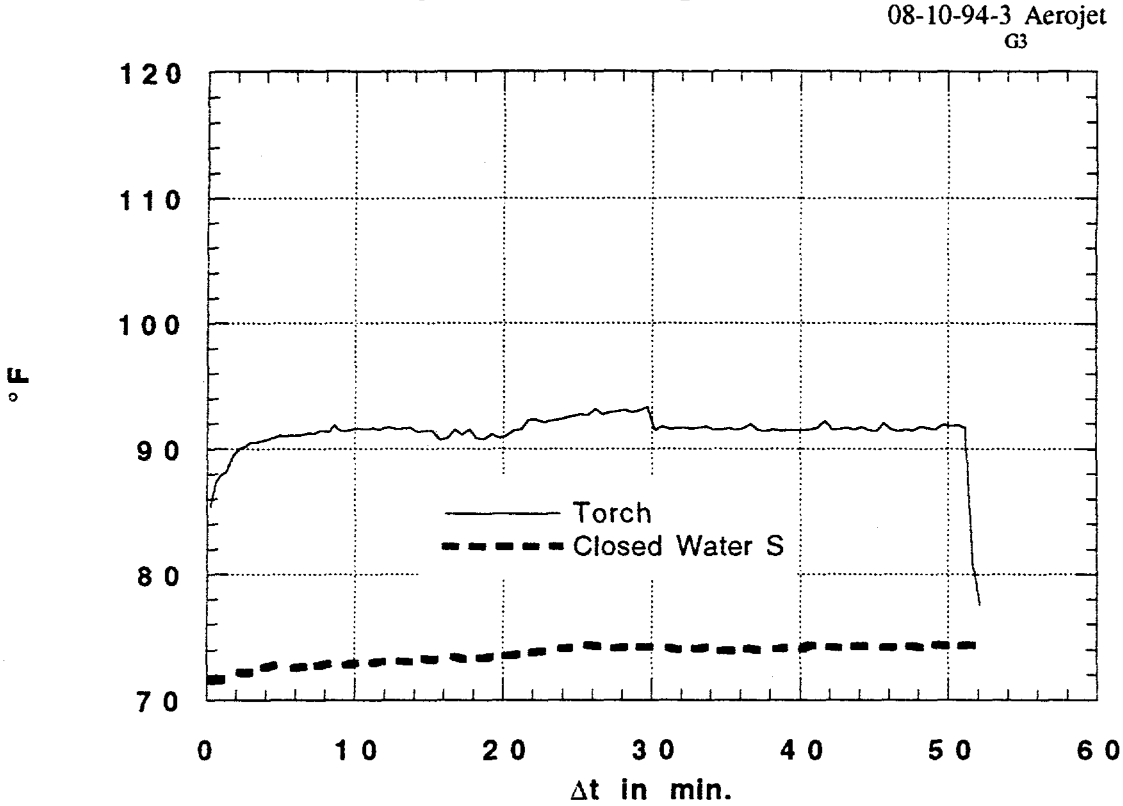
Torch Voltage and Current



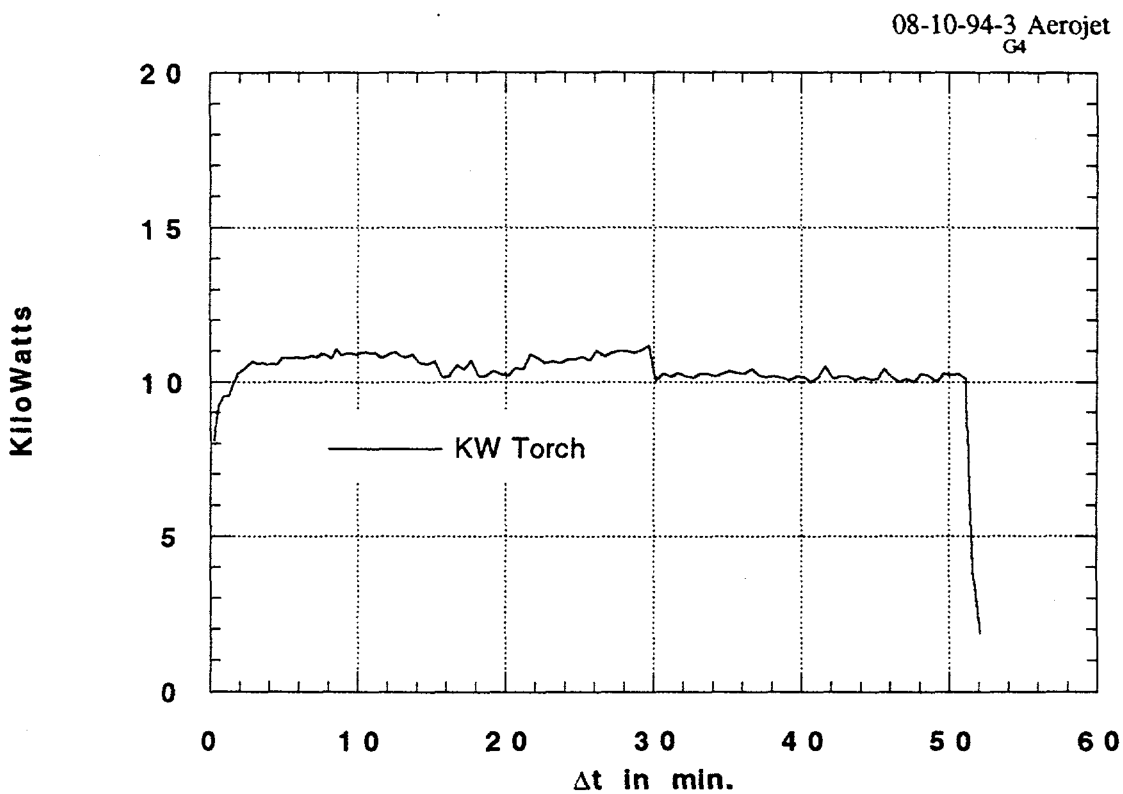
KiloWatts Into Torch



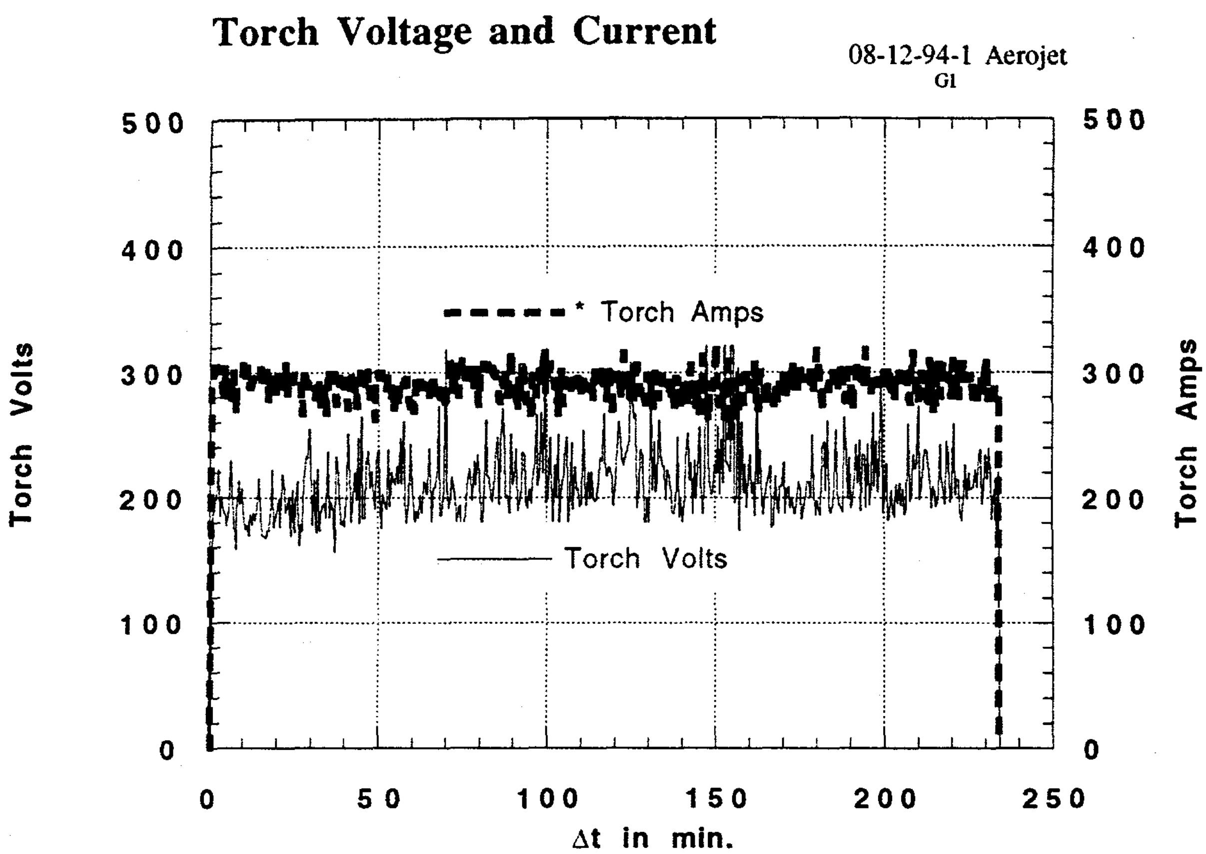
Torch Cooling Circuit Temperature



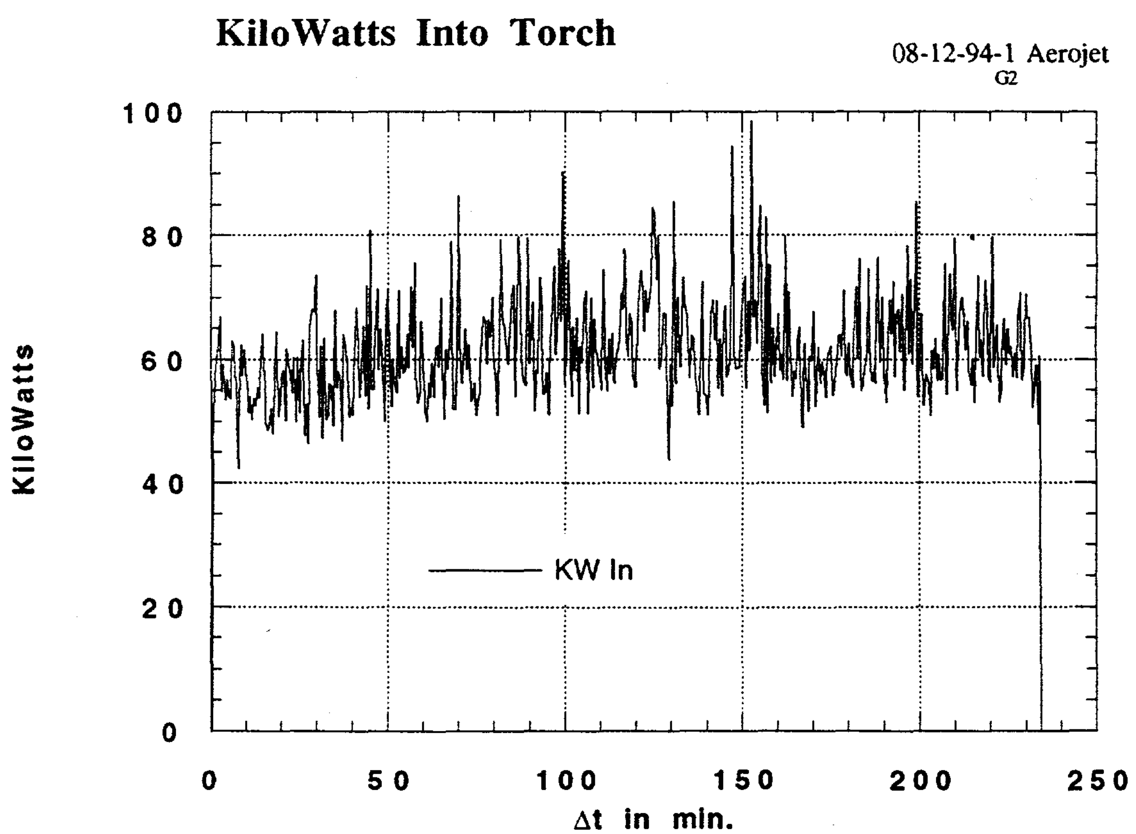
KiloWatts Removed by Torch Cooling Circuit



1/4 Scale Data Summary		
	Run Date: 8/12/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: small amt steel grit		Video Tape #: 7-25-94 Aerojet
Furnace Configuration: rotary		Video Start: about 2.5 hr (?)
Type of Feedstock: none		Supply Gas: N2
Estimated Electrode Hours: 0		Operators: PSW, MAK
Remarks: Continue with Aerojet power tube assembly, and electrode (until failure.)		Results: Stopped after four hours to check electrode. It looks good. We will continue the run in a half hour.

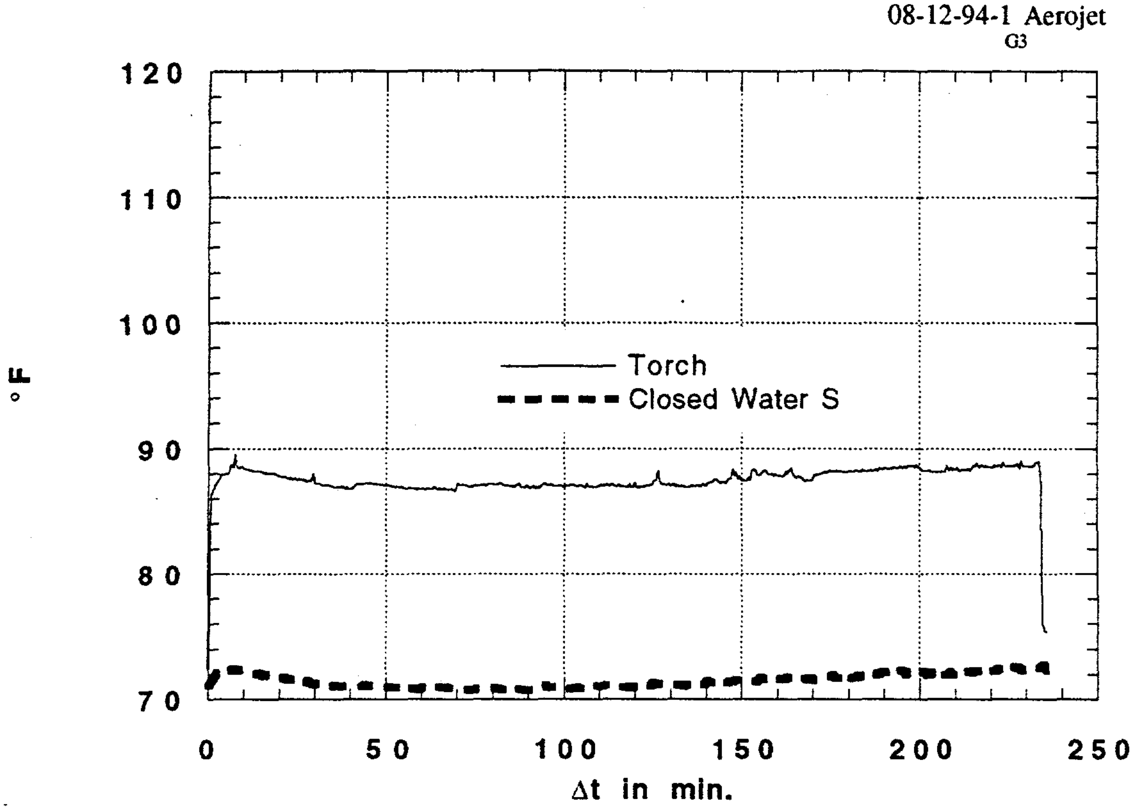


Torch Voltage and Current
08-12-94-1 Aerojet
G1
500
400
300
200
100
0
Torch Volts
Torch Amps
* Torch Amps
Torch Volts
0
50
100
150
200
250
Δt in min.

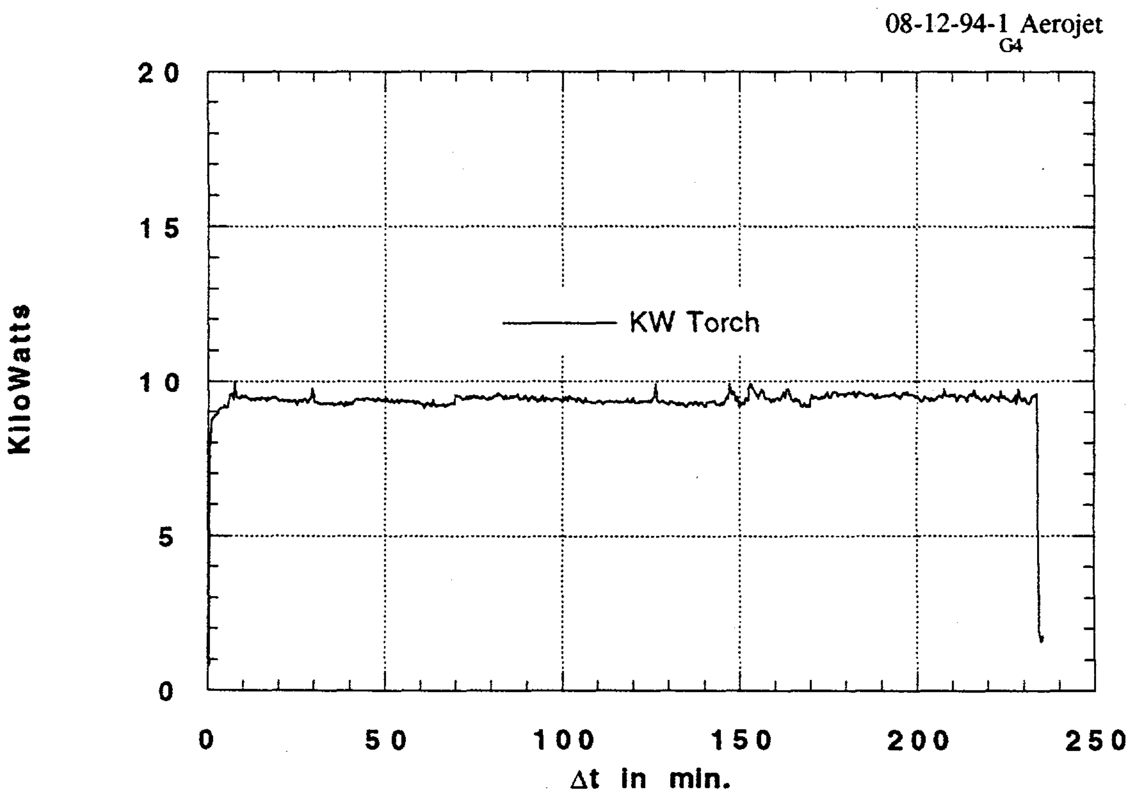


KiloWatts Into Torch
08-12-94-1 Aerojet
G2
100
80
60
40
20
0
KiloWatts
KW In
0
50
100
150
200
250
Δt in min.

Torch Cooling Circuit Temperature

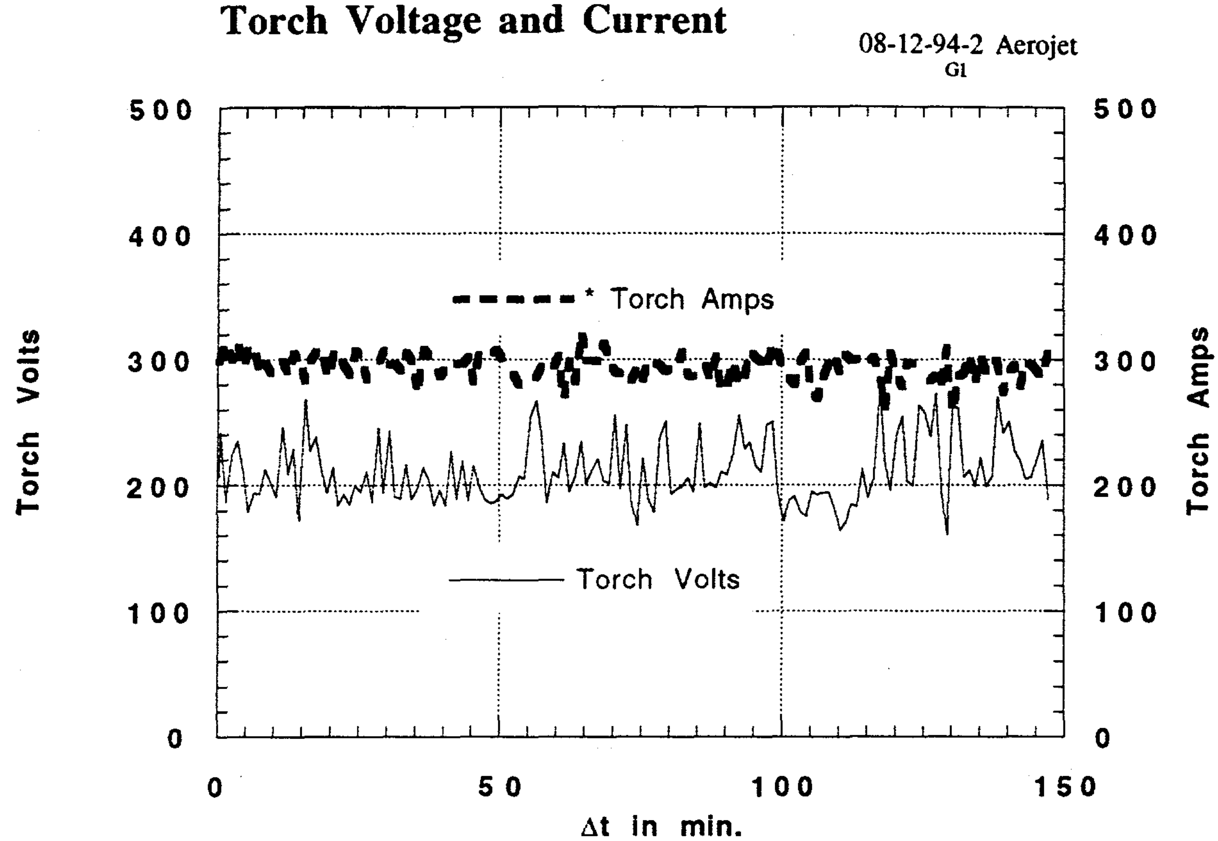


KiloWatts Removed by Torch Cooling Circuit

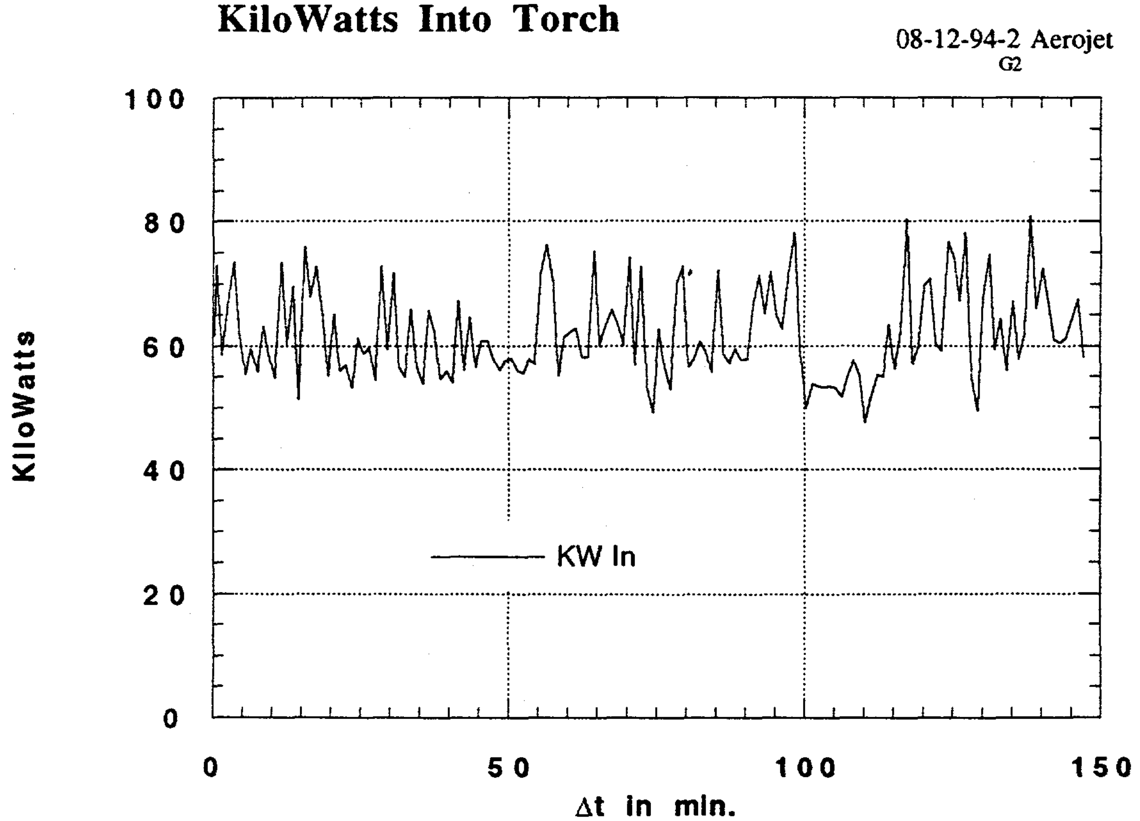


1/4 Scale Data Summary		
	Run Date: 8/12/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: small amt steel grit		Video Tape #: 7-25-94 Aerojet
Furnace Configuration: rotary		Video Start: no video
Type of Feedstock: none		Supply Gas: N2
Estimated Electrode Hours: 0		Operators: PSW, MAK
Remarks: Continue with Aerojet power tube assembly, and electrode (until 8 hrs or failure.)		Results: End of the day shutdown. The electrode looks great. We will run 8 hrs straight on Monday.

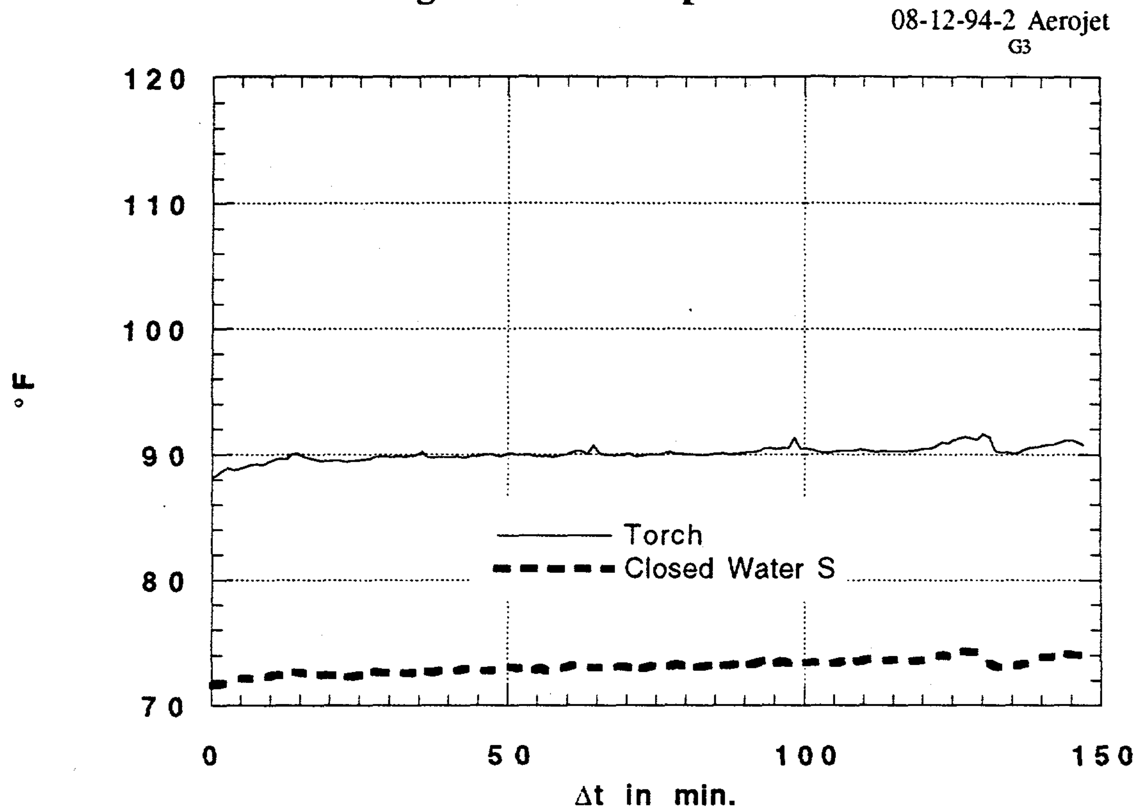
Torch Voltage and Current



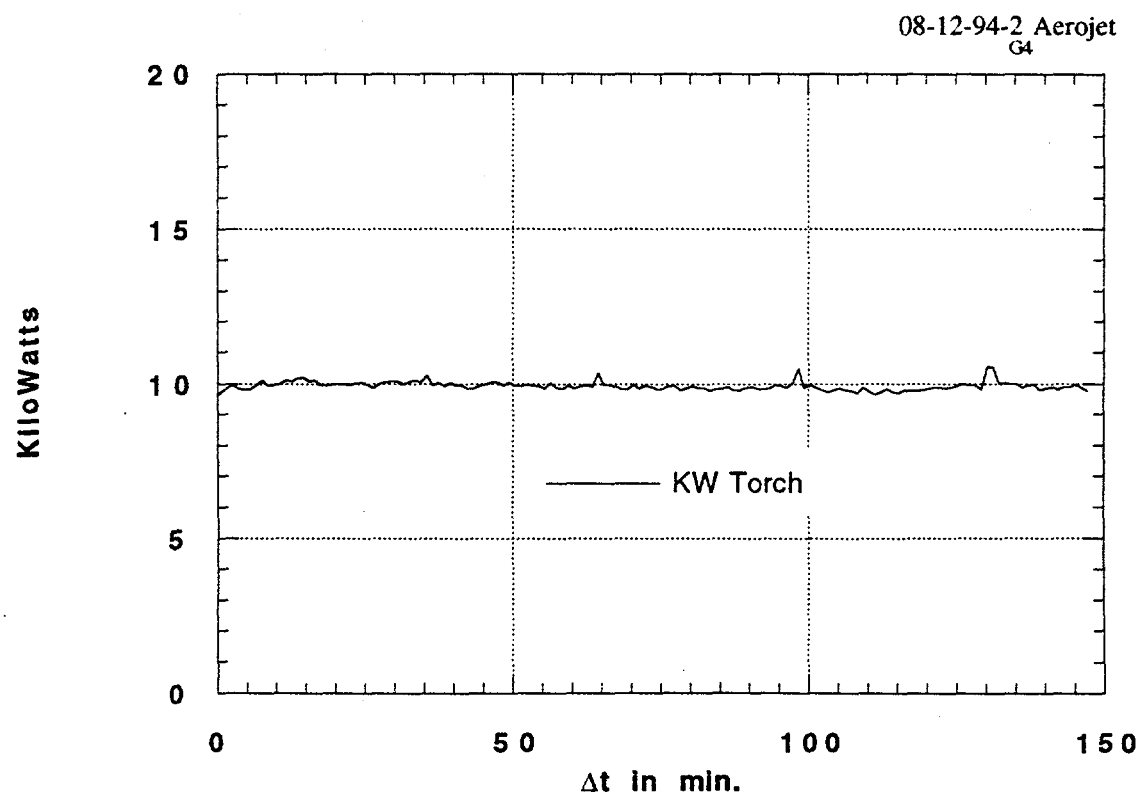
KiloWatts Into Torch



Torch Cooling Circuit Temperature

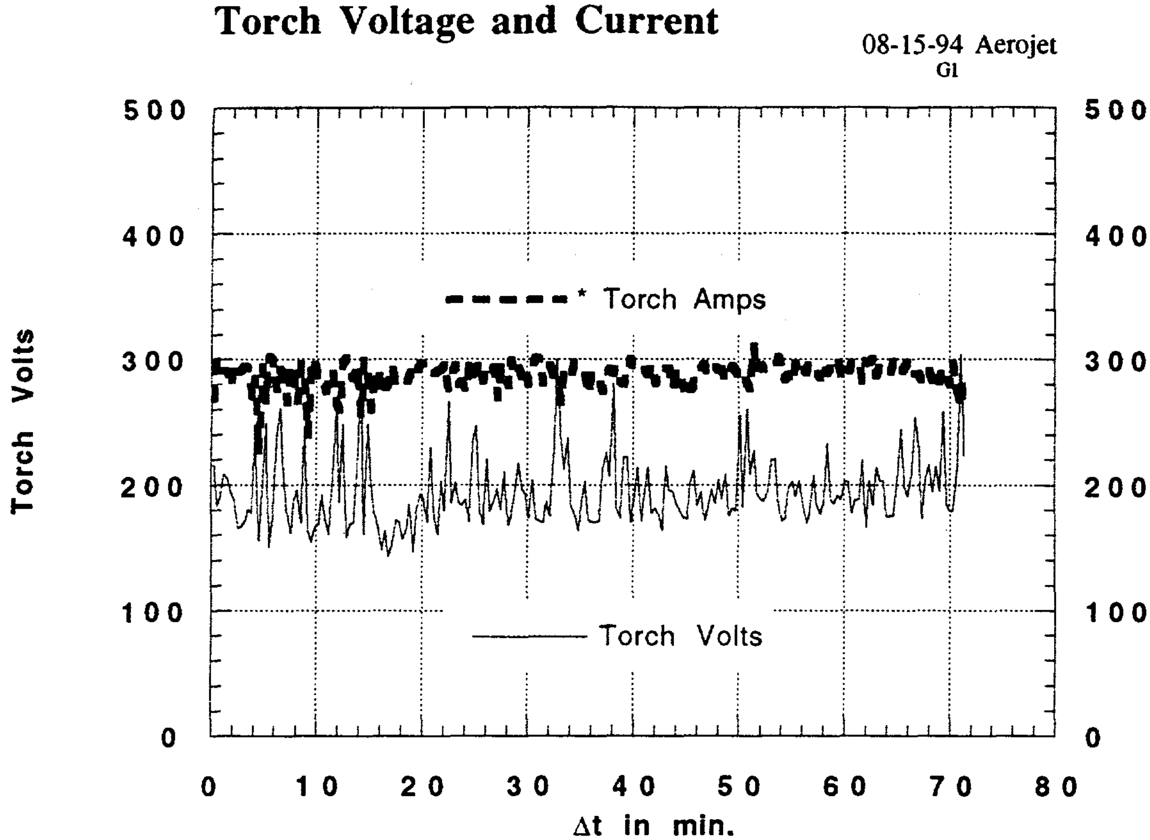


KiloWatts Removed by Torch Cooling Circuit

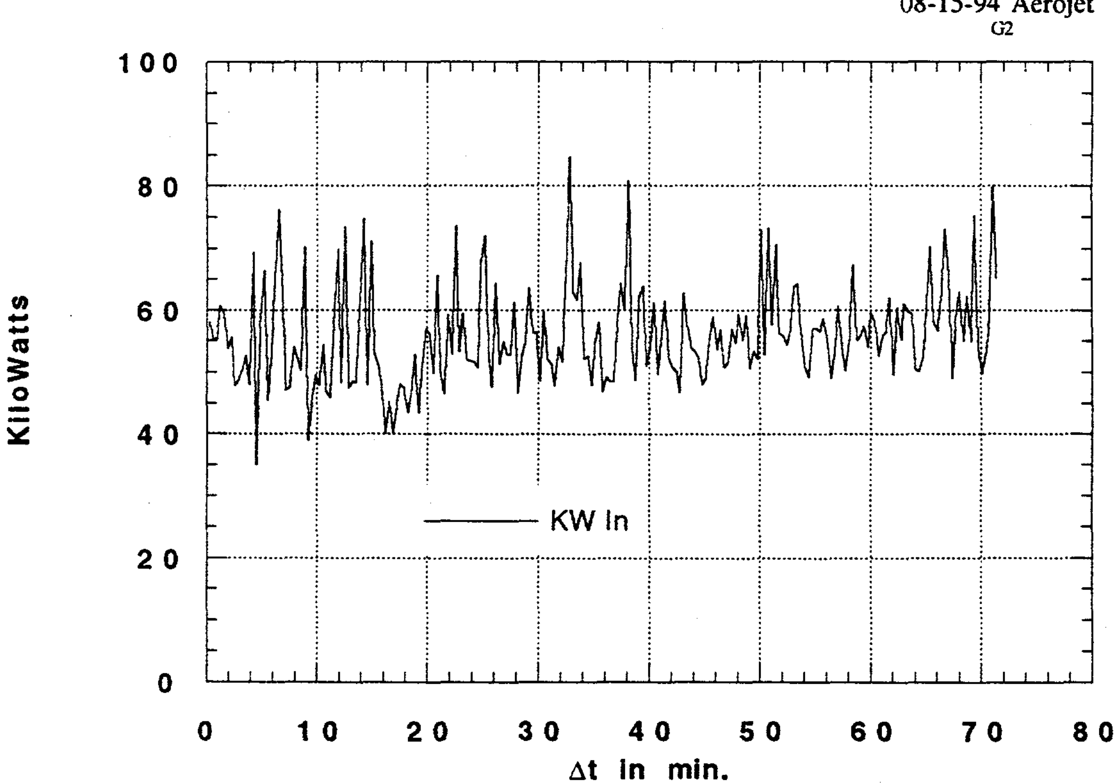


1/4 Scale Data Summary		
	Run Date: 8/15/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: N/A		Video Tape #: no video
Furnace Configuration: rotary		Video Start: N/A
Type of Feedstock:		Supply Gas: N
Estimated Electrode Hours: 7.75		Operators: MAK
Remarks:		Results: Only ran data acquisition for about an hour, still running Aerojet electrode, however.

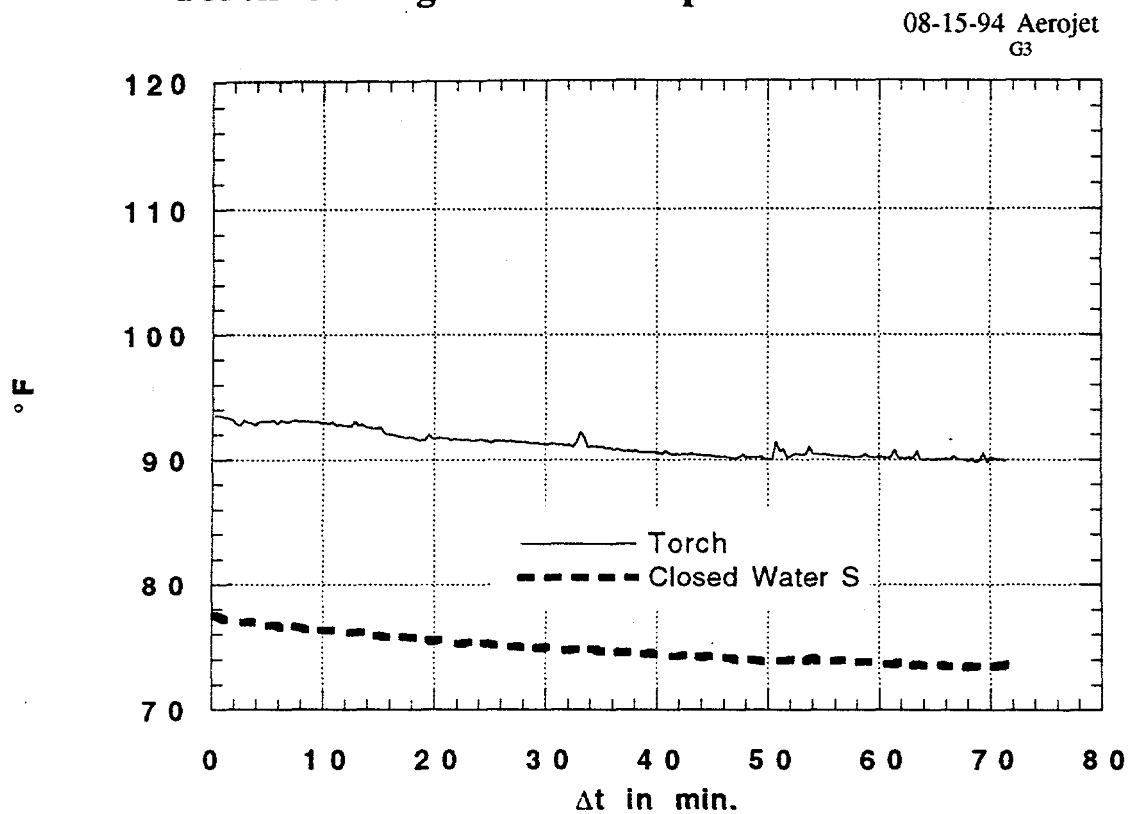
Torch Voltage and Current



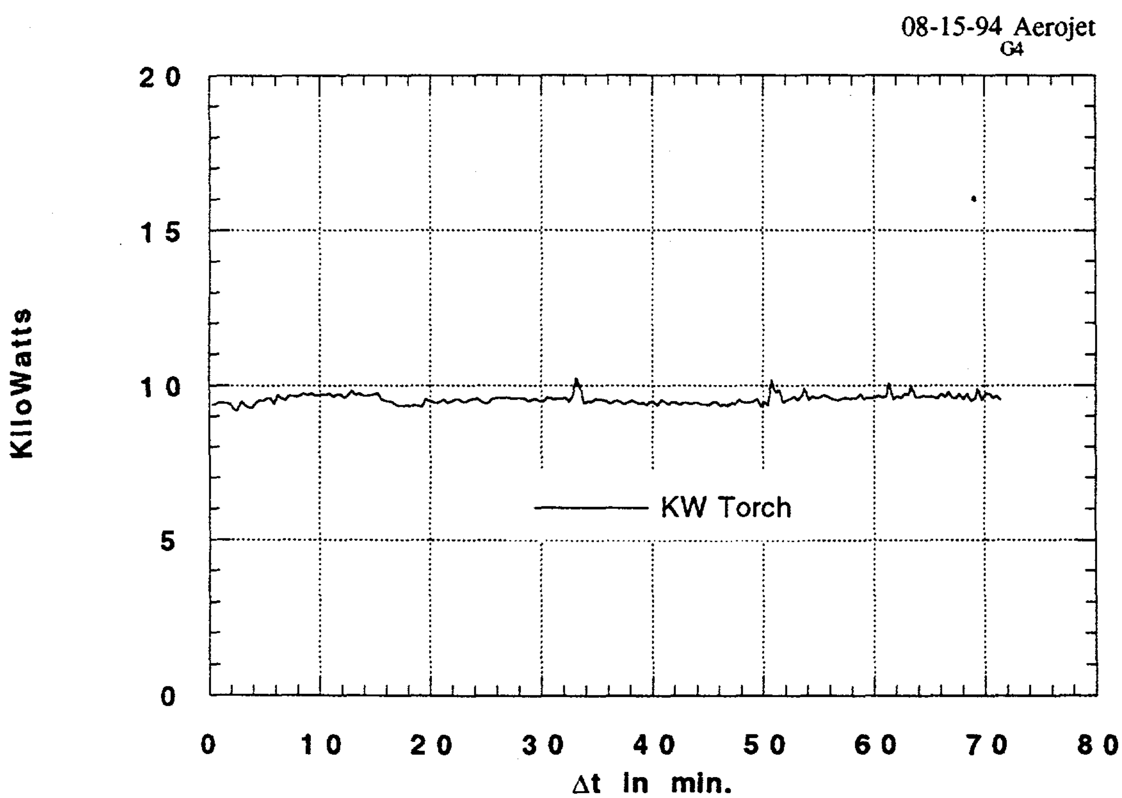
KiloWatts Into Torch



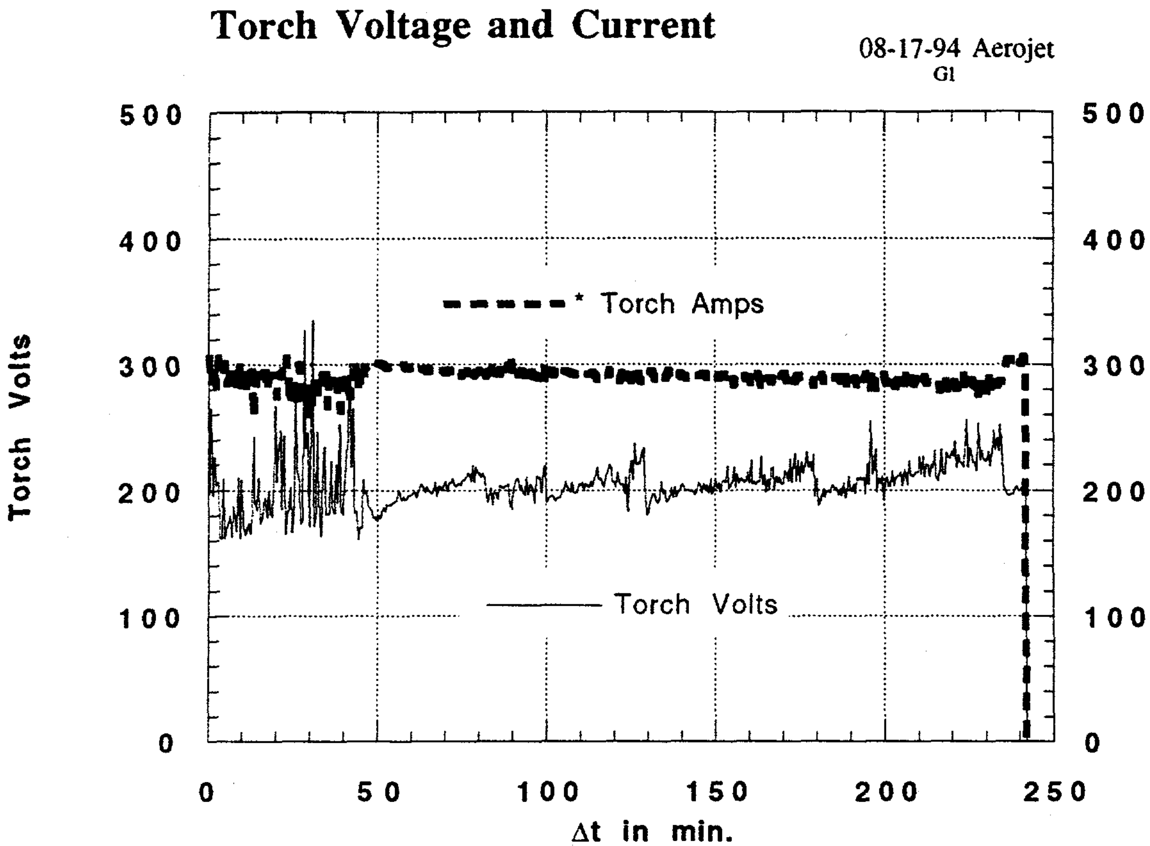
Torch Cooling Circuit Temperature

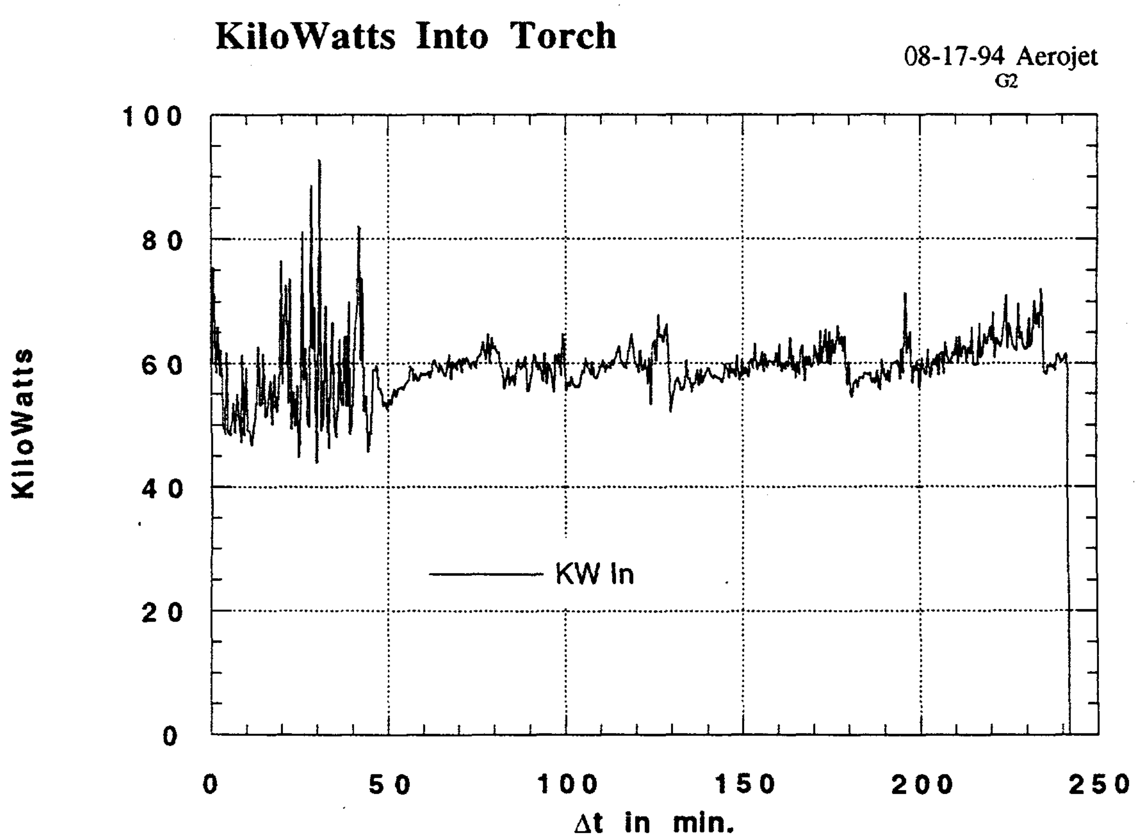


KiloWatts Removed by Torch Cooling Circuit

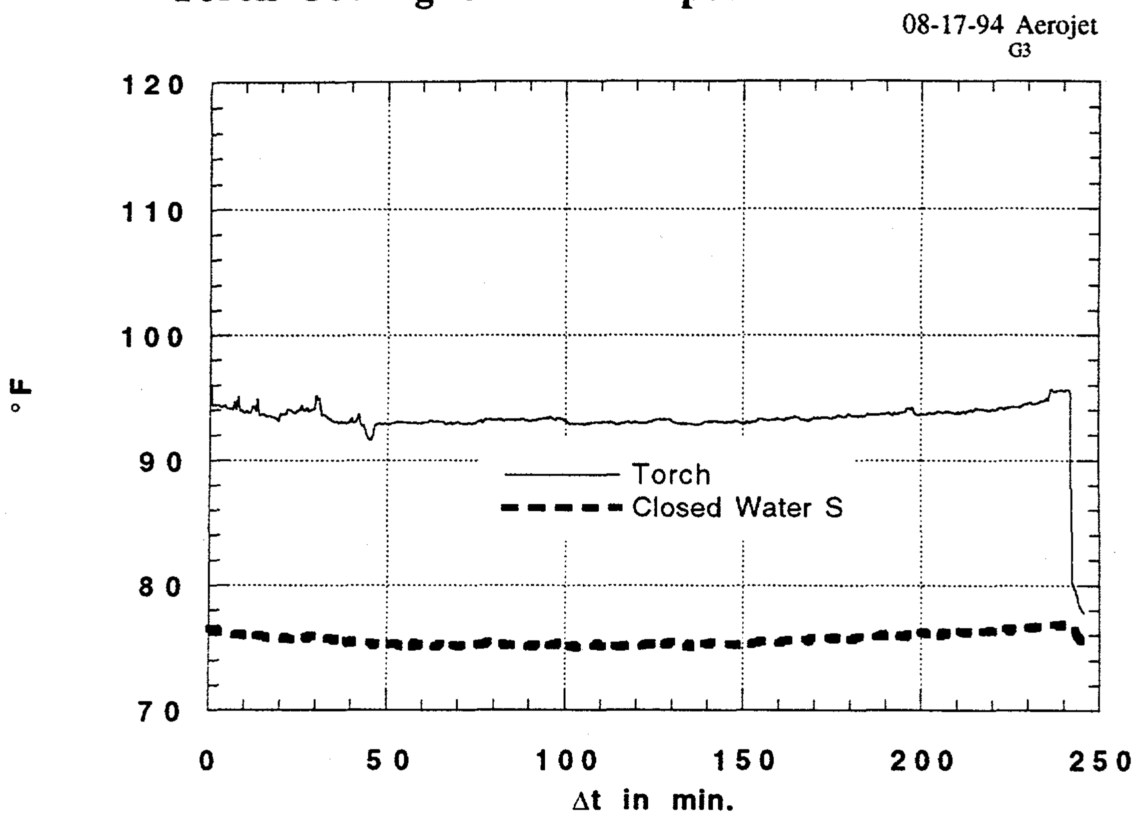


1/4 Scale Data Summary		
	Run Date: 8/17/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: small amount of dirt		Video Tape #: N/A
Furnace Configuration: rotating crucible		Video Start: N/A
Type of Feedstock: N/A		Supply Gas: N
Estimated Electrode Hours: 14.75		Operators: MAK
Remarks:		Results: Torch shut down after 4.5 hours. Will check electrode and try to start it up again.

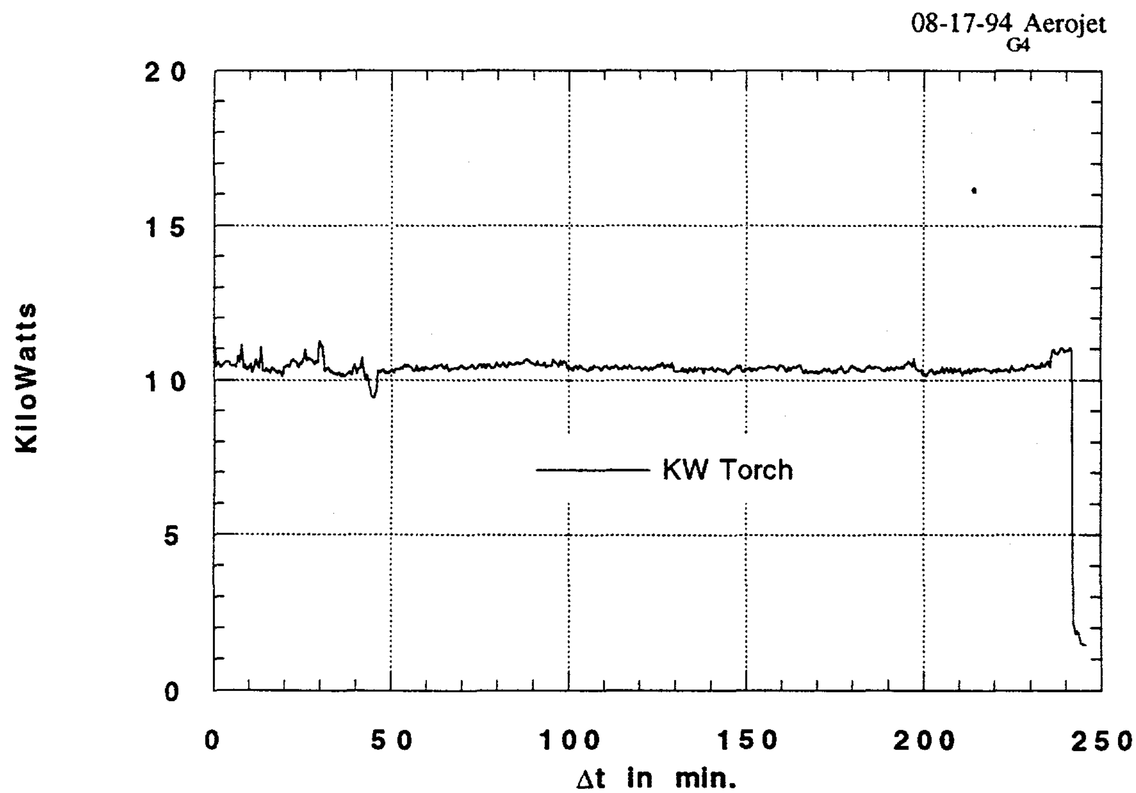

Torch Voltage and Current
08-17-94 Aerojet
G1
500
400
300
200
100
0
Torch Volts
Torch Amps
* Torch Amps
Torch Volts
0
50
100
150
200
250
Δt in min.


KiloWatts Into Torch
08-17-94 Aerojet
G2
100
80
60
40
20
0
KiloWatts
KW In
0
50
100
150
200
250
Δt in min.

Torch Cooling Circuit Temperature



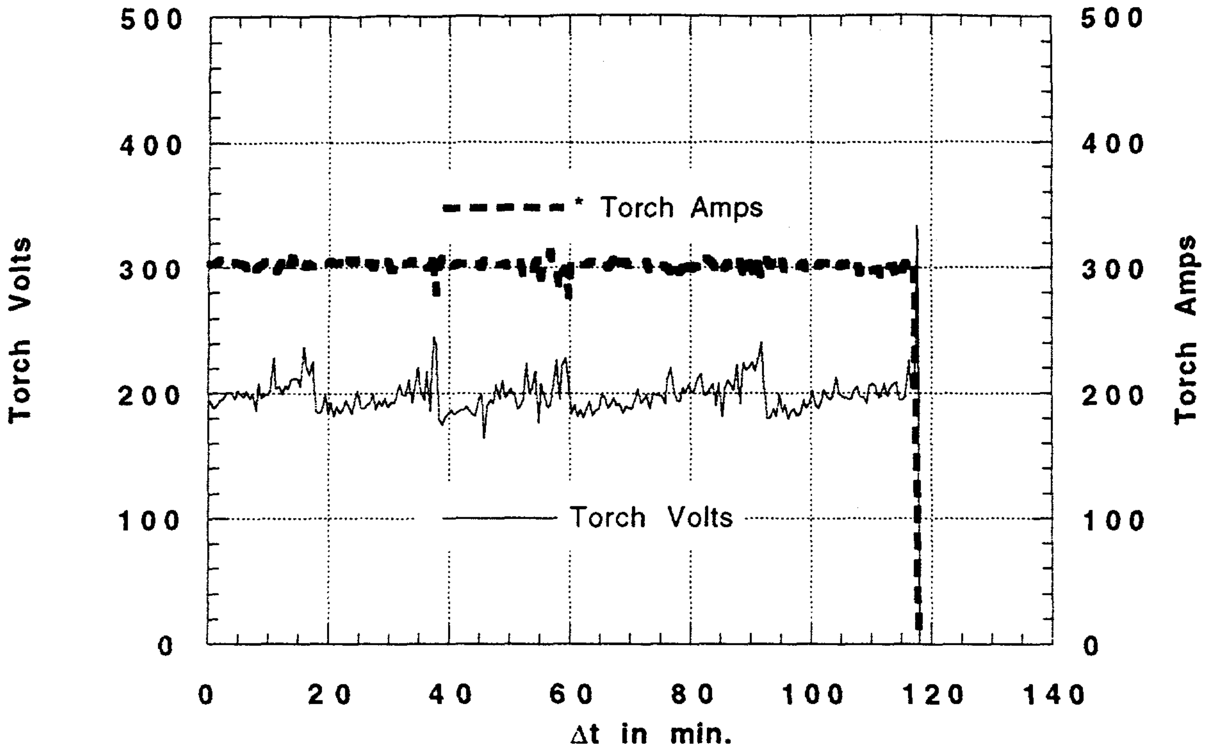
KiloWatts Removed by Torch Cooling Circuit



1/4 Scale Data Summary		
	Run Date: 8/17/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: small amount of dirt		Video Tape #: N/A
Furnace Configuration: rotating crucible		Video Start: N/A
Type of Feedstock: N/A		Supply Gas: N
Estimated Electrode Hours: 19.25		Operators: MAK
Remarks:		Results: Approximately 21to 22 hours now on the electrode, will continue testing.

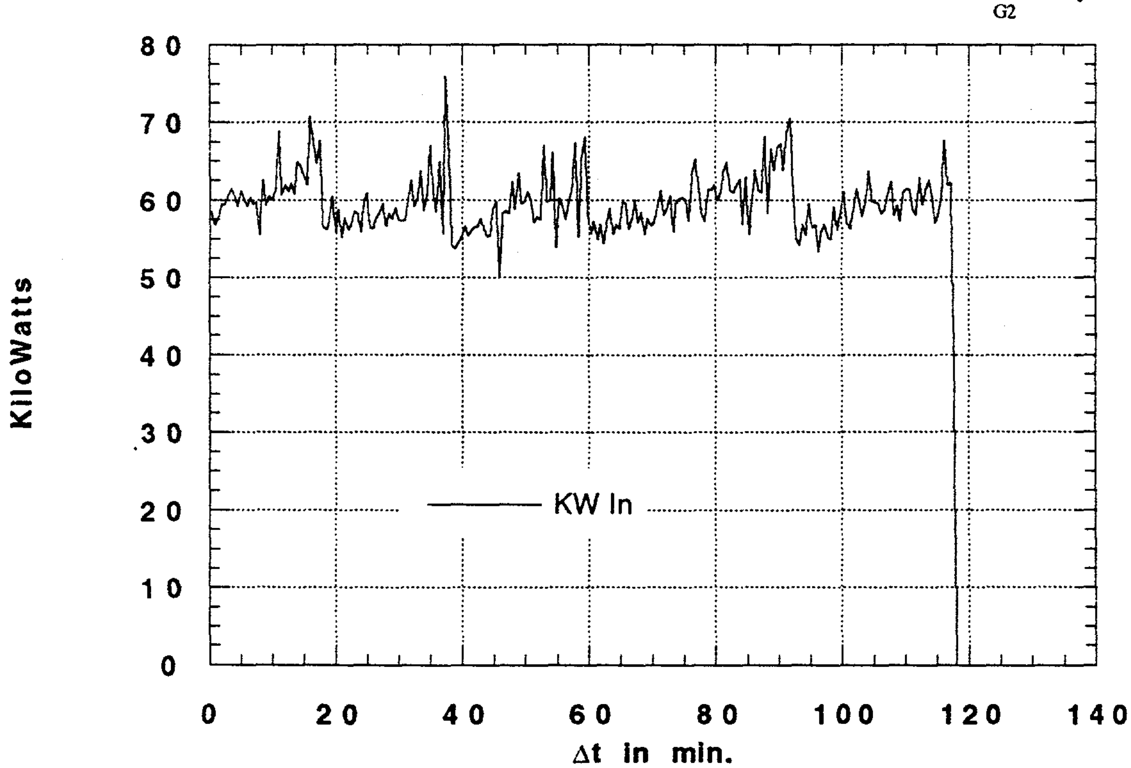
Torch Voltage and Current

08-17-94-2 Aerojet
G1

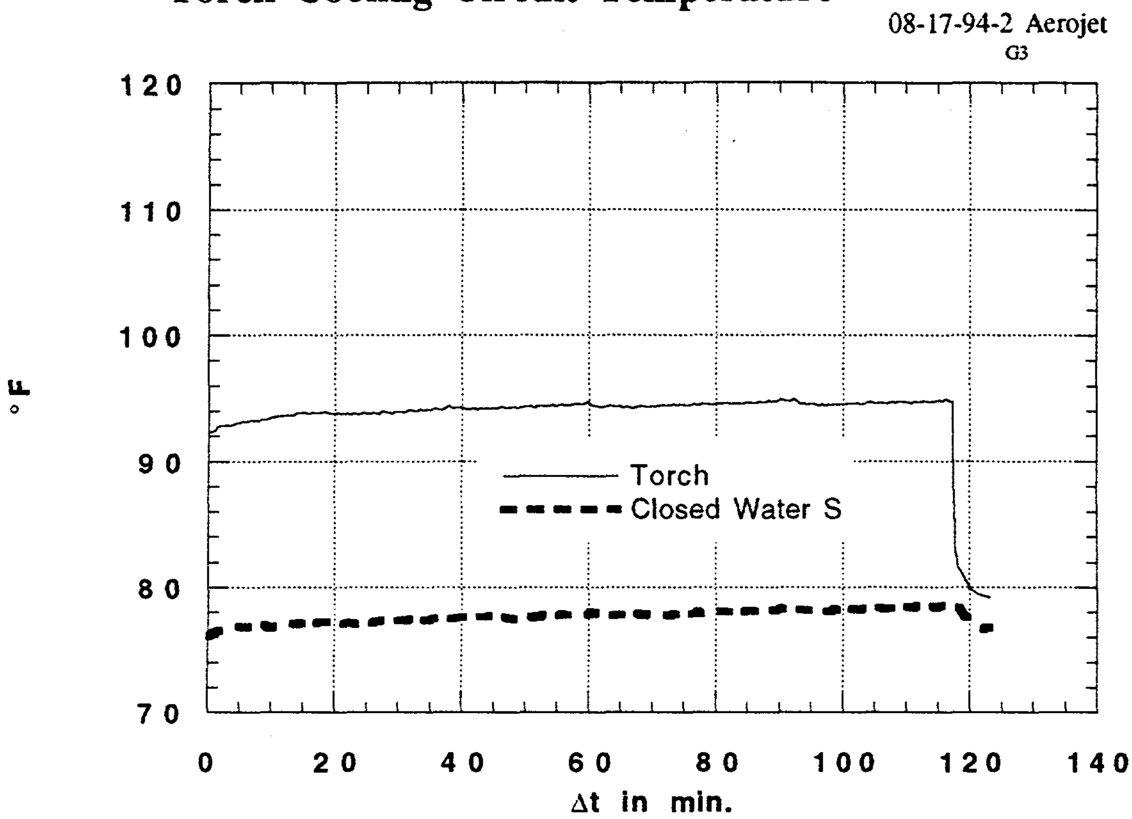


KiloWatts Into Torch

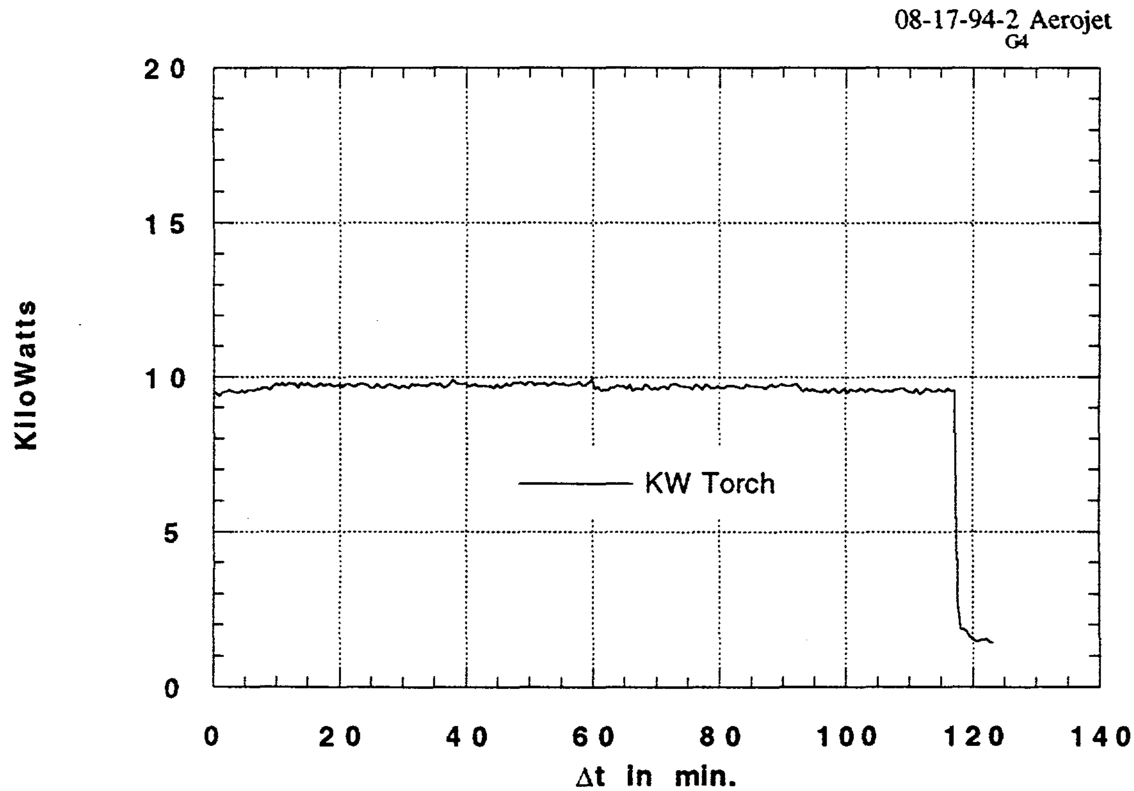
08-17-94-2 Aerojet
G2



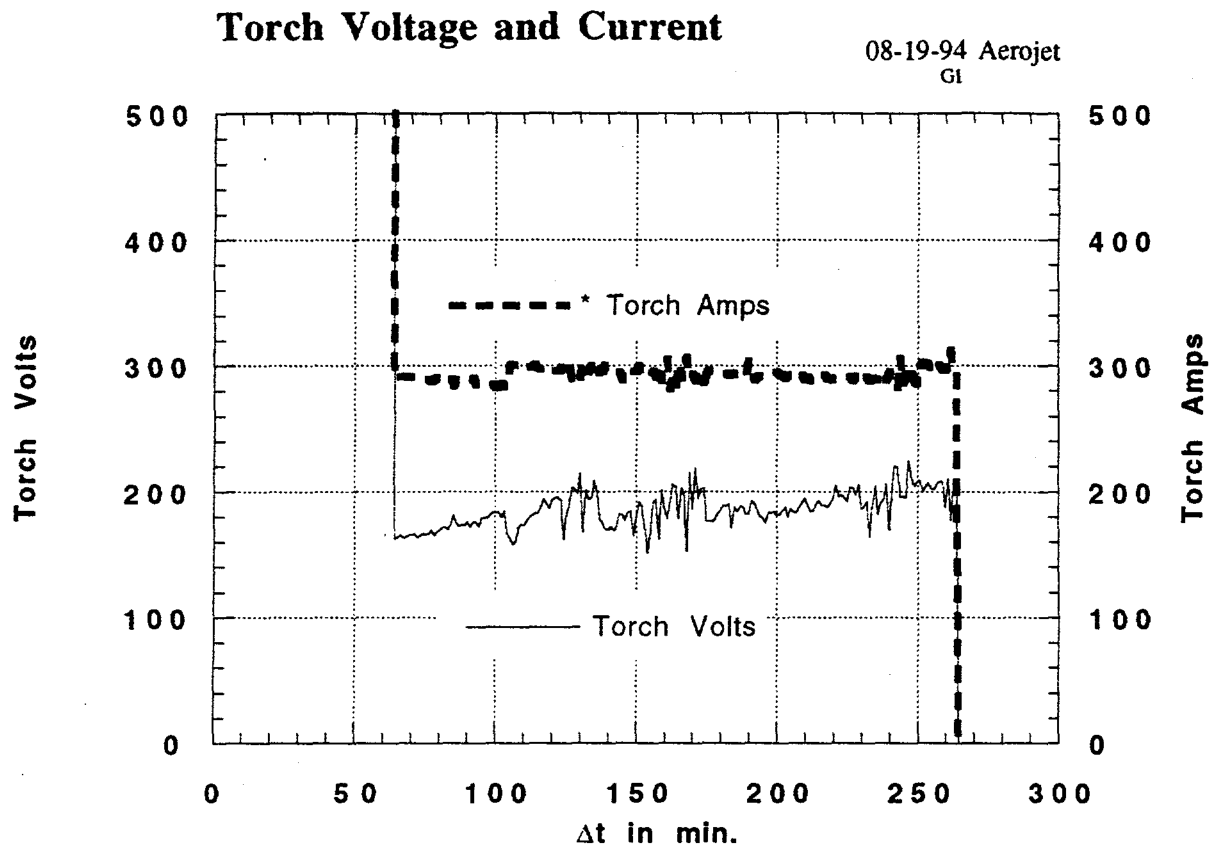
Torch Cooling Circuit Temperature

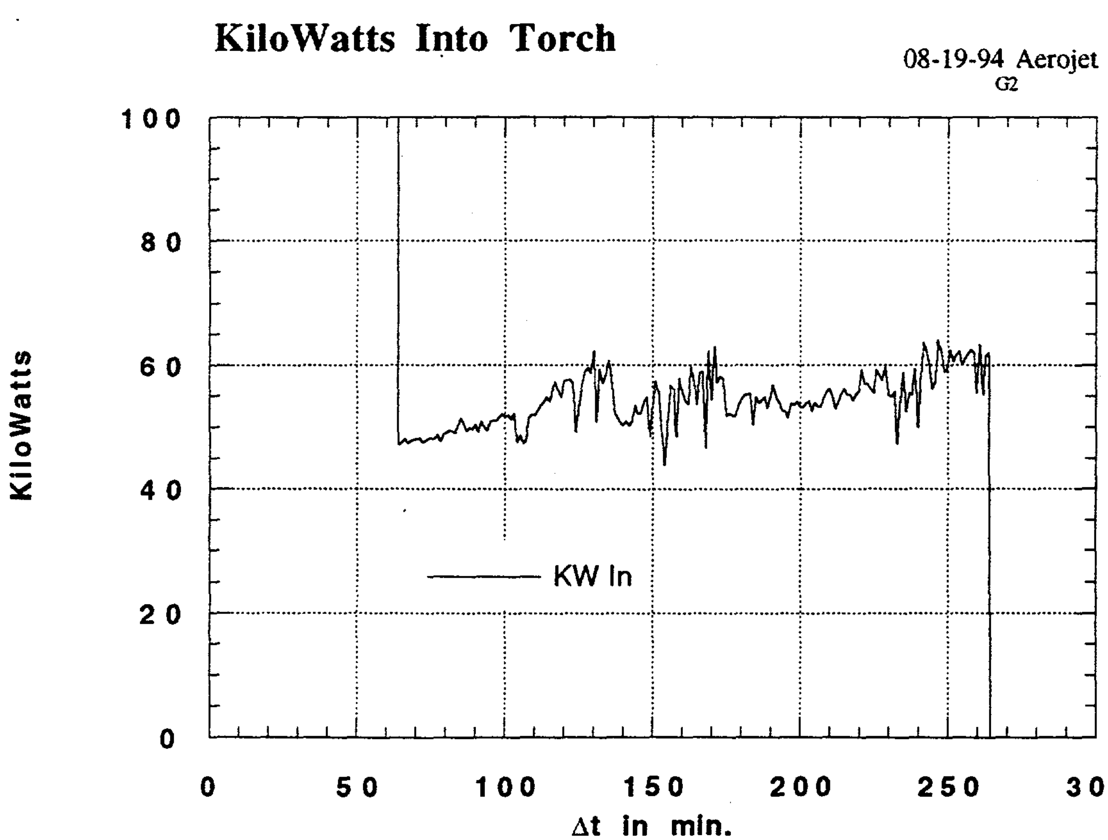


KiloWatts Removed by Torch Cooling Circuit

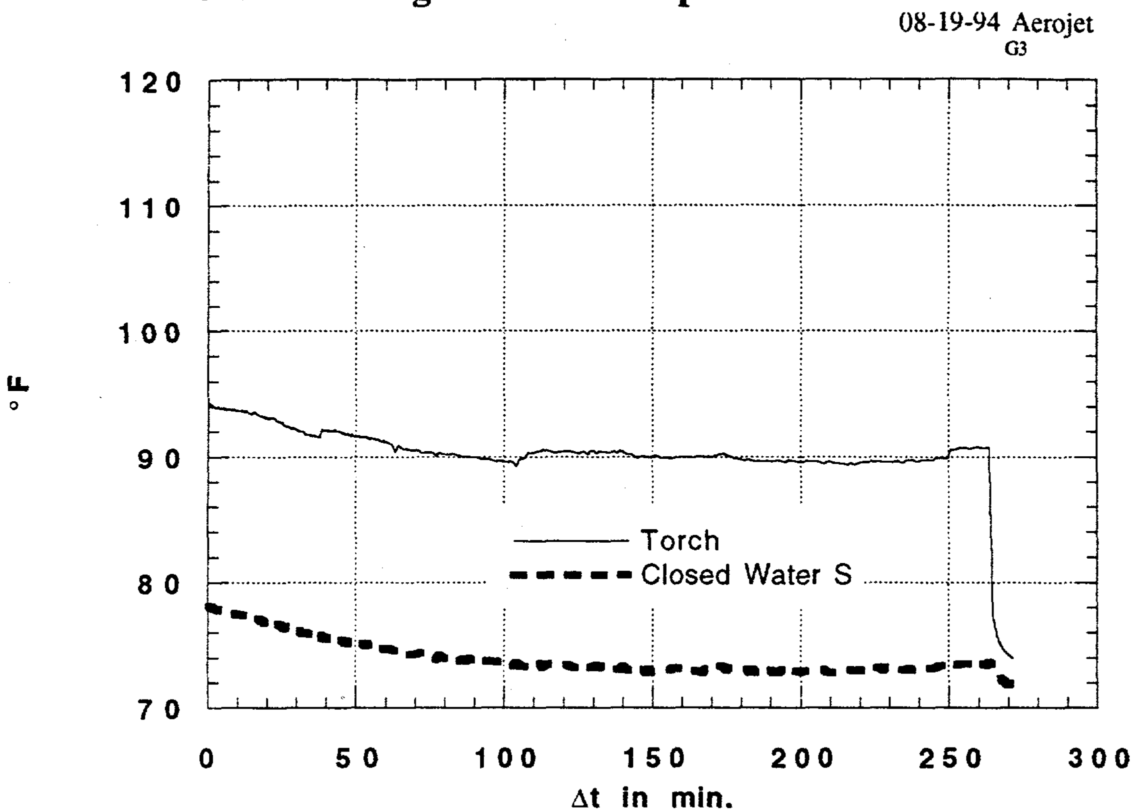


1/4 Scale Data Summary		
	Run Date: 8/19/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: dirt, soda ash		Video Tape #: N/A
Furnace Configuration: rotating crucible		Video Start: N/A
Type of Feedstock: N/A		Supply Gas: N
Estimated Electrode Hours: @21		Operators: MAK
Remarks:		Results:

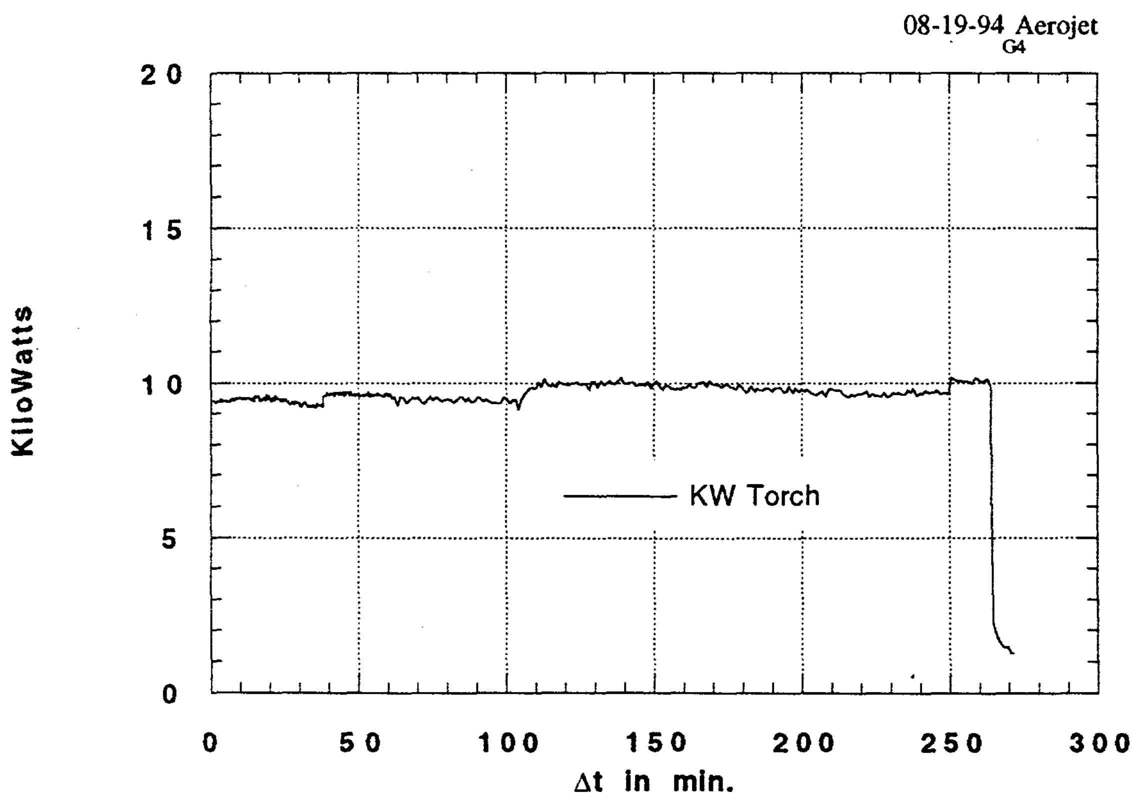

Torch Voltage and Current
08-19-94 Aerojet
G1
500
400
300
200
100
0
Torch Volts
Torch Amps
* Torch Amps
Torch Volts
0
50
100
150
200
250
300
Δt in min.


KiloWatts Into Torch
08-19-94 Aerojet
G2
100
80
60
40
20
0
KiloWatts
KW In
0
50
100
150
200
250
300
Δt in min.

Torch Cooling Circuit Temperature

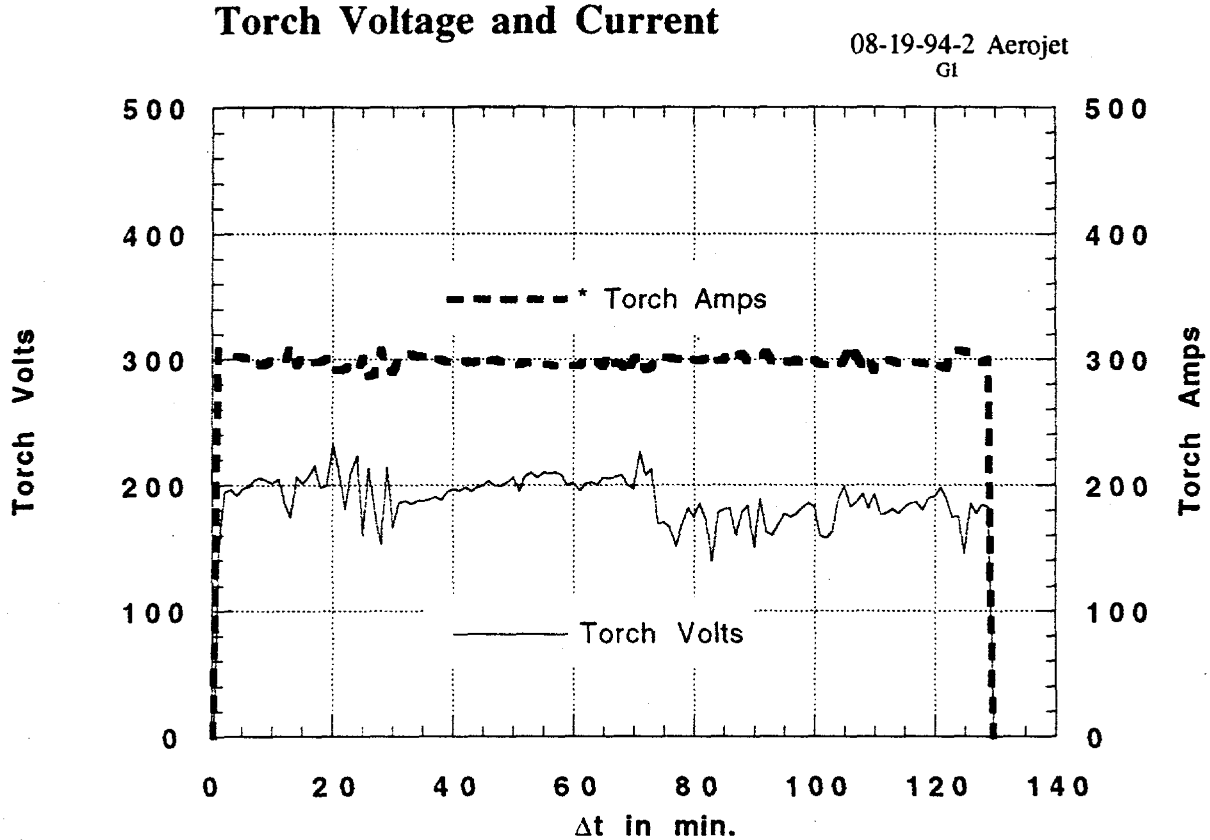


KiloWatts Removed by Torch Cooling Circuit

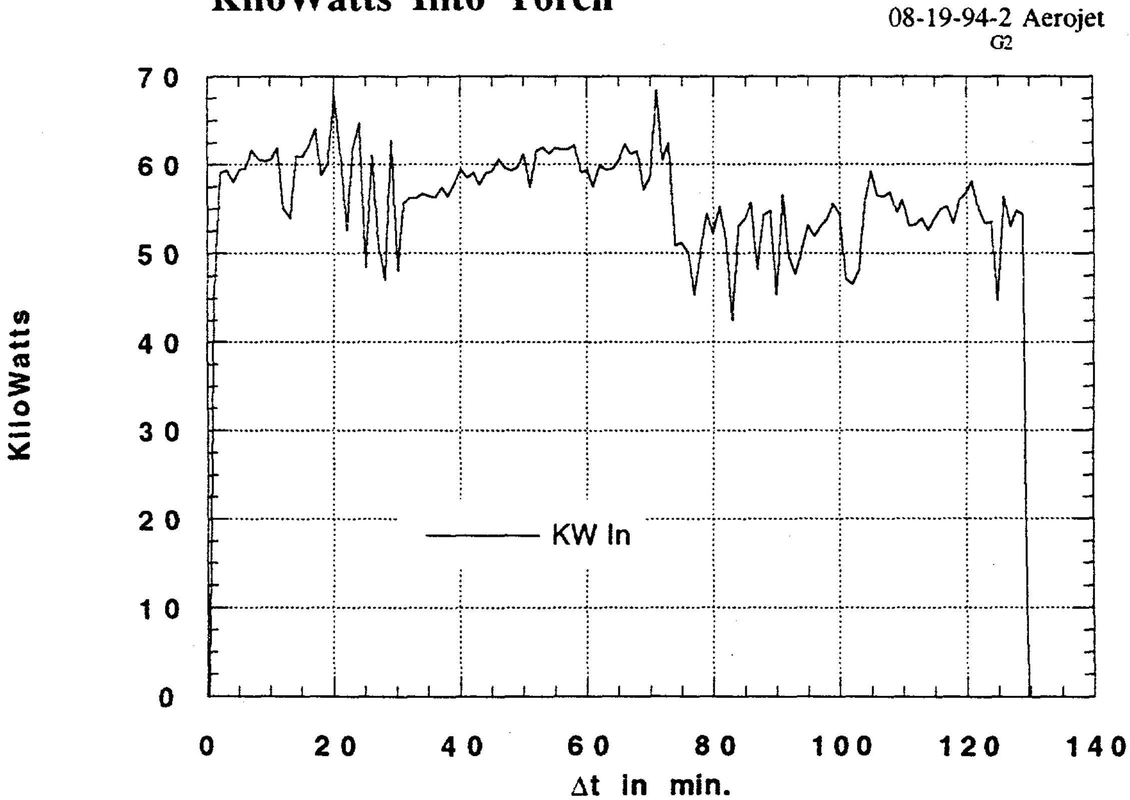


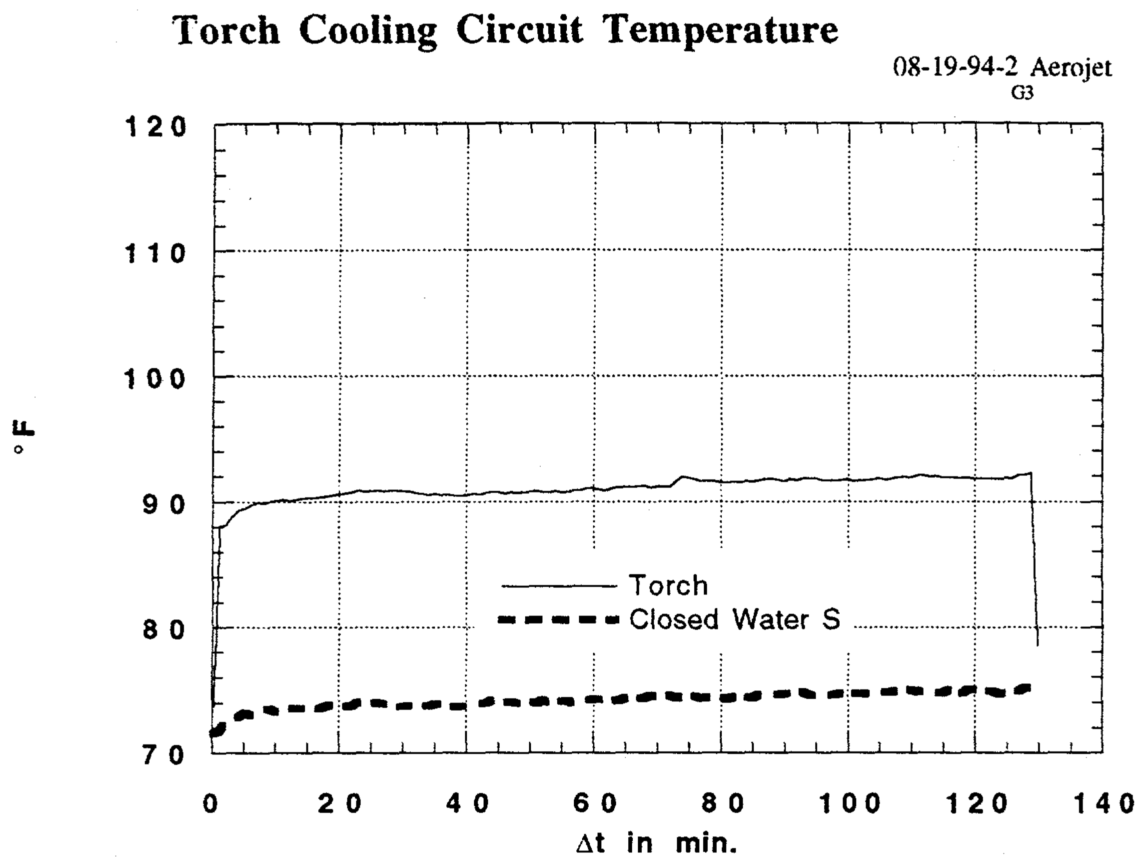
1/4 Scale Data Summary		
	Run Date: 8/19/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: dirt, soda ash		Video Tape #: N/A
Furnace Configuration: rotating crucible		Video Start: N/A
Type of Feedstock: N/A		Supply Gas: N
Estimated Electrode Hours: @25		Operators: MAK
Remarks:		Results: Electrode looks good.

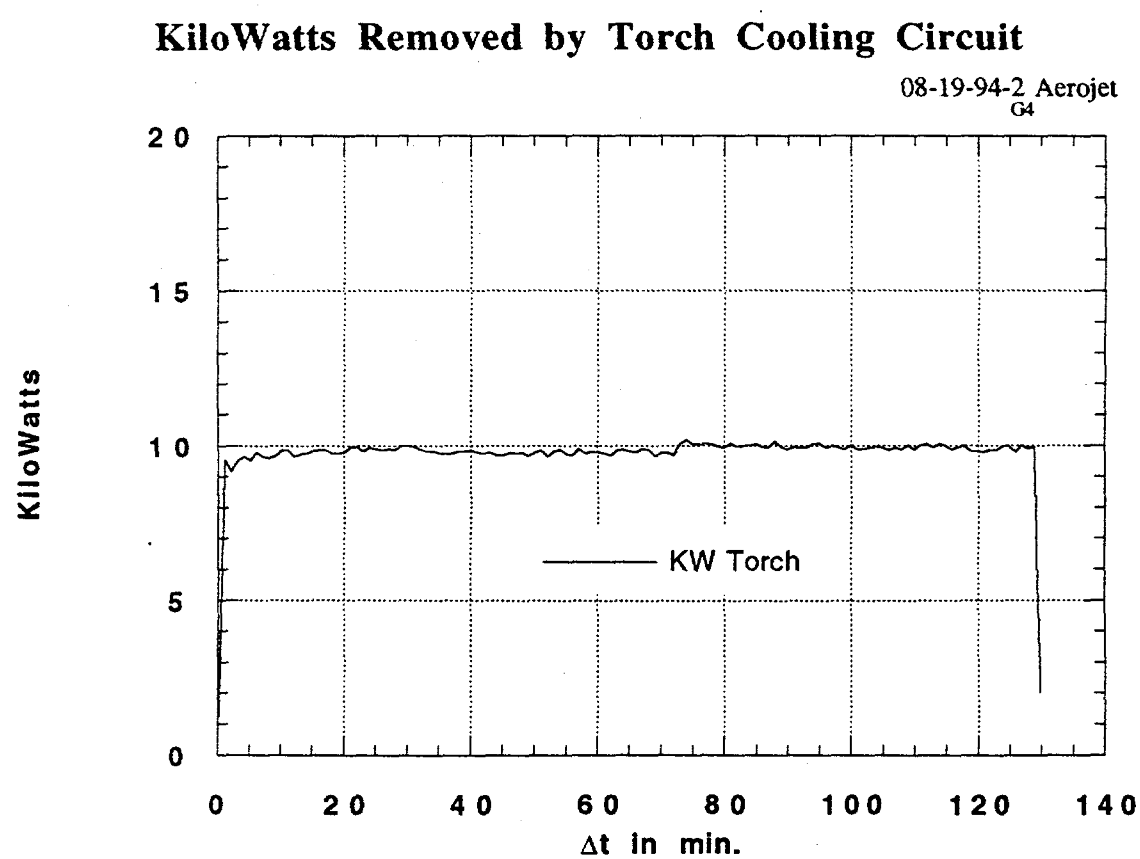
Torch Voltage and Current



KiloWatts Into Torch

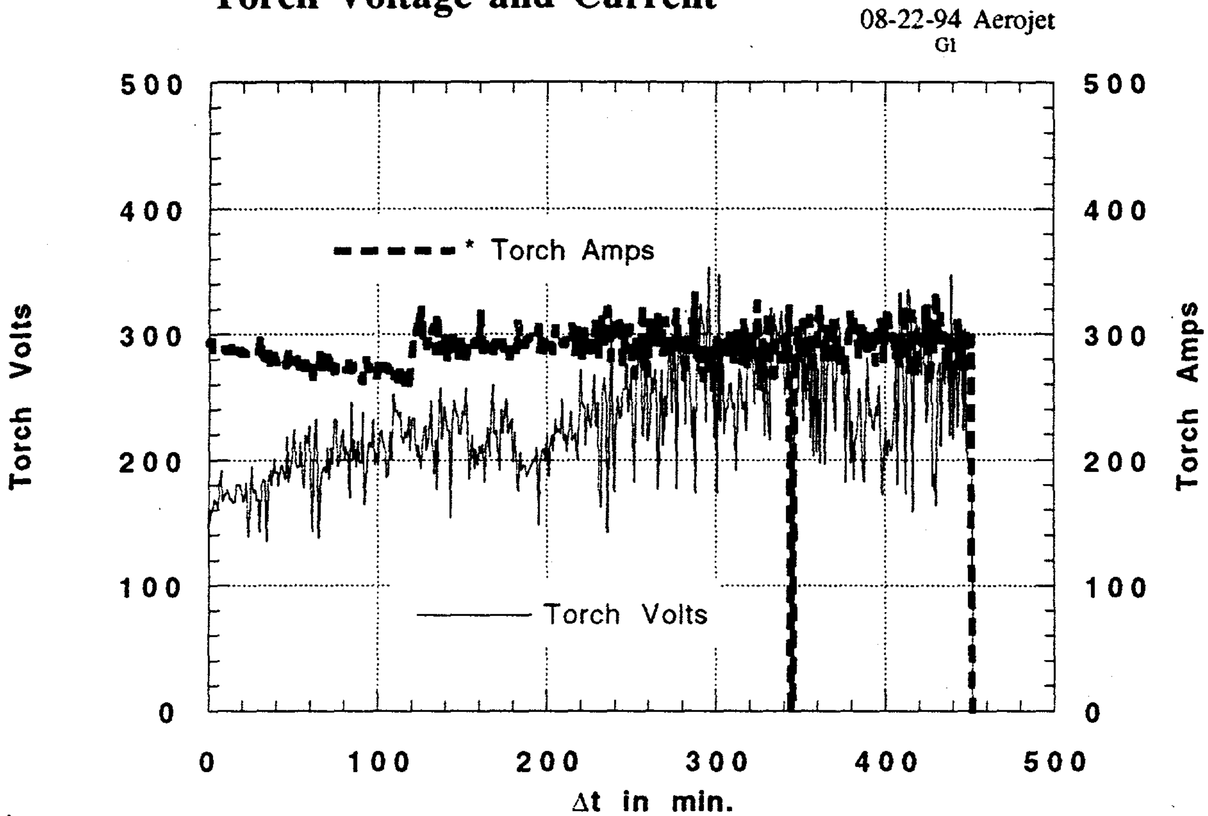



Torch Cooling Circuit Temperature
08-19-94-2 Aerojet
G3
120
110
100
90
80
70
° F
Torch
Closed Water S
0
20
40
60
80
100
120
140
Δt in min.

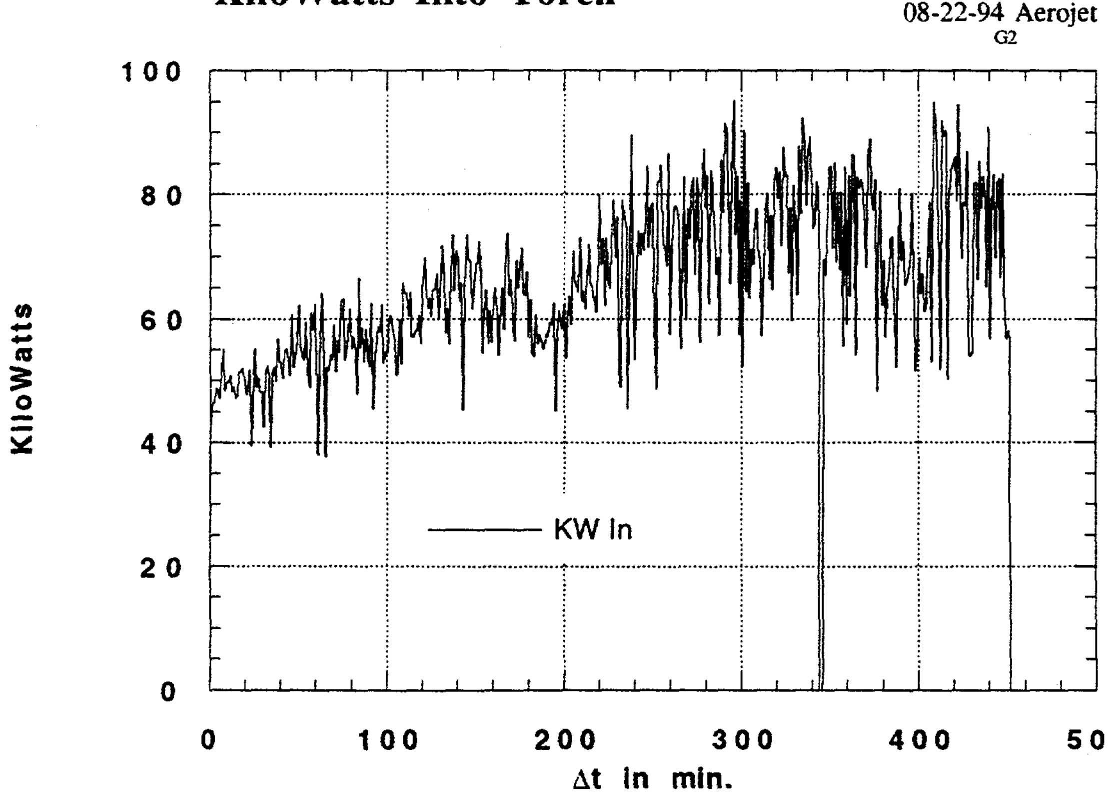

KiloWatts Removed by Torch Cooling Circuit
08-19-94-2 Aerojet
G4
20
15
10
5
0
KiloWatts
KW Torch
0
20
40
60
80
100
120
140
Δt in min.

1/4 Scale Data Summary		
	Run Date: 8/22/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: Slag bed		Video Tape #: Not used
Furnace Configuration: Rotary		Video Start:
Type of Feedstock: Not used		Supply Gas: N2-Ar
Estimated Electrode Hours: 27.75		Operators: MAK
Remarks: A full day of running again		Results:

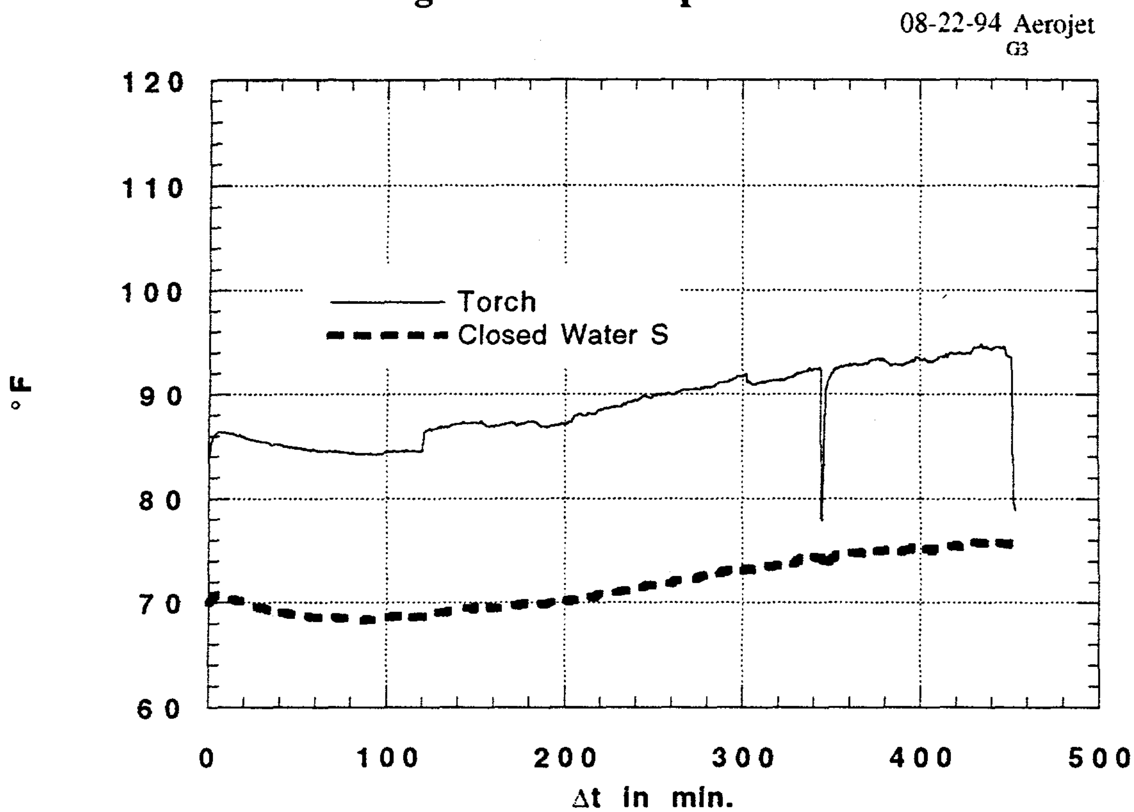
Torch Voltage and Current



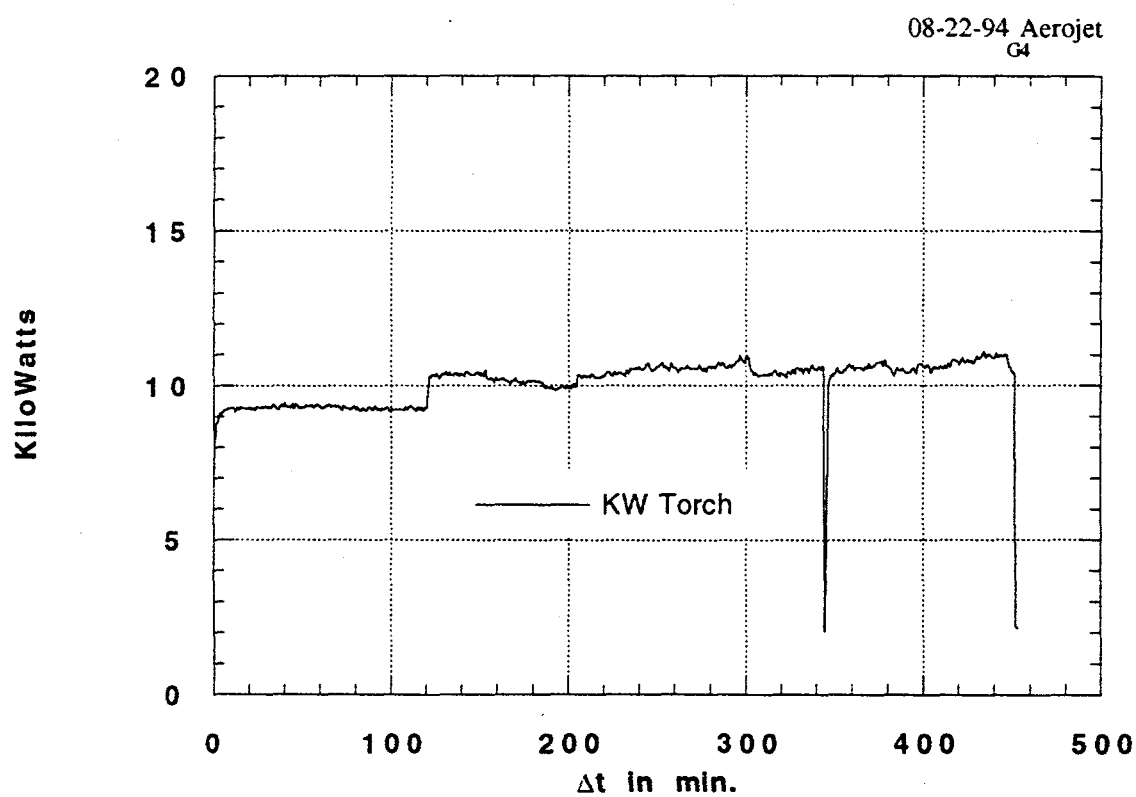
KiloWatts Into Torch



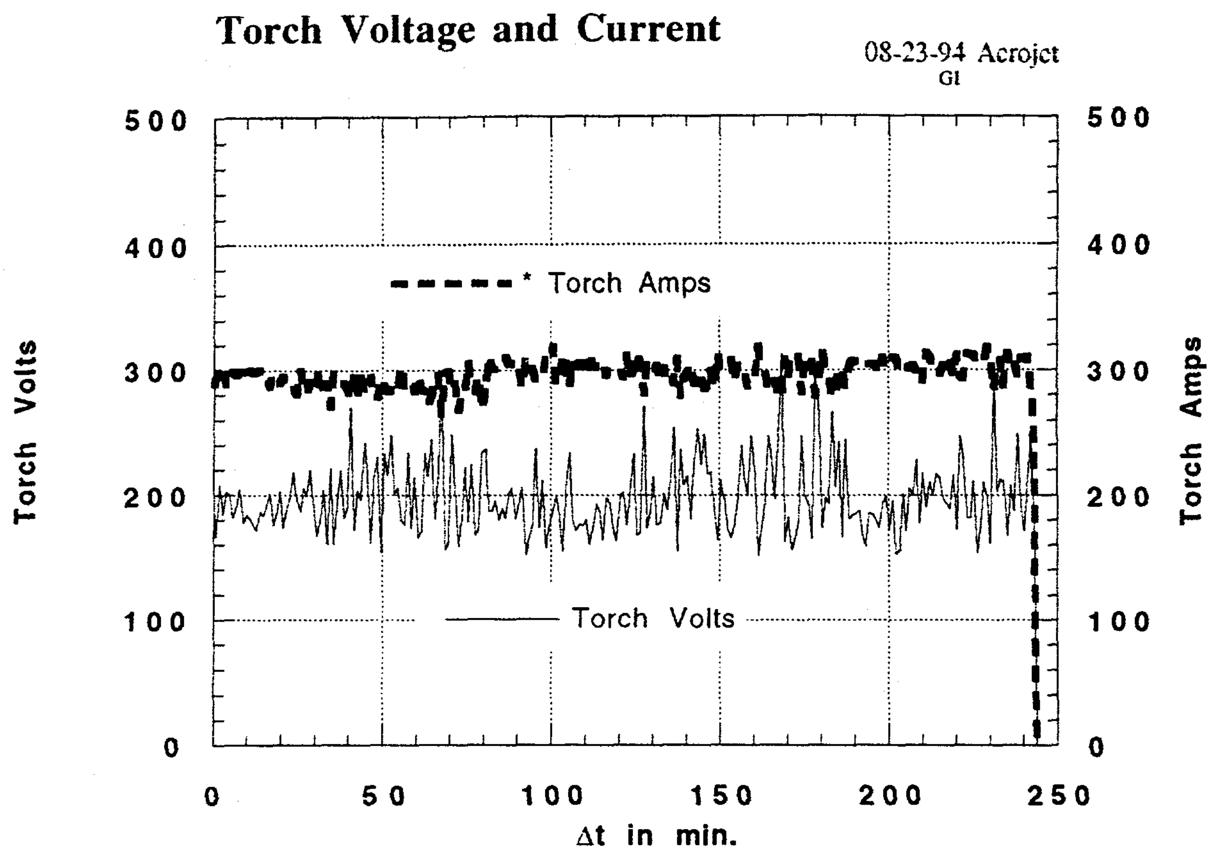
Torch Cooling Circuit Temperature

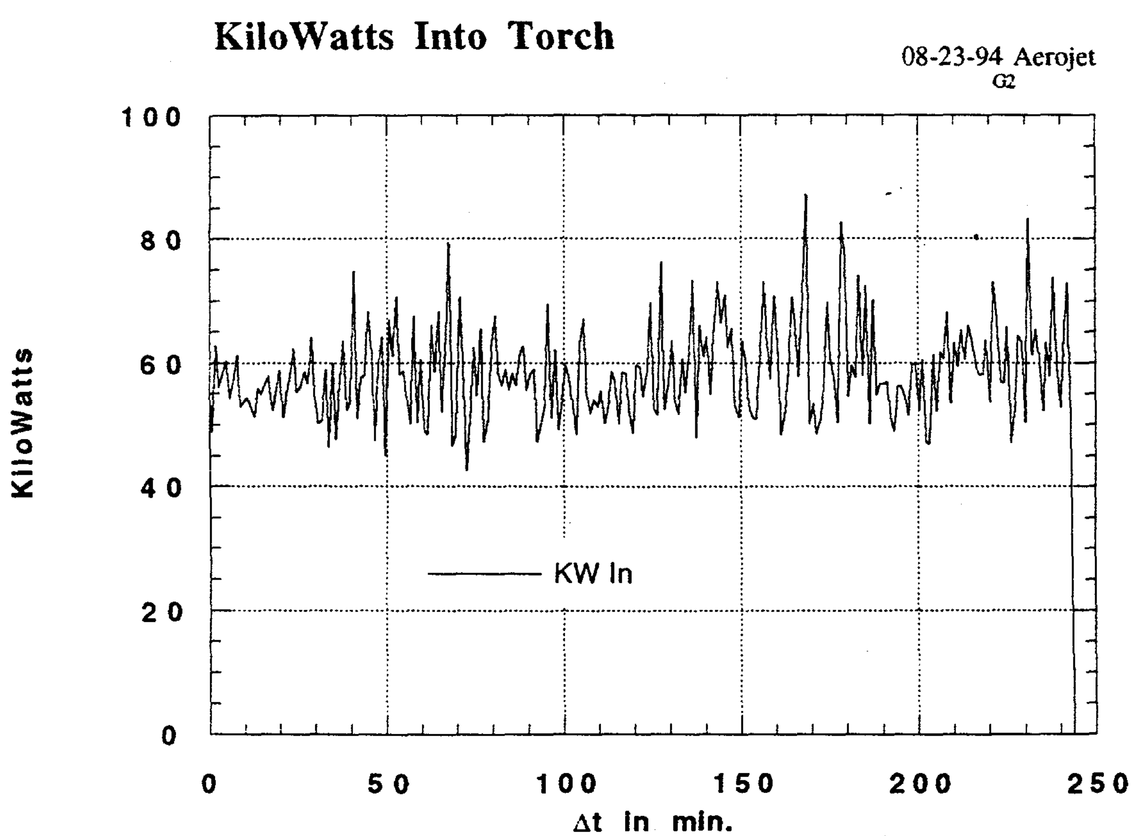


KiloWatts Removed by Torch Cooling Circuit

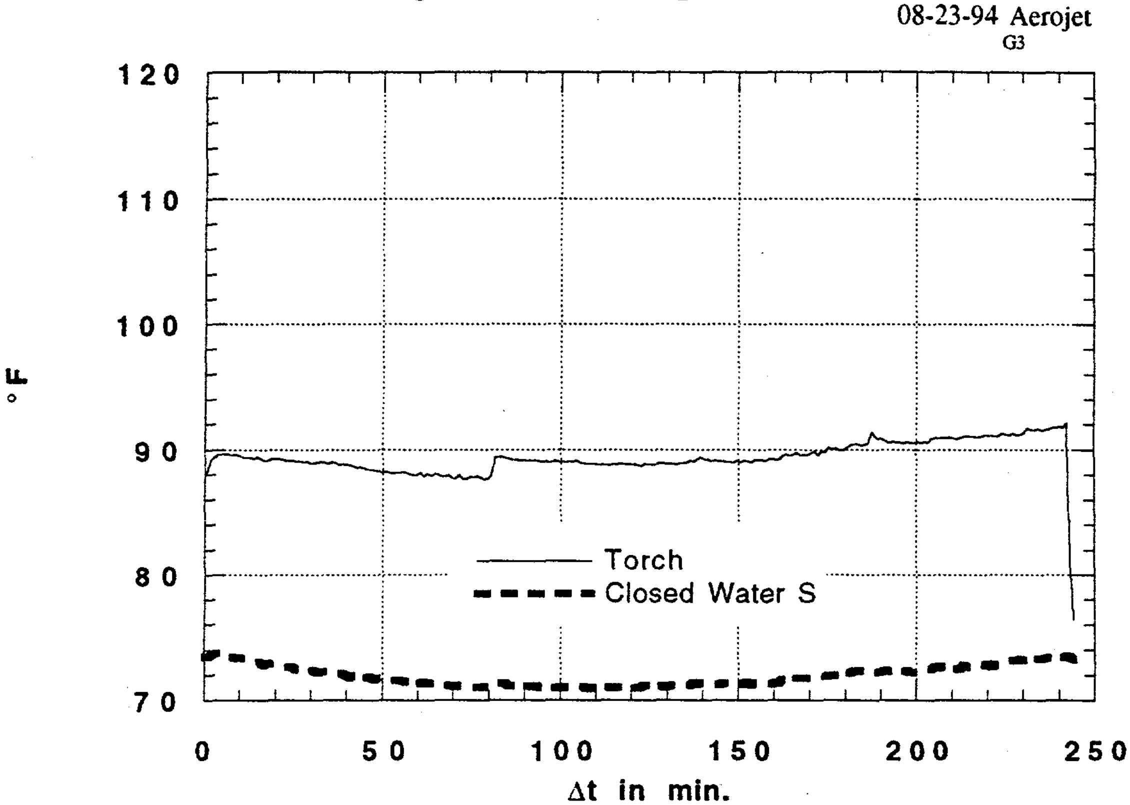


1/4 Scale Data Summary		
	Run Date: 8/23/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: Slag bed		Video Tape #: Not used
Furnace Configuration: Rotary		Video Start: N/A
Type of Feedstock: Not used		Supply Gas: N2-Ar
Estimated Electrode Hours: 35.9		Operators: MAK
Remarks: 4 hours left to complete 40 hour test		Results: 40 hour test completed with no electrode failure. Visible signs of wear at base of electrode.

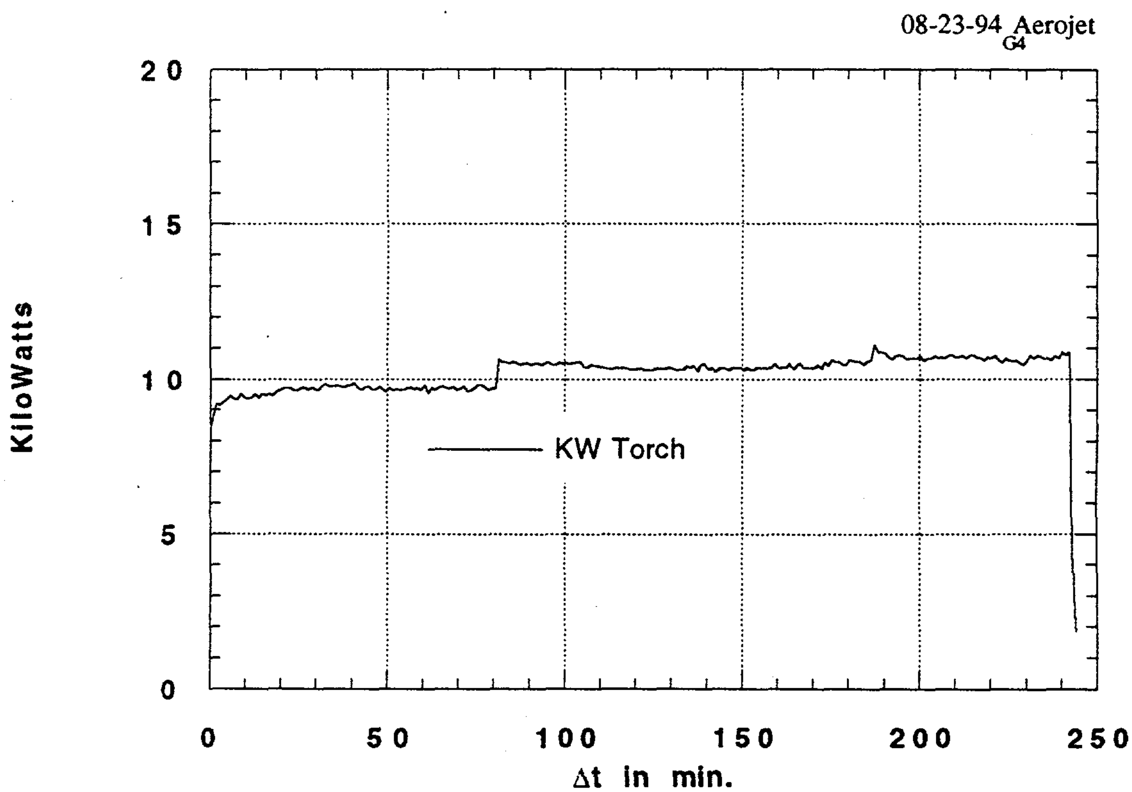

Torch Voltage and Current
08-23-94 Aerojet
G1
500
400
300
200
100
0
Torch Volts
Torch Amps
* Torch Amps
Torch Volts
0
50
100
150
200
250
Δt in min.


KiloWatts Into Torch
08-23-94 Aerojet
G2
100
80
60
40
20
0
KiloWatts
KW In
0
50
100
150
200
250
Δt in min.

Torch Cooling Circuit Temperature

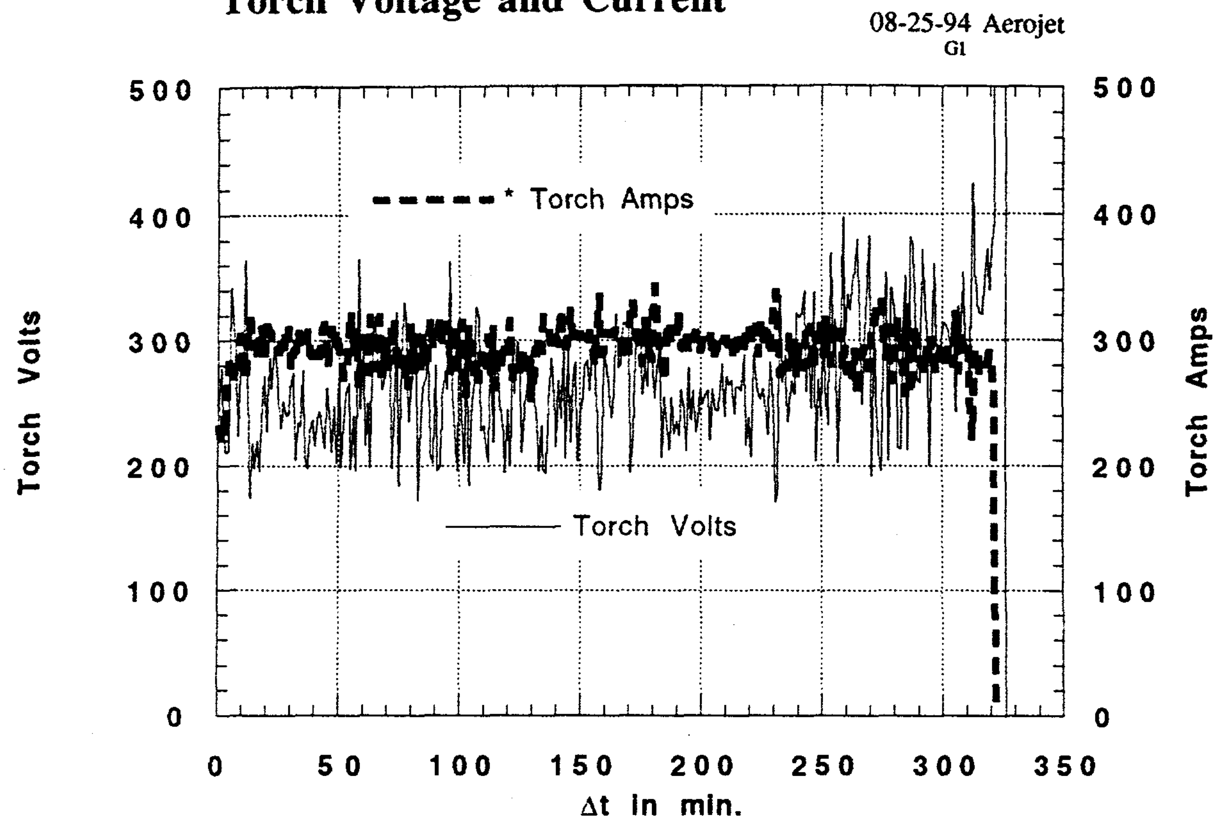


KiloWatts Removed by Torch Cooling Circuit

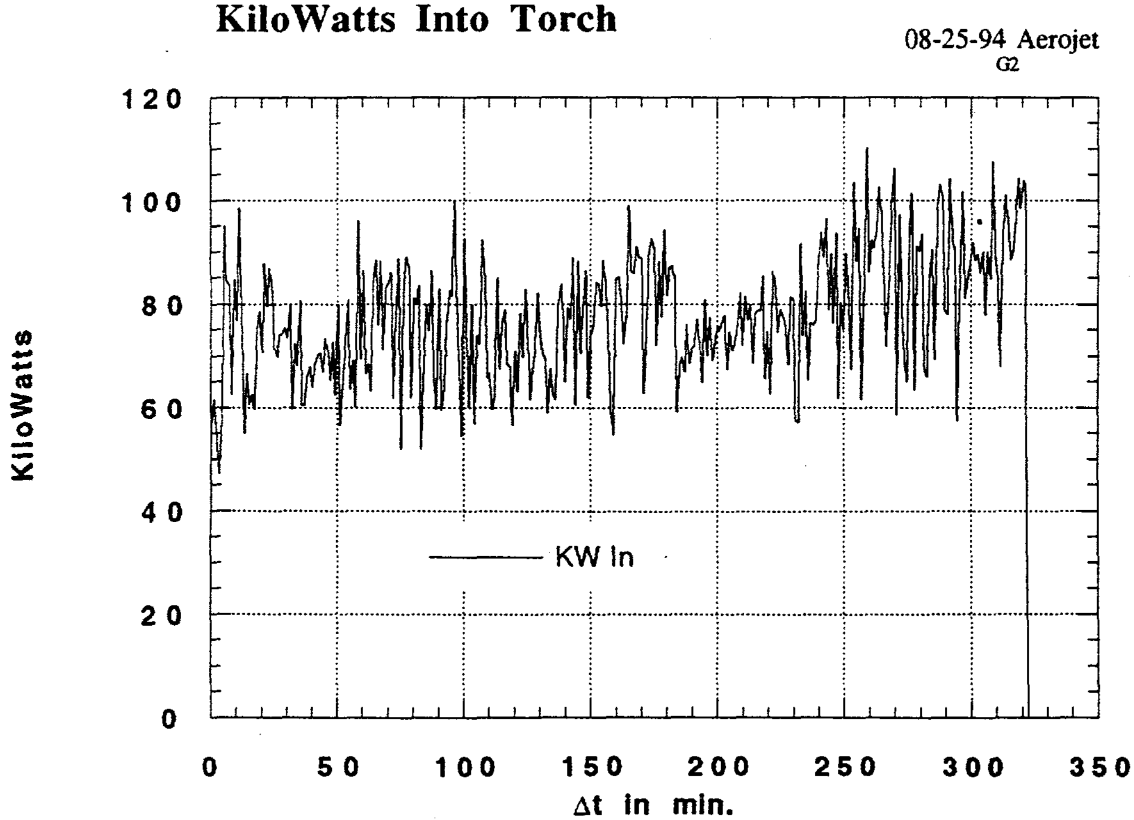


1/4 Scale Data Summary		
	Run Date: 8/25/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: Slag bed		Video Tape #: Not used
Furnace Configuration: Rotary		Video Start: N/A
Type of Feedstock: Not used		Supply Gas: N2-Ar
Estimated Electrode Hours: 0		Operators: MAK
Remarks: Retech electrode, using Nitrogen and Argon torch gas. 1.26 scfm N2 & 1.0 scfm Ar.		Results: The electrode failed by water leak after 5 1/2 hours.

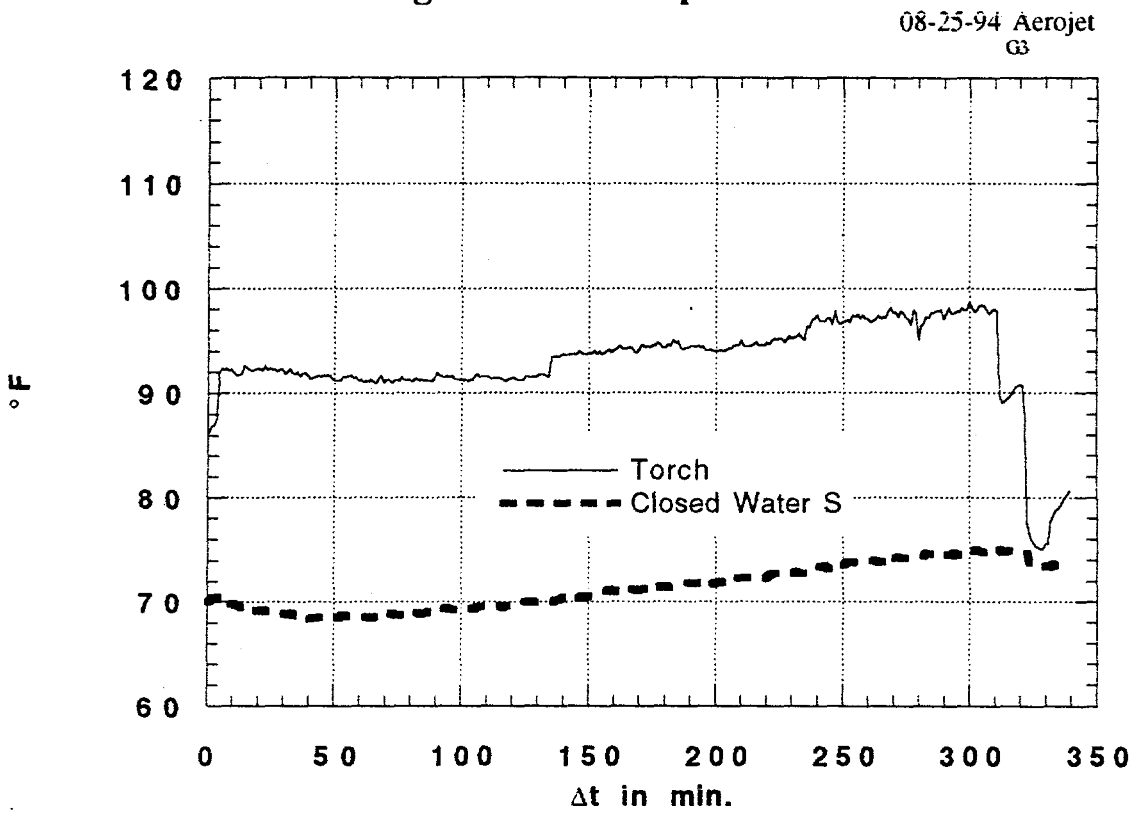
Torch Voltage and Current



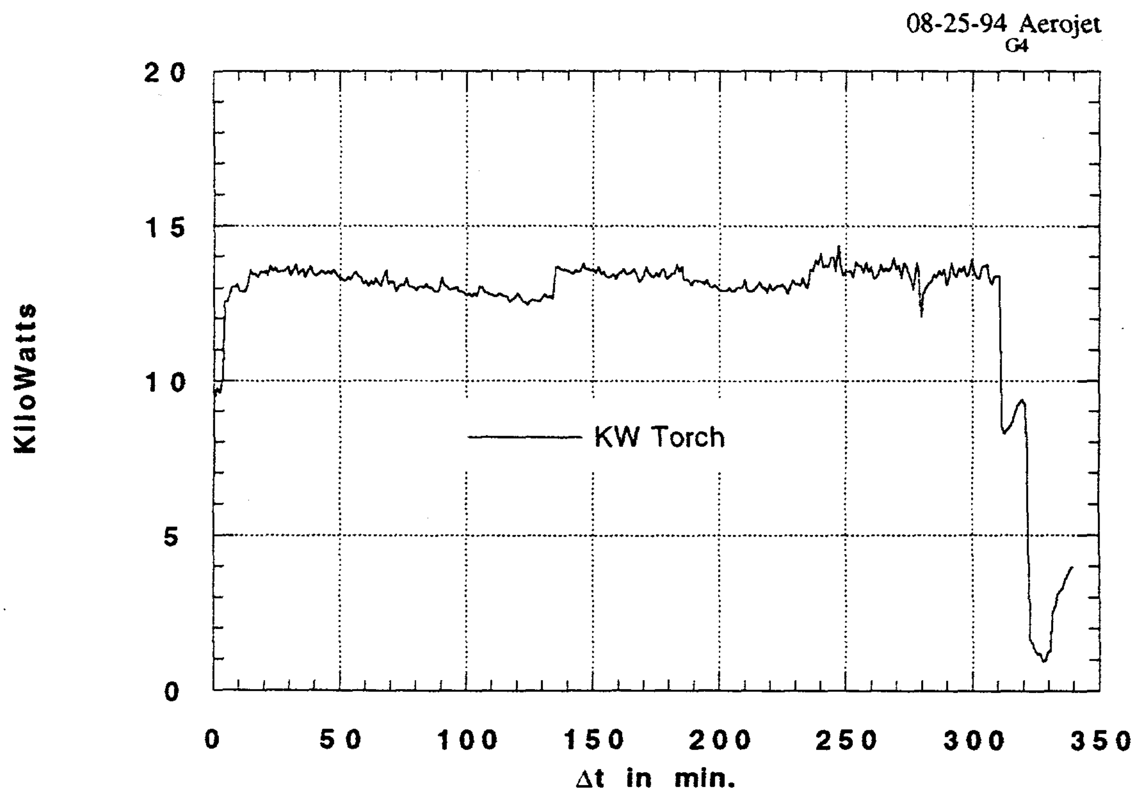
KiloWatts Into Torch



Torch Cooling Circuit Temperature

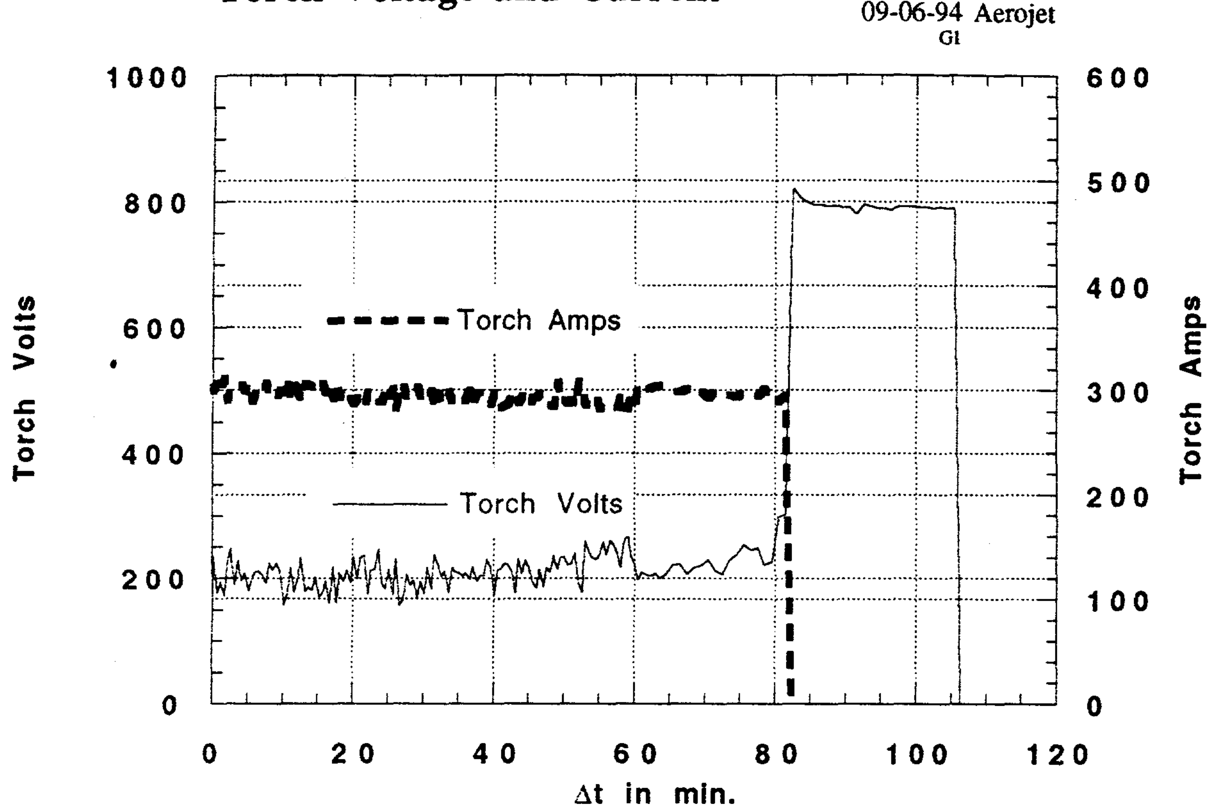


KiloWatts Removed by Torch Cooling Circuit

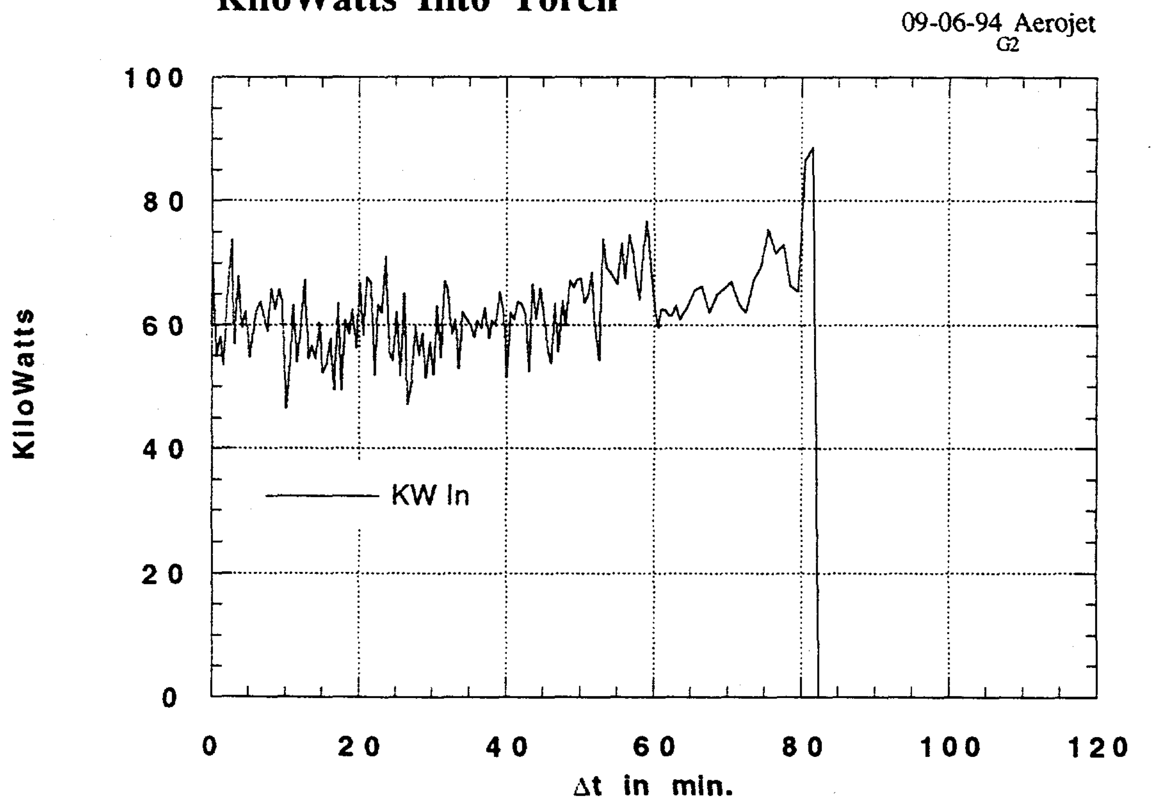


1/4 Scale Data Summary		
	Run Date: 9/6/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: slag bed/soda ash		Video Tape #: N/A
Furnace Configuration: rotating crucible		Video Start: N/A
Type of Feedstock: not applicable (N/A)		Supply Gas: N/Ar
Estimated Electrode Hours: 0		Operators: MAK
Remarks: Retech electrode, attempt to run at 59 kW throughout run until electrode failure with 1.2 scfm Nitrogen and 1 scfm Argon.		Results: Electrode failed after about 80 min.

Torch Voltage and Current

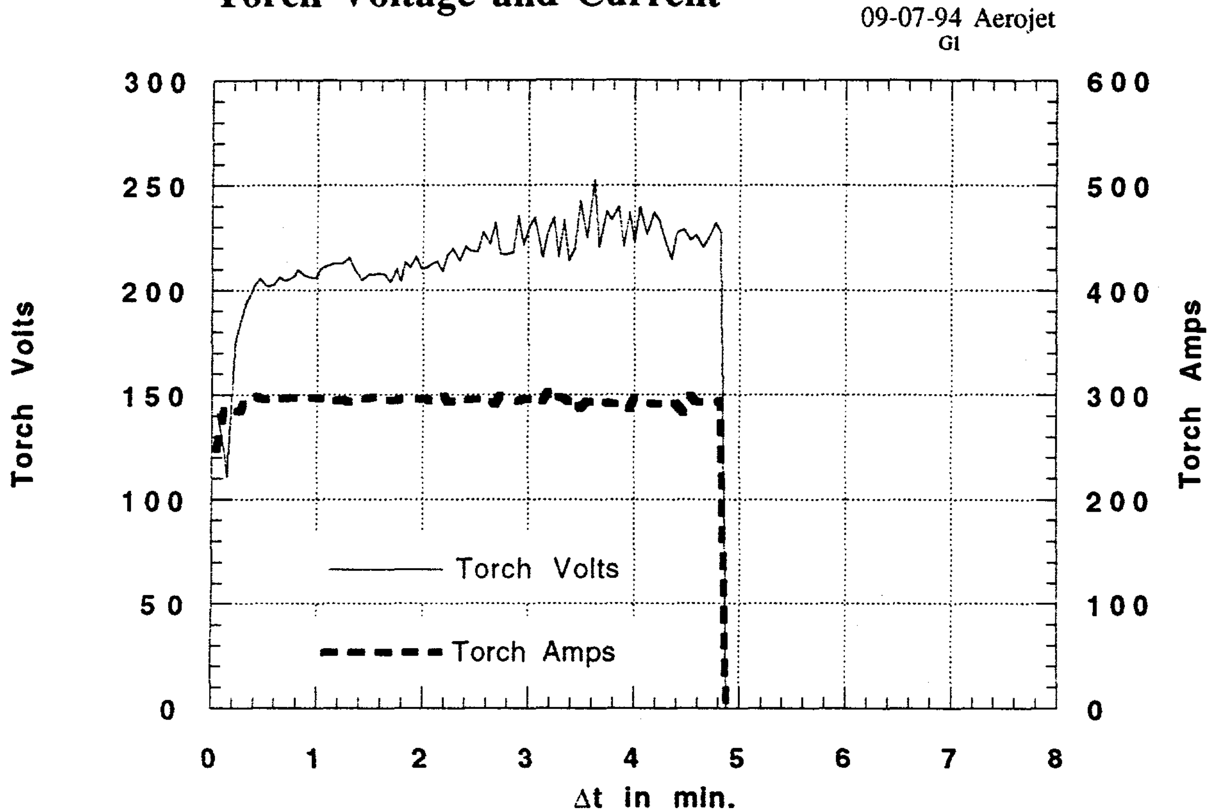


KiloWatts Into Torch

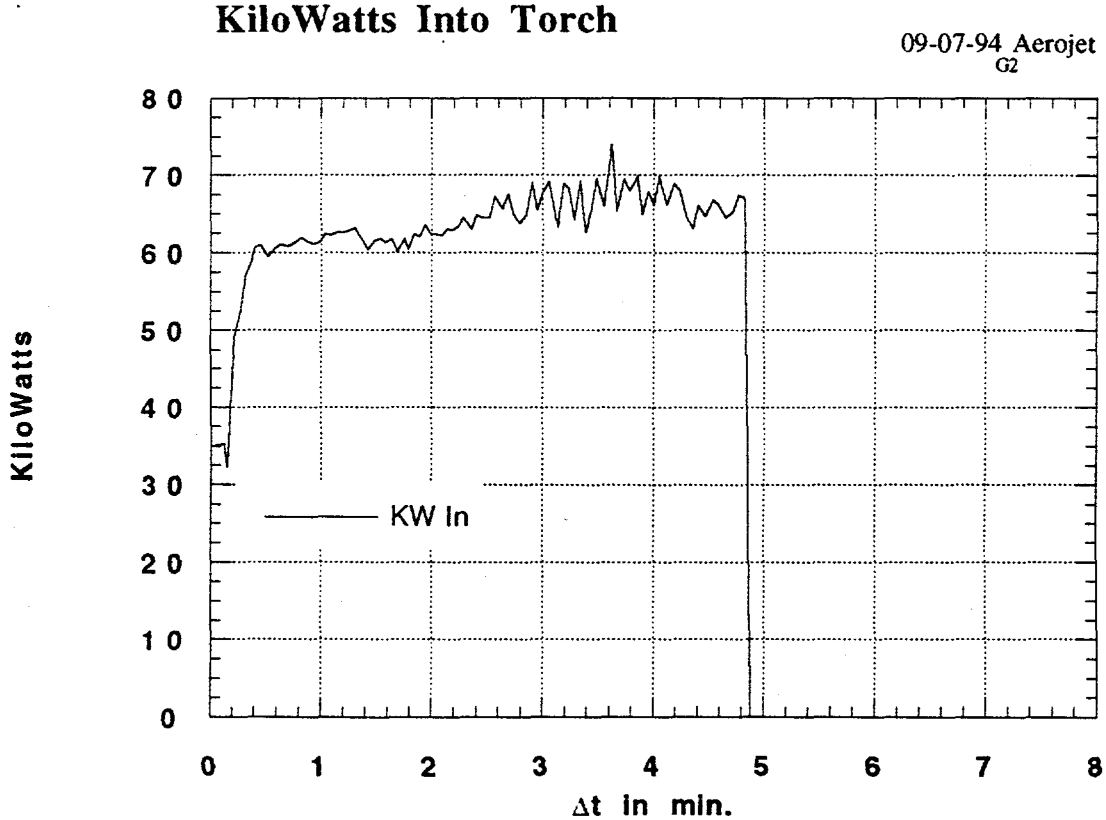


1/4 Scale Data Summary		
	Run Date: 9/7/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: slag bed		Video Tape #: N/A
Furnace Configuration: rotating crucible		Video Start: N/A
Type of Feedstock: not applicable (N/A)		Supply Gas: N
Estimated Electrode Hours: 30		Operators: PW, MAK
Remarks: Aerojet electrode, using 1.2 scfm Nitrogen		Results:

Torch Voltage and Current

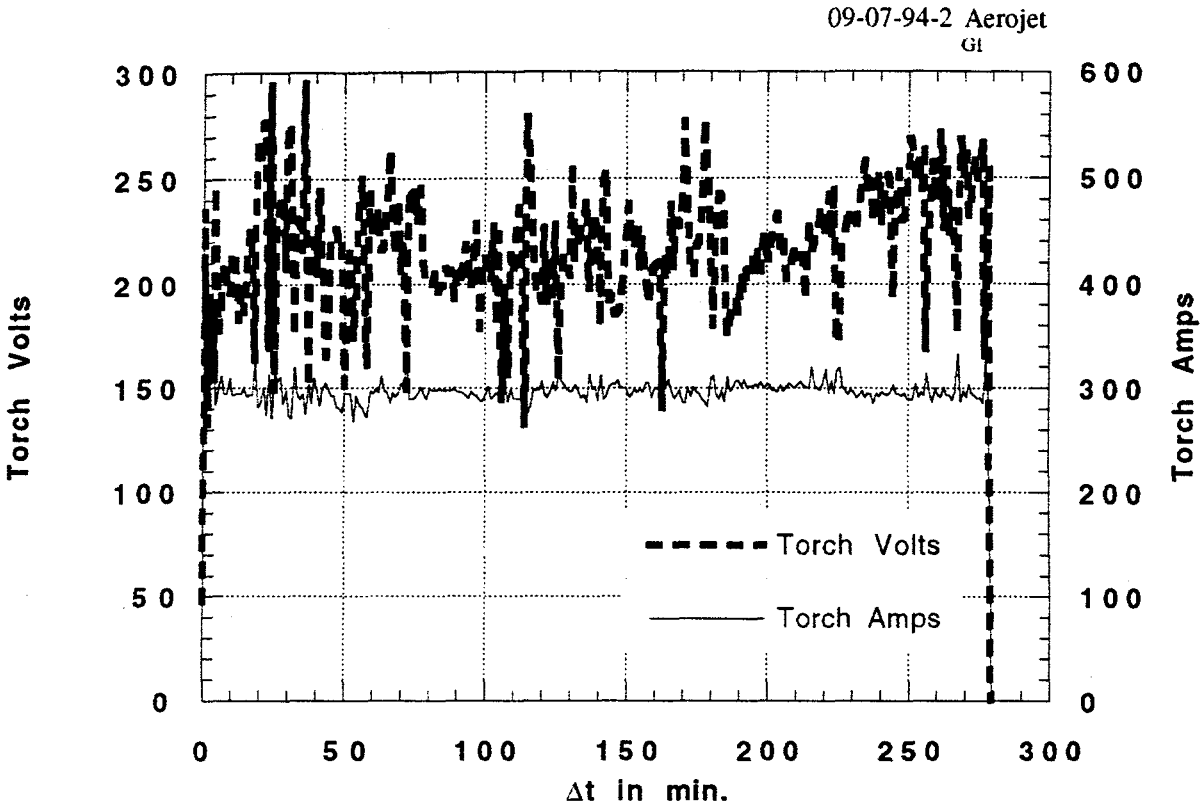


KiloWatts Into Torch

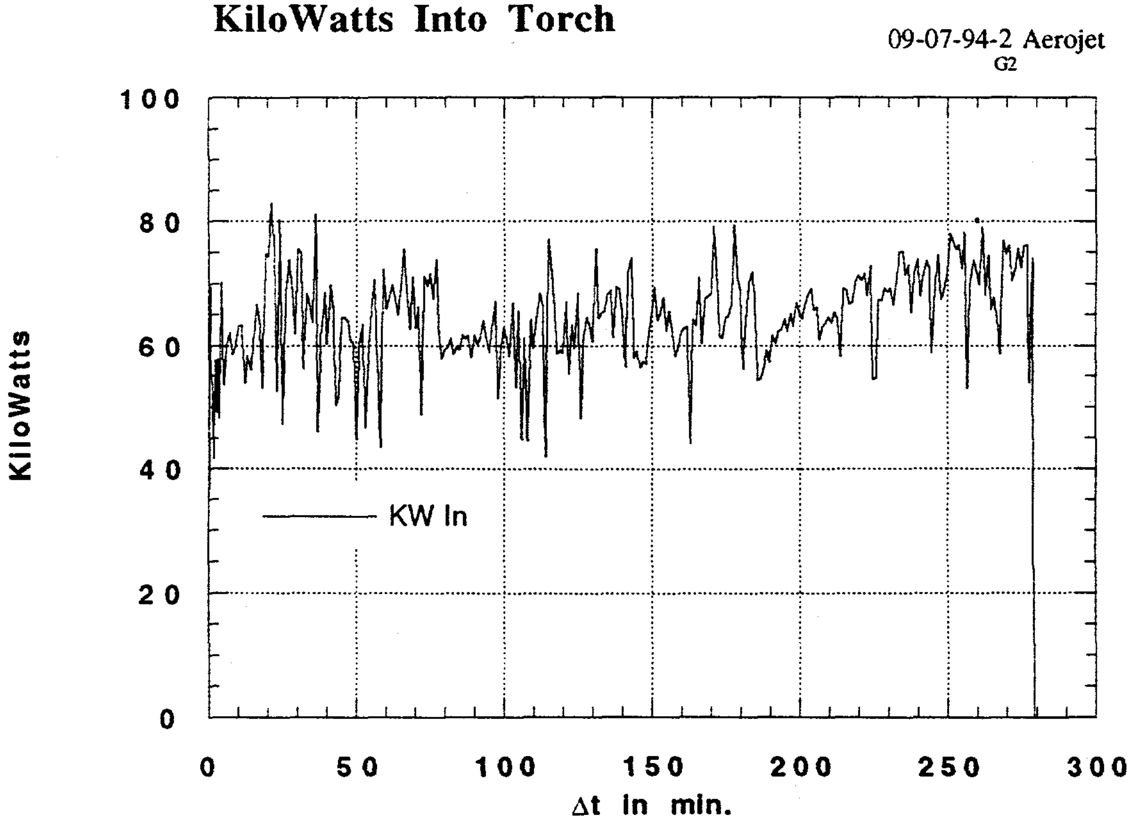


1/4 Scale Data Summary		
	Run Date: 9/7/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: slag bed		Video Tape #: N/A
Furnace Configuration: rotating crucible		Video Start: N/A
Type of Feedstock: not applicable (N/A)		Supply Gas: N
Estimated Electrode Hours: 30		Operators: PW, MAK
Remarks: Aerojet electrode, using 1.2 scfm Nitrogen and 1 scfm Argon.		Results: Electrode still in good shape.

Torch Voltage & Current



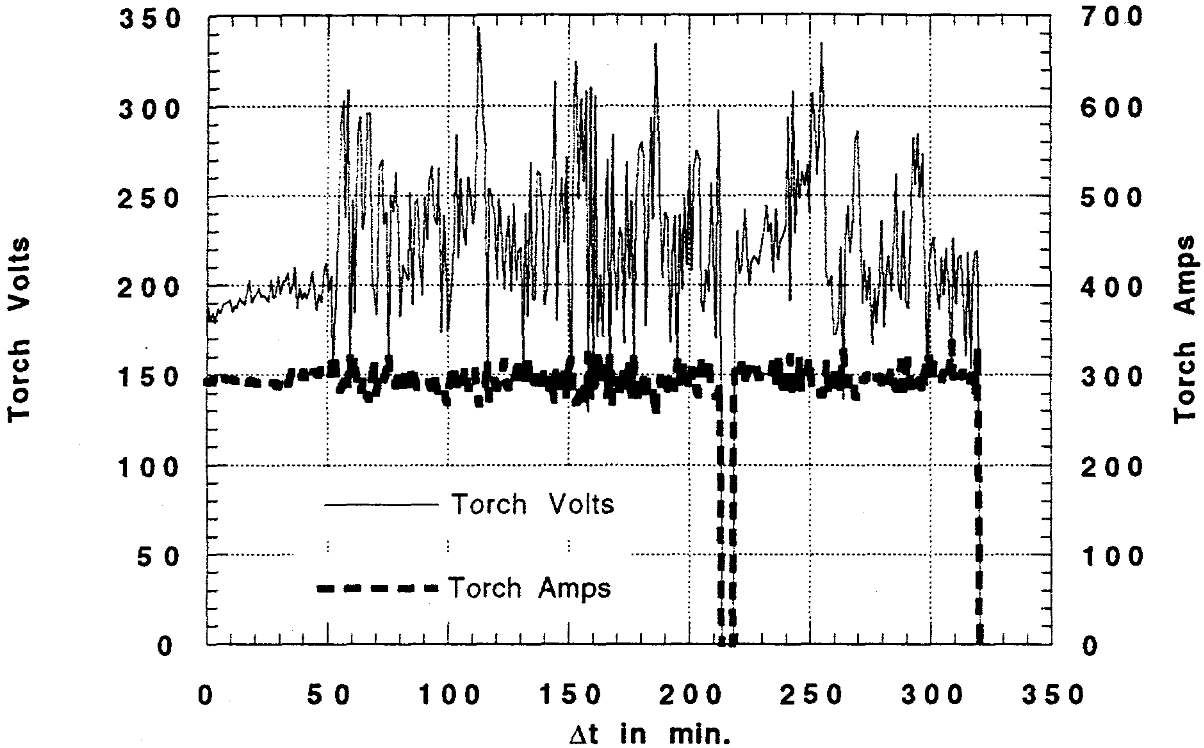
KiloWatts Into Torch



1/4 Scale Data Summary		
	Run Date: 9/8/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: slag bed		Video Tape #: N/A
Furnace Configuration: rotating crucible		Video Start: N/A
Type of Feedstock: not applicable (N/A)		Supply Gas: N
Estimated Electrode Hours: 46		Operators: PW, MAK
Remarks: Aerojet electrode, using 1.2 scfm Nitrogen and 1 scfm Argon.		Results: 10 additional hours now on electrode.

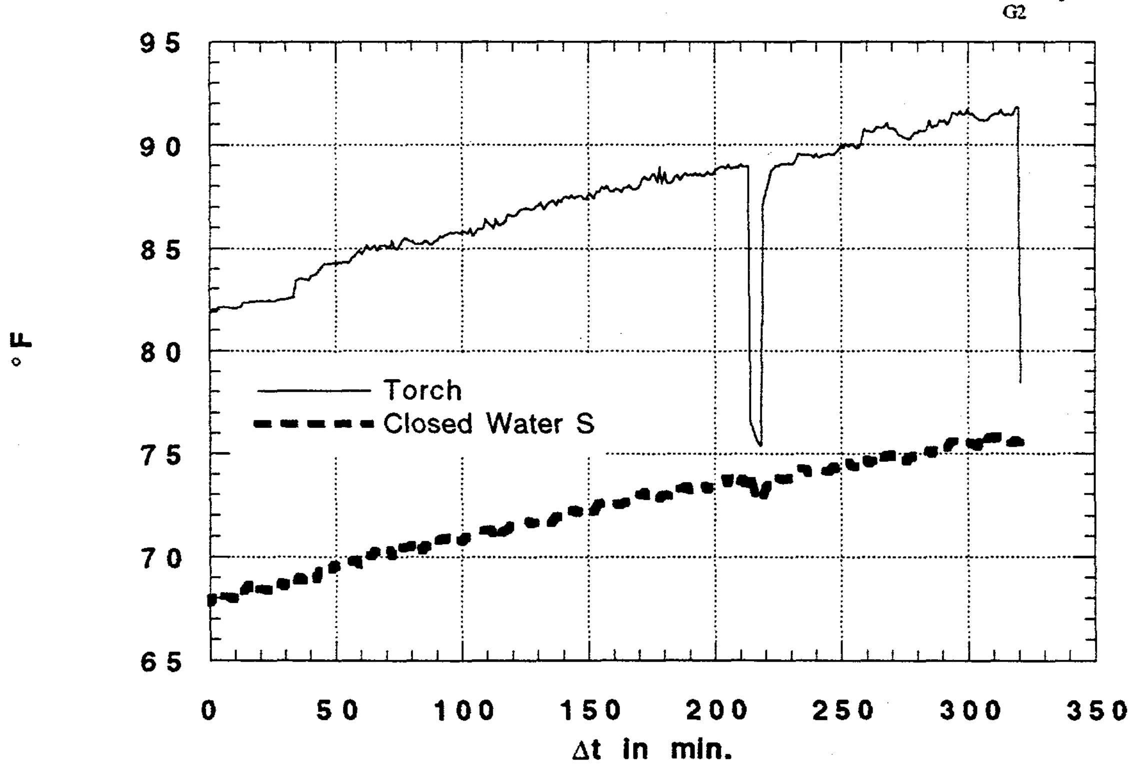
Torch Voltage and Current

09-08-94 Aerojet
G1

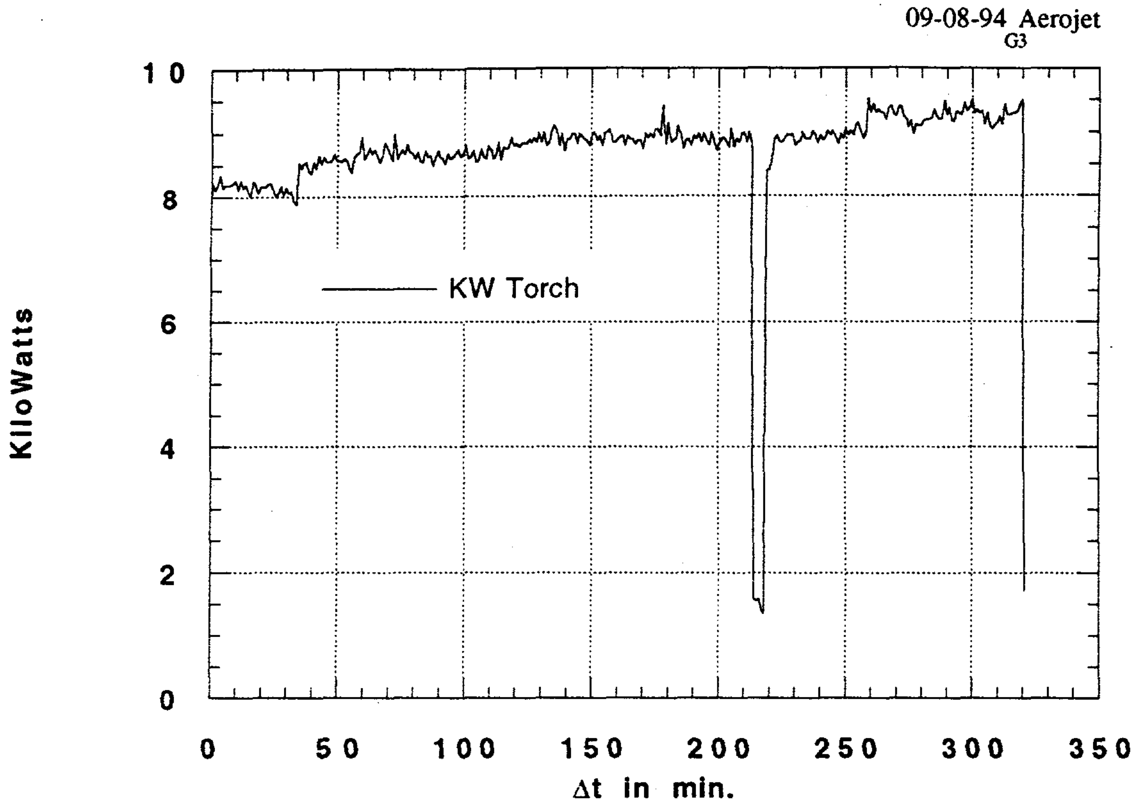


Torch Cooling Circuit Temperature

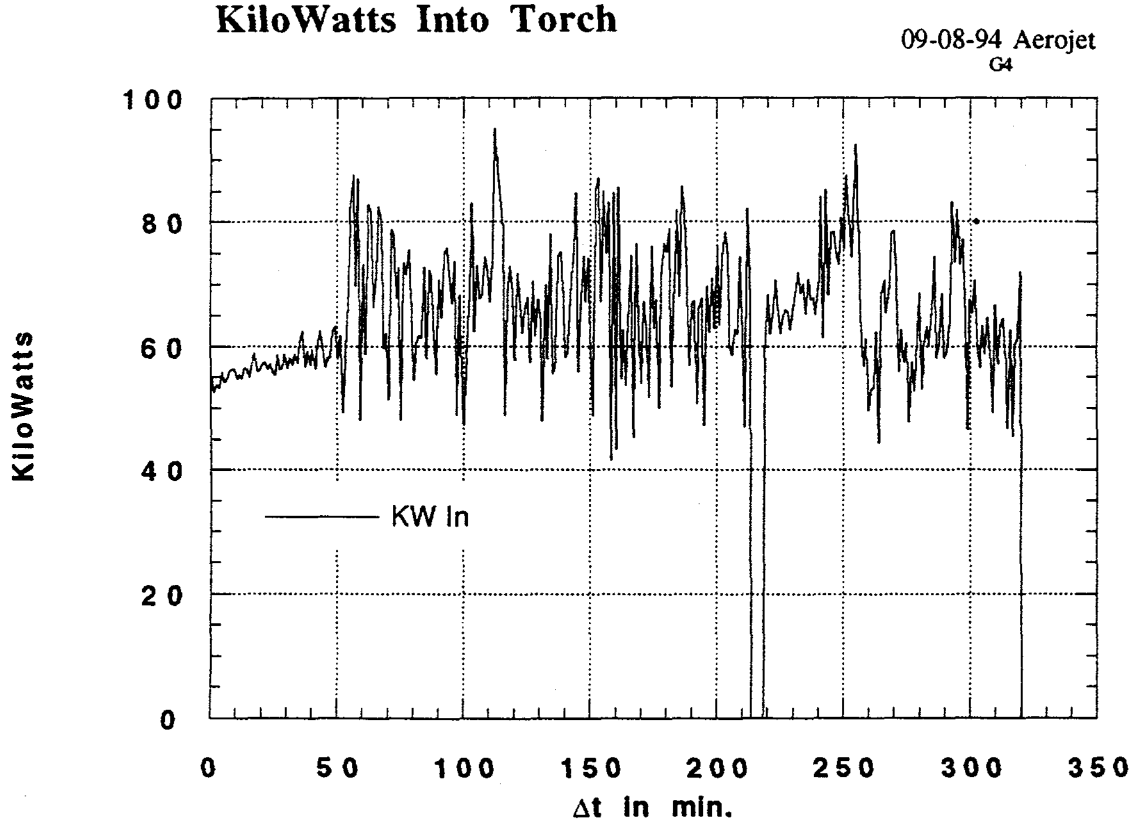
09-08-94 Aerojet
G2



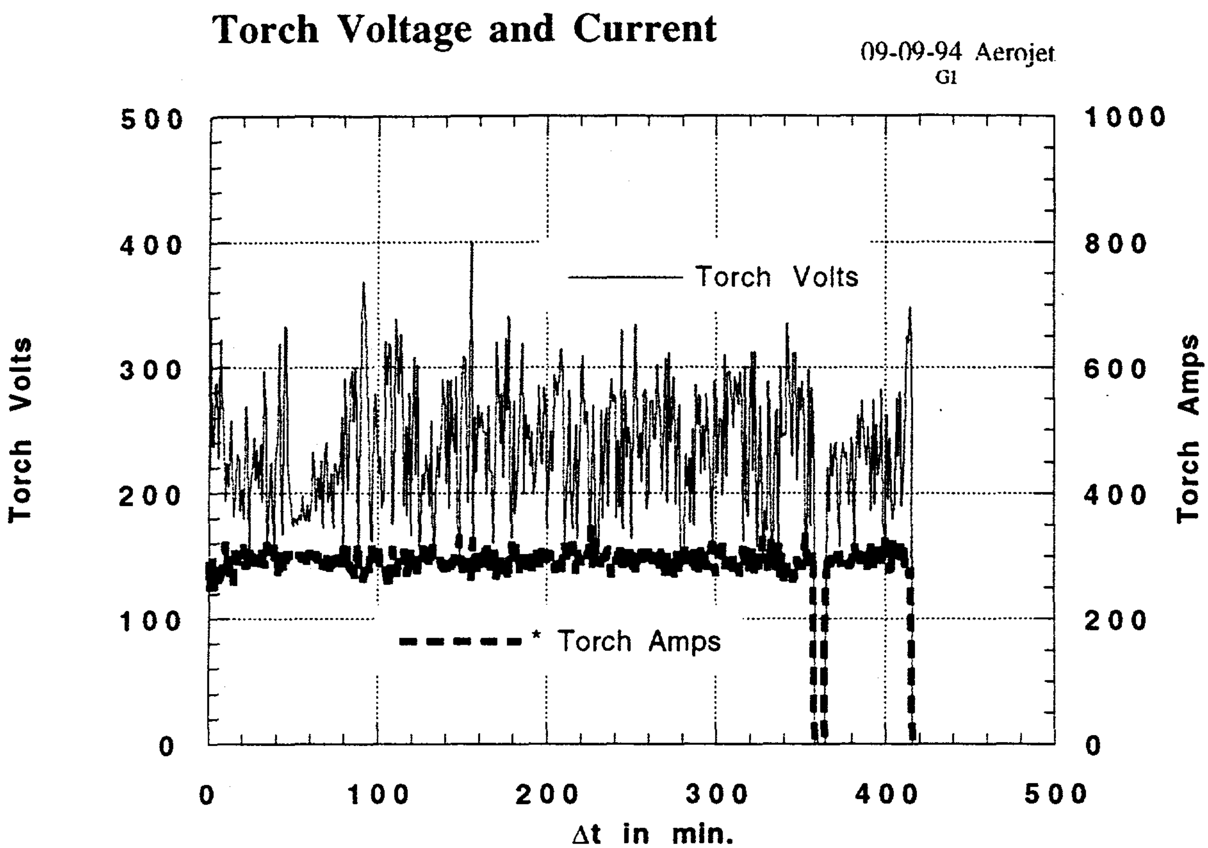
KiloWatts Removed by Torch Cooling Circuit

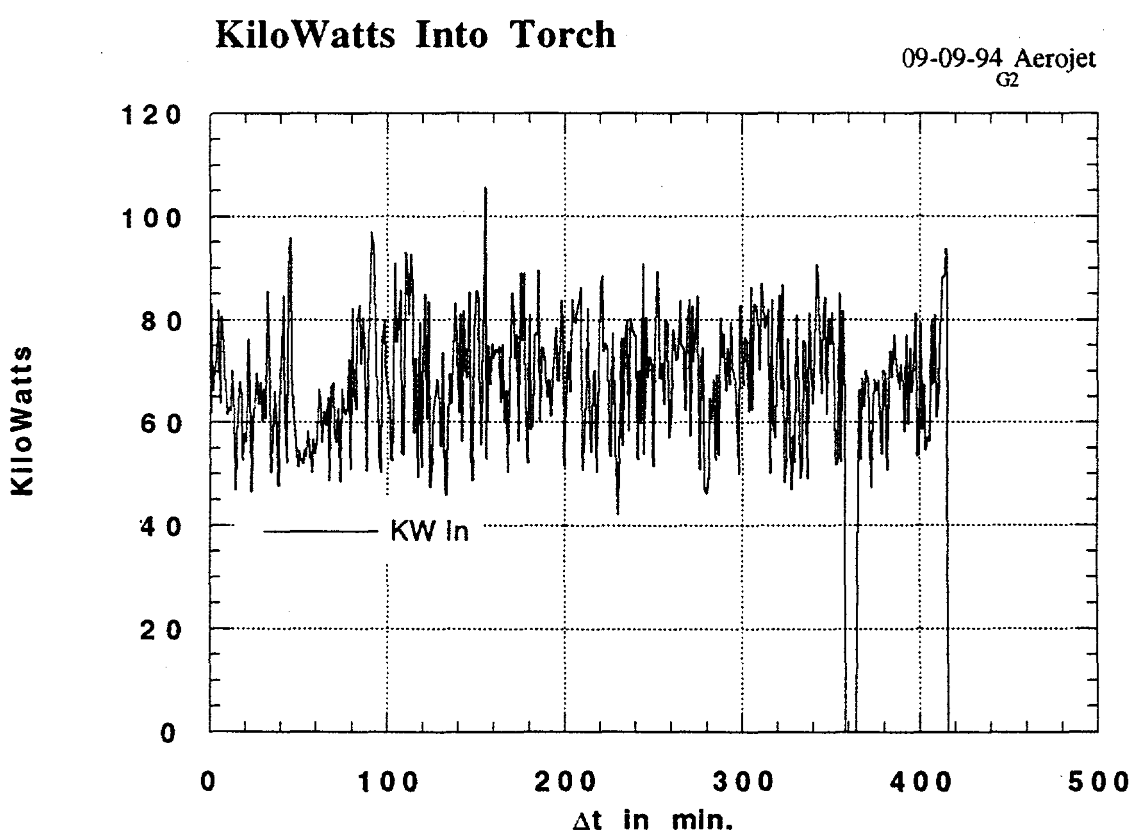


KiloWatts Into Torch

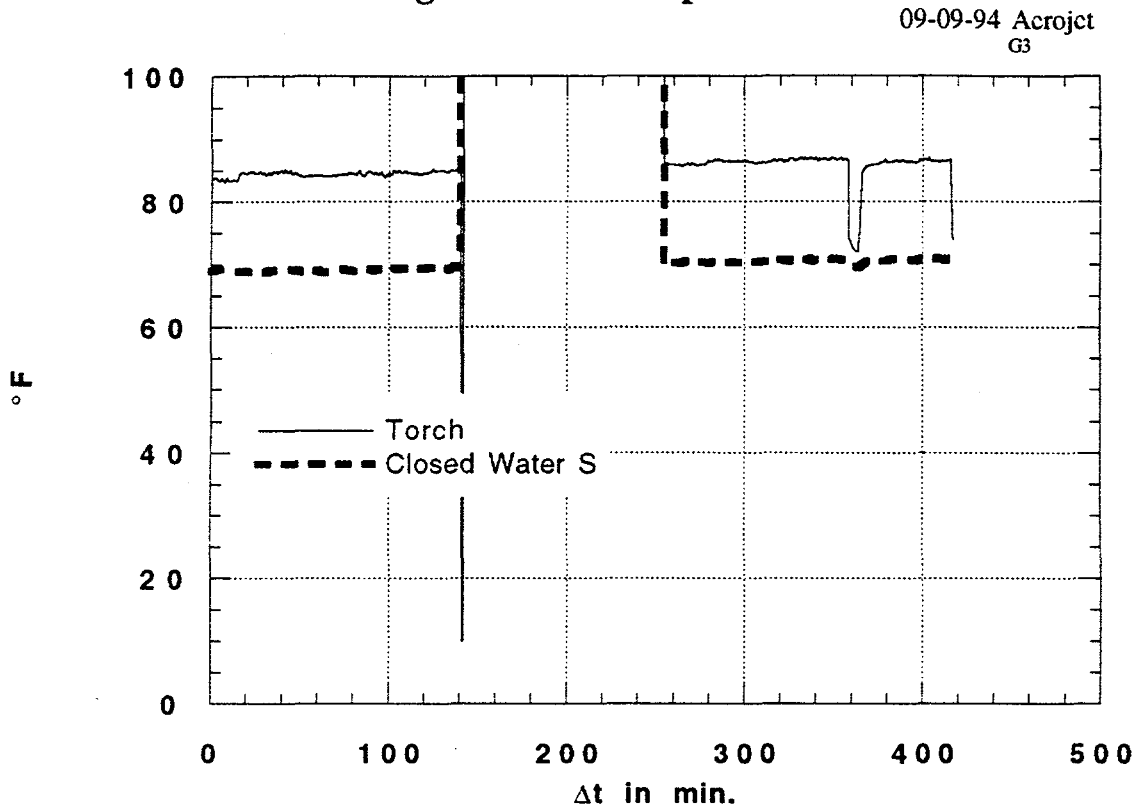


1/4 Scale Data Summary		
	Run Date: 9/9/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: Previous slag bed		Video Tape #: Not used
Furnace Configuration: rotary		Video Start:
Type of Feedstock: none		Supply Gas: N2 & Ar
Estimated Electrode Hours: 50		Operators: MAK
Remarks: More testing all day.		Results: Must run for 2 hrs and 13 minutes on 9/12 to complete 20 hour test (60 total hours on electrode).

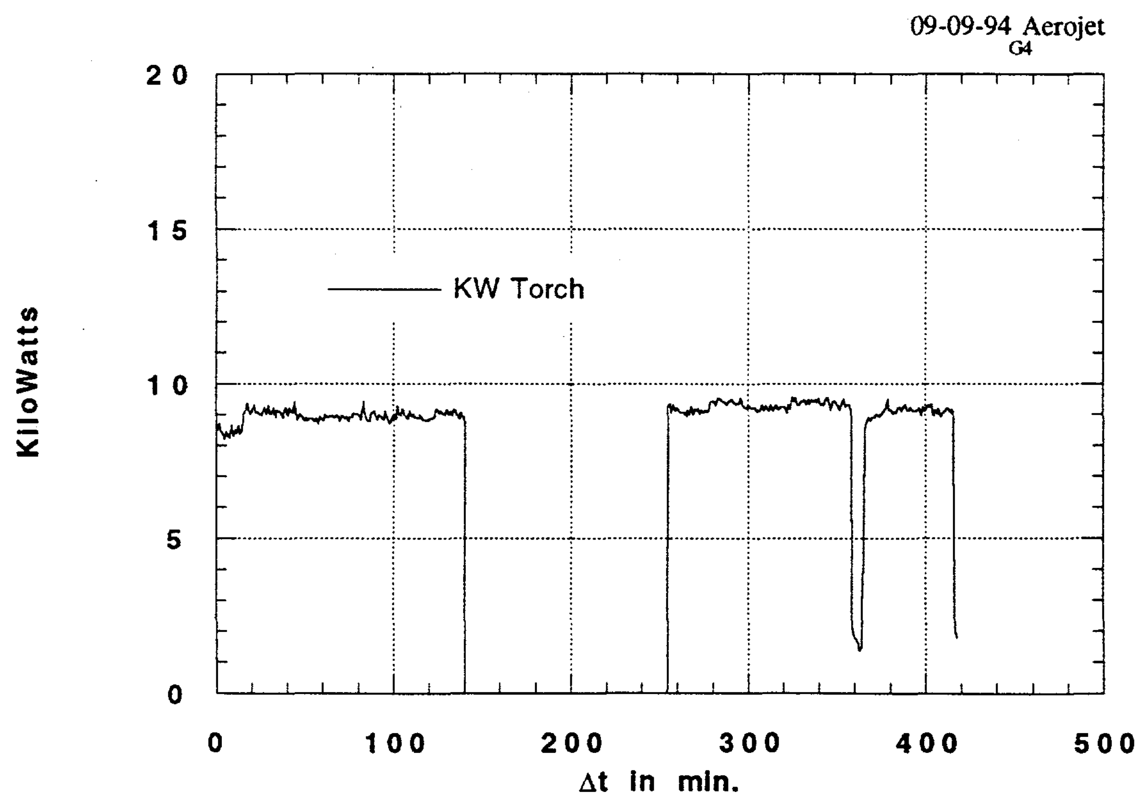

Torch Voltage and Current
09-09-94 Aerojet
G1
Torch Volts
Torch Amps
Torch Volts
* Torch Amps
Δt in min.
0
100
200
300
400
500
1000
800
600
400
200


KiloWatts Into Torch
09-09-94 Aerojet
G2
KiloWatts
KW In
Δt in min.
0
20
40
60
80
100
120
200
300
400
500

Torch Cooling Circuit Temperature

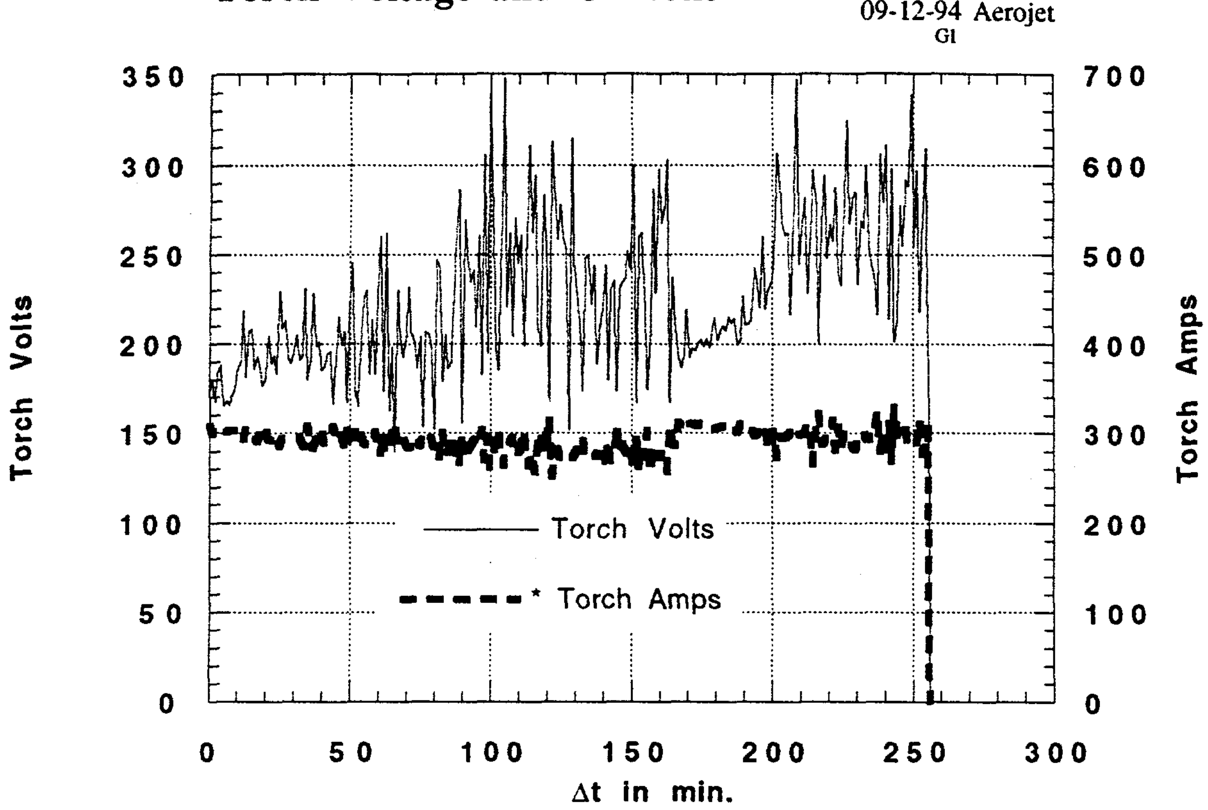


KiloWatts Removed by Torch Cooling Circuit

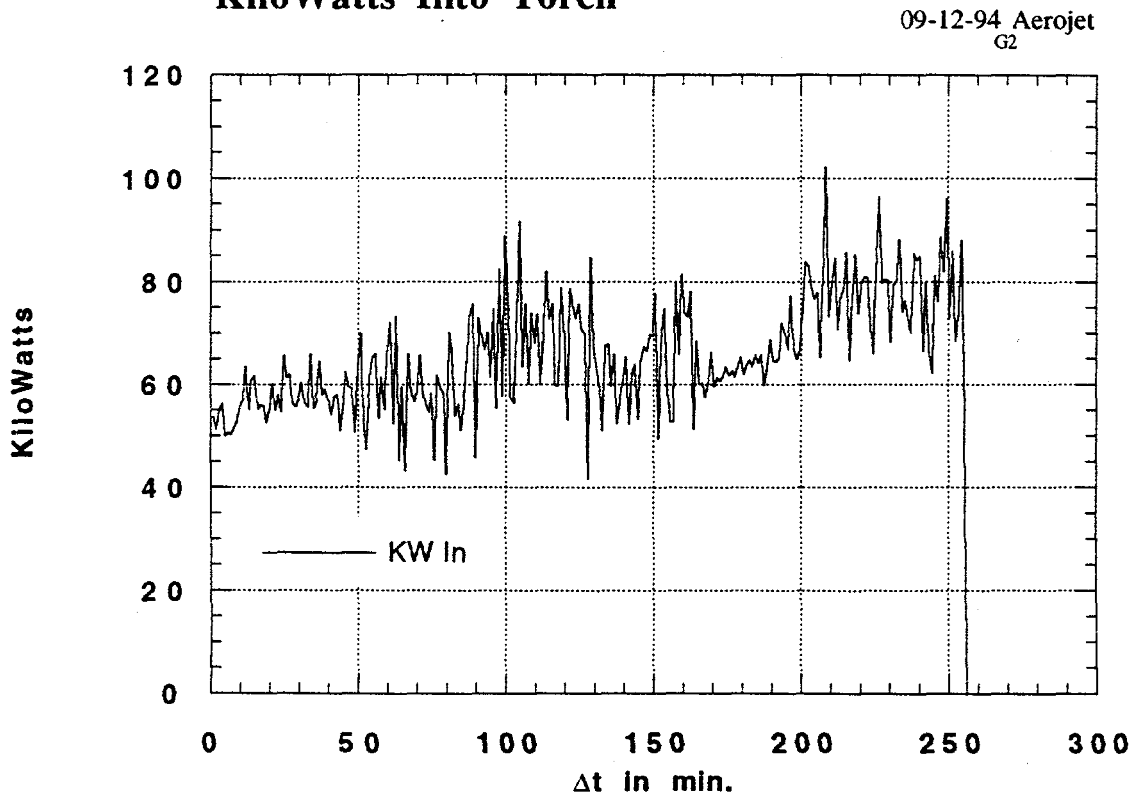


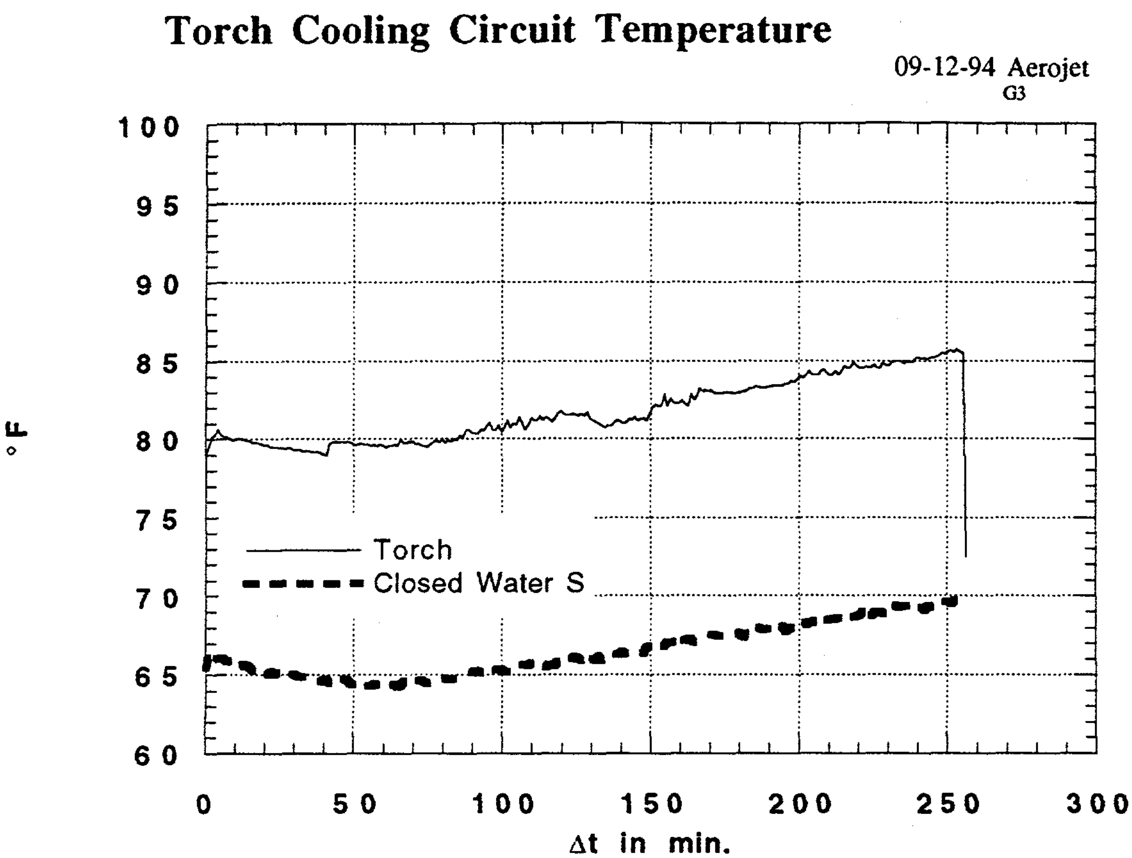
1/4 Scale Data Summary		
	Run Date: 9/8/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: slag bed		Video Tape #: N/A
Furnace Configuration: rotating crucible		Video Start: N/A
Type of Feedstock: not applicable (N/A)		Supply Gas: N
Estimated Electrode Hours: 58		Operators: PW, MAK
Remarks: Aerojet electrode, using 1.2 scfm Nitrogen and 1 scfm Argon.		Results: Morning run. Will start up after lunch.

Torch Voltage and Current

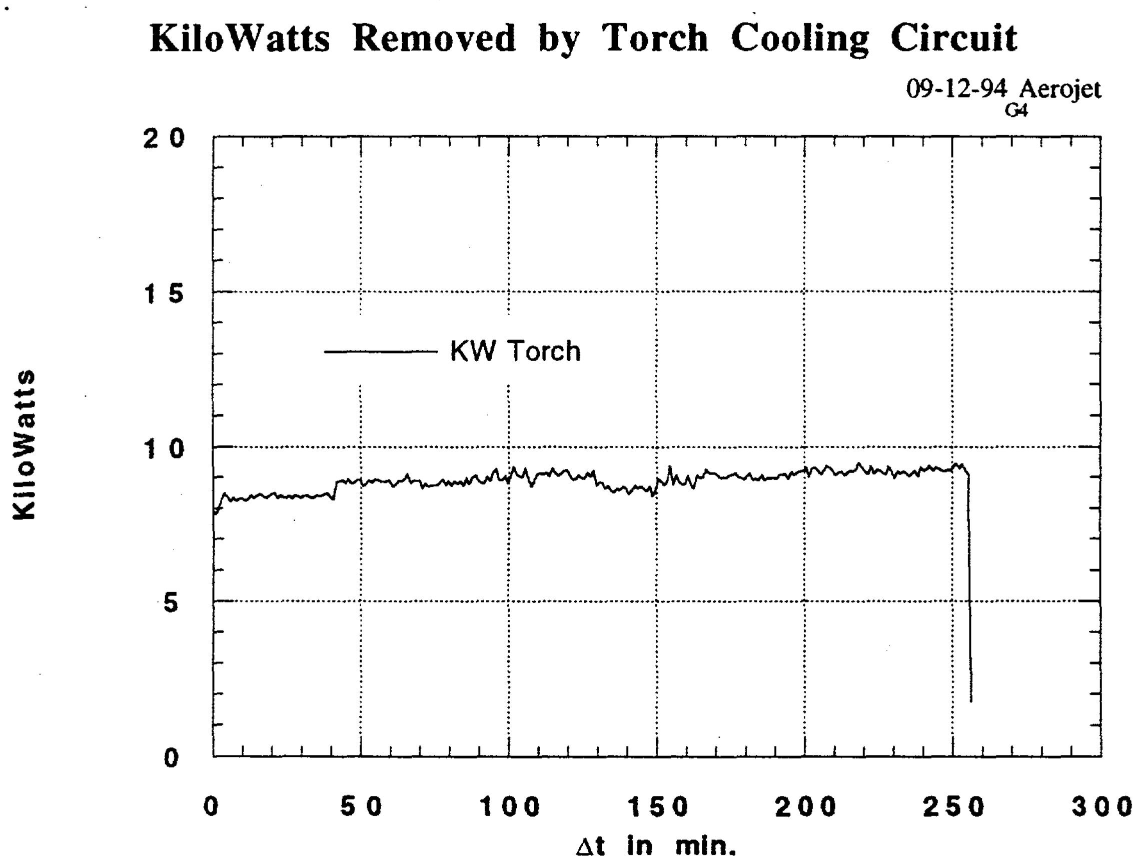


KiloWatts Into Torch





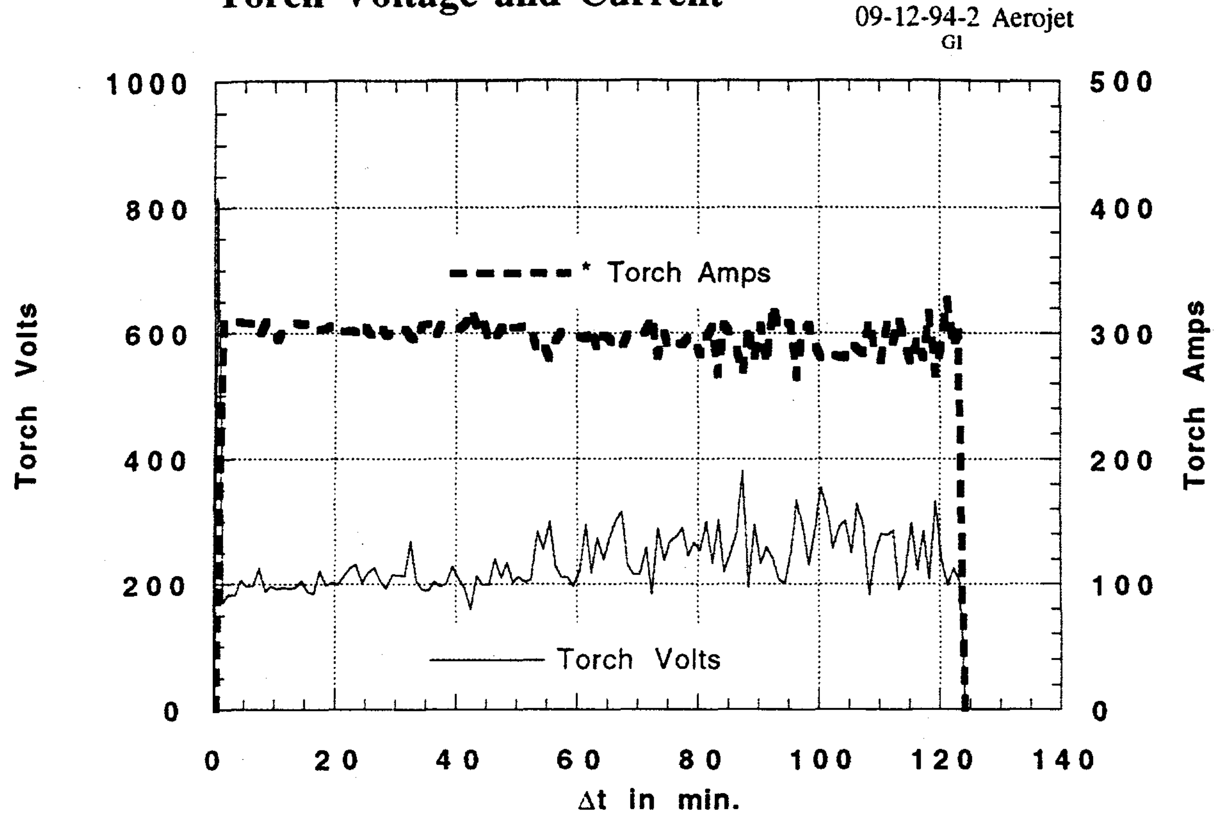
Torch Cooling Circuit Temperature
09-12-94 Aerojet
G3
°F
100
95
90
85
80
75
70
65
60
Torch
Closed Water S
0
50
100
150
200
250
300
Δt in min.



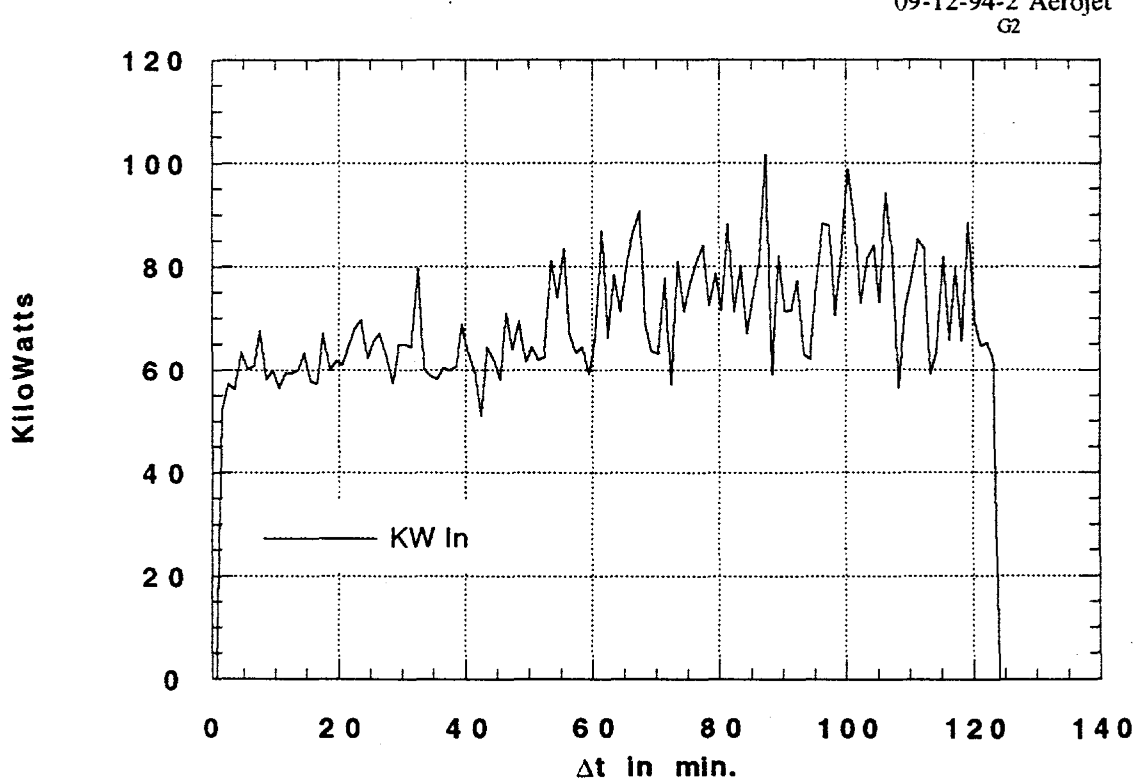
KiloWatts Removed by Torch Cooling Circuit
09-12-94 Aerojet
G4
KiloWatts
20
15
10
5
0
KW Torch
0
50
100
150
200
250
300
Δt in min.

1/4 Scale Data Summary		
	Run Date: 9/8/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: slag bed		Video Tape #: N/A
Furnace Configuration: rotating crucible		Video Start: N/A
Type of Feedstock: not applicable (N/A)		Supply Gas: N
Estimated Electrode Hours: 60		Operators: PW, MAK
Remarks: Aerojet electrode, using 1.2 scfm Nitrogen and 1 scfm Argon.		Results: Afternoon test.

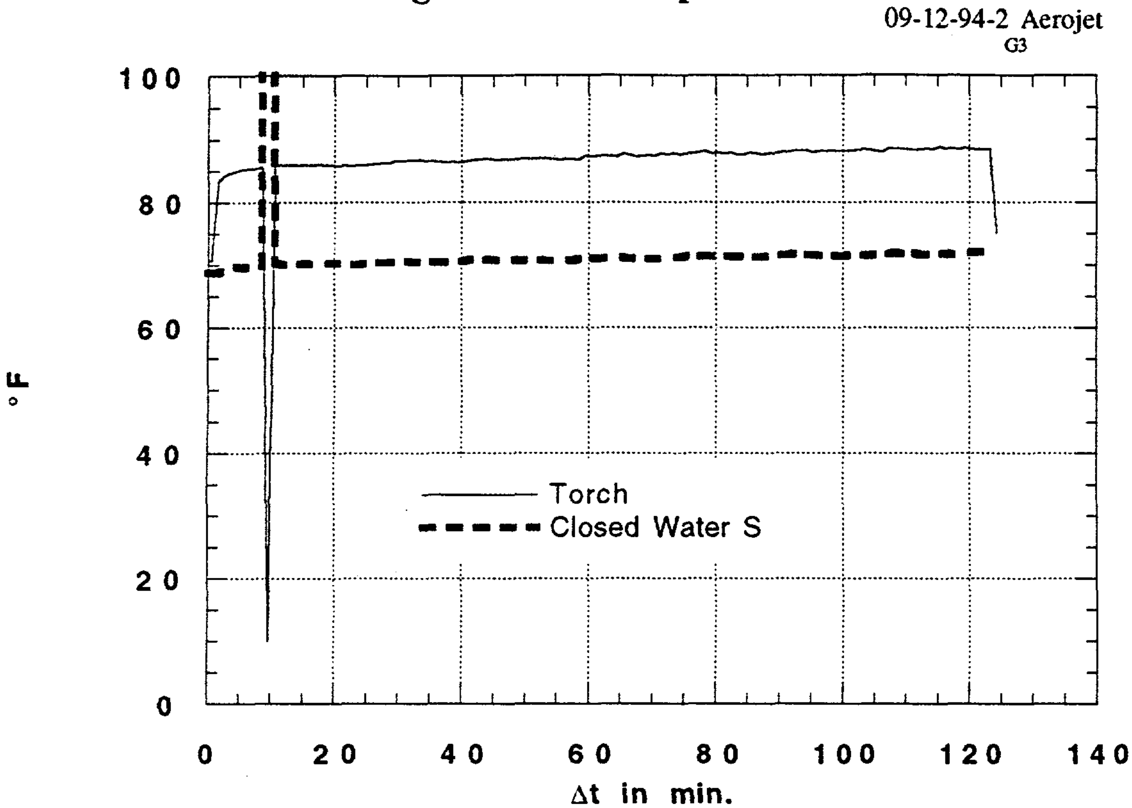
Torch Voltage and Current



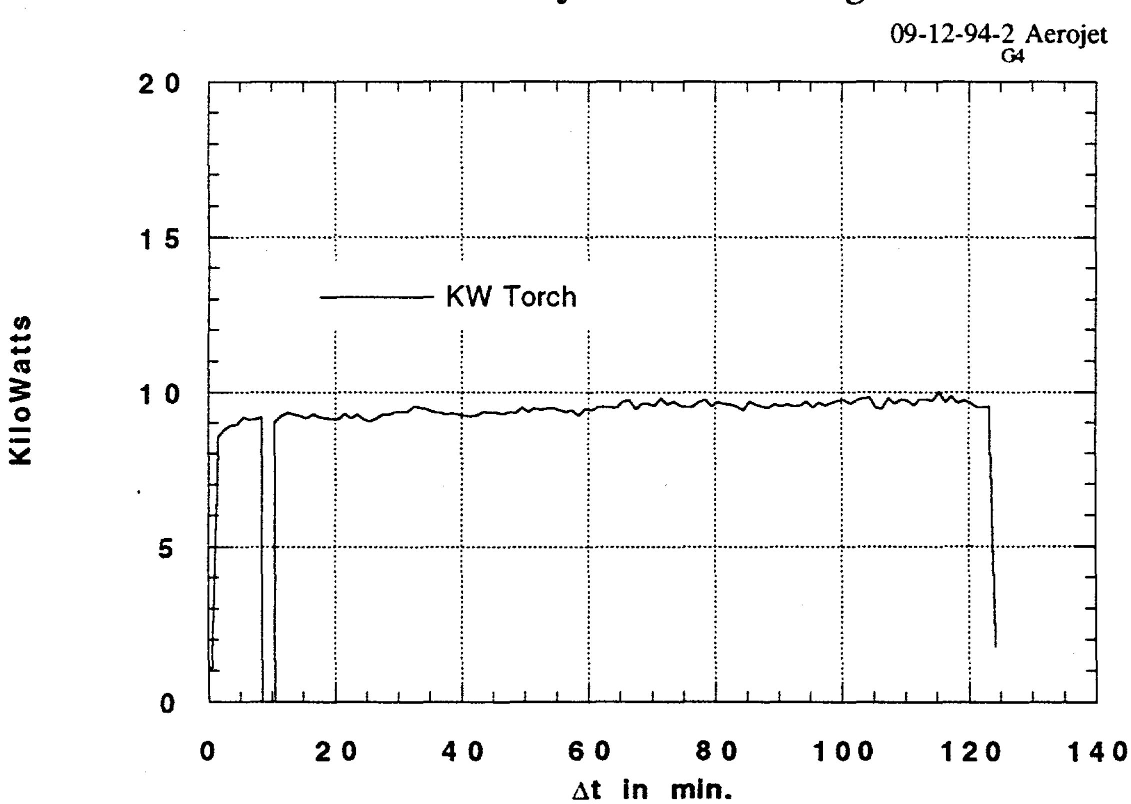
KiloWatts Into Torch



Torch Cooling Circuit Temperature

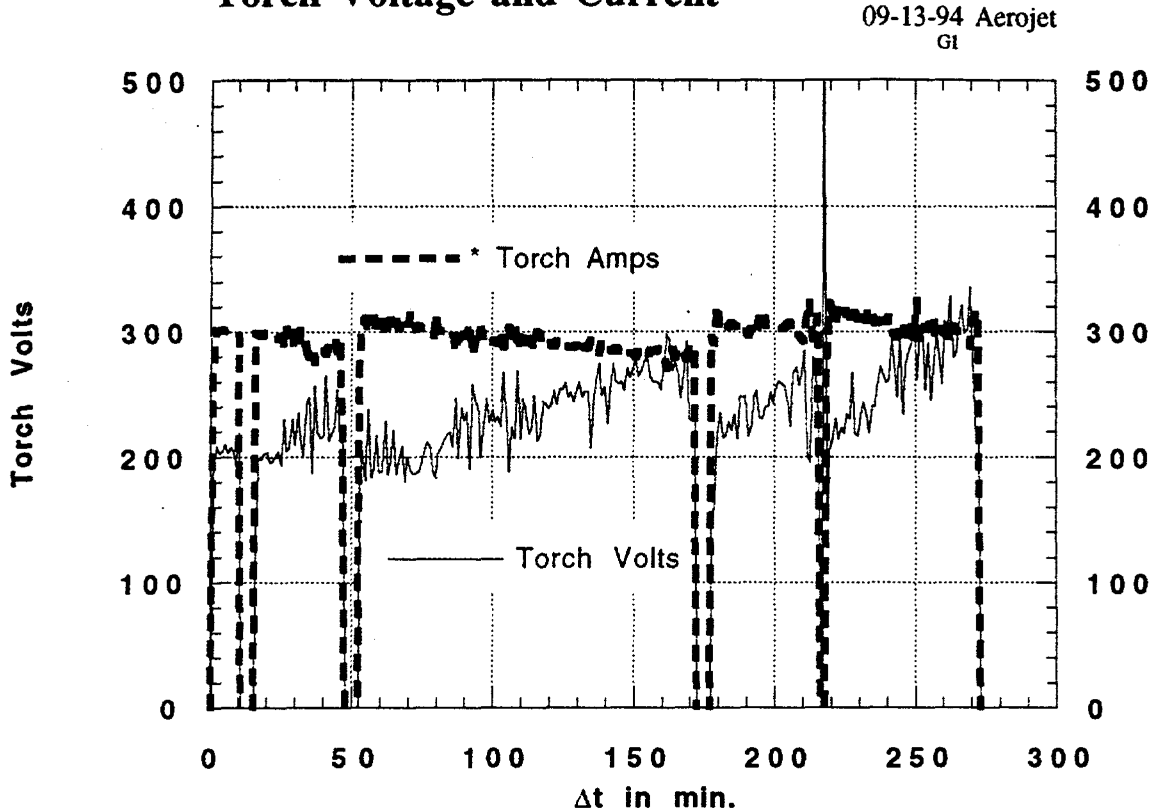


KiloWatts Removed by Torch Cooling Circuit

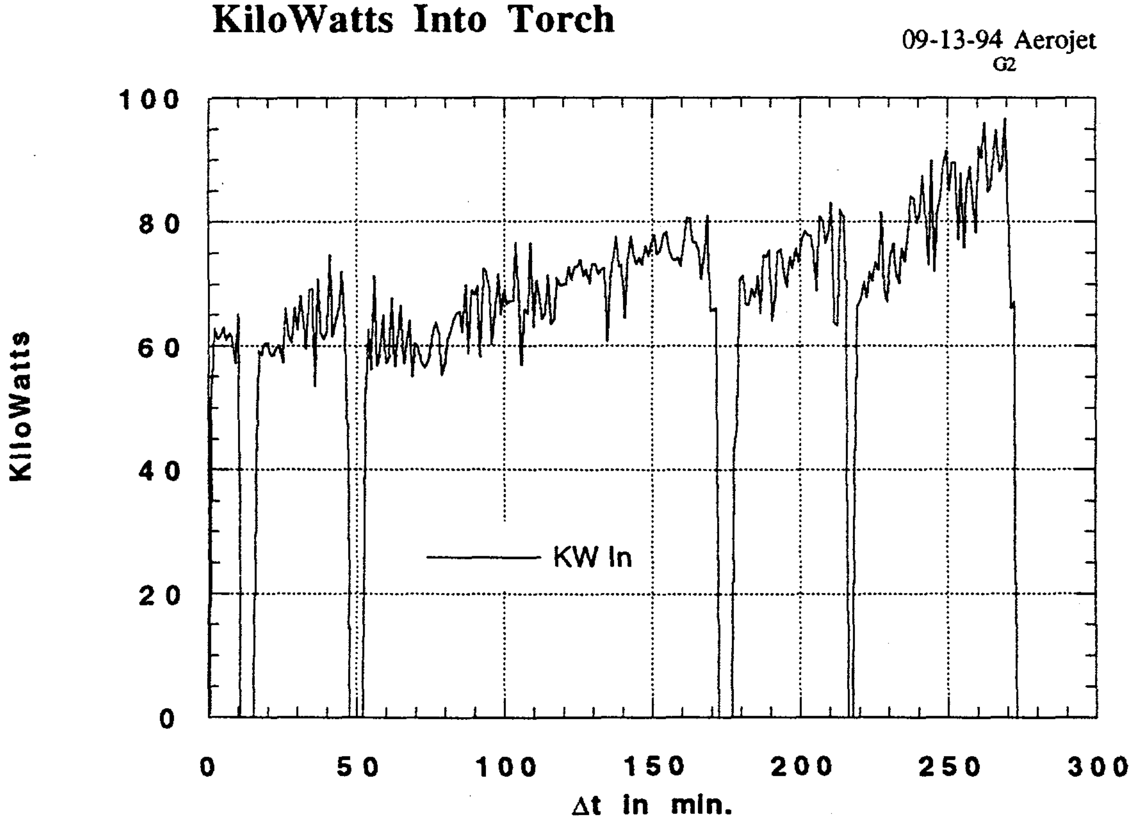


1/4 Scale Data Summary		
	Run Date: 9/13/94	
	Customer: Aerojet	
	Work Order #: 9094-0268	
Material: Previous slag bed		Video Tape #: 09-13-94
Furnace Configuration: rotary		Video Start: 0
Type of Feedstock: none		Supply Gas: N2 & N2
Estimated Electrode Hours: 0		Operators: pw
Remarks: Start with new Electrode		Results: Ran the whole day without problems. Changed at 2:20 N2 bottles

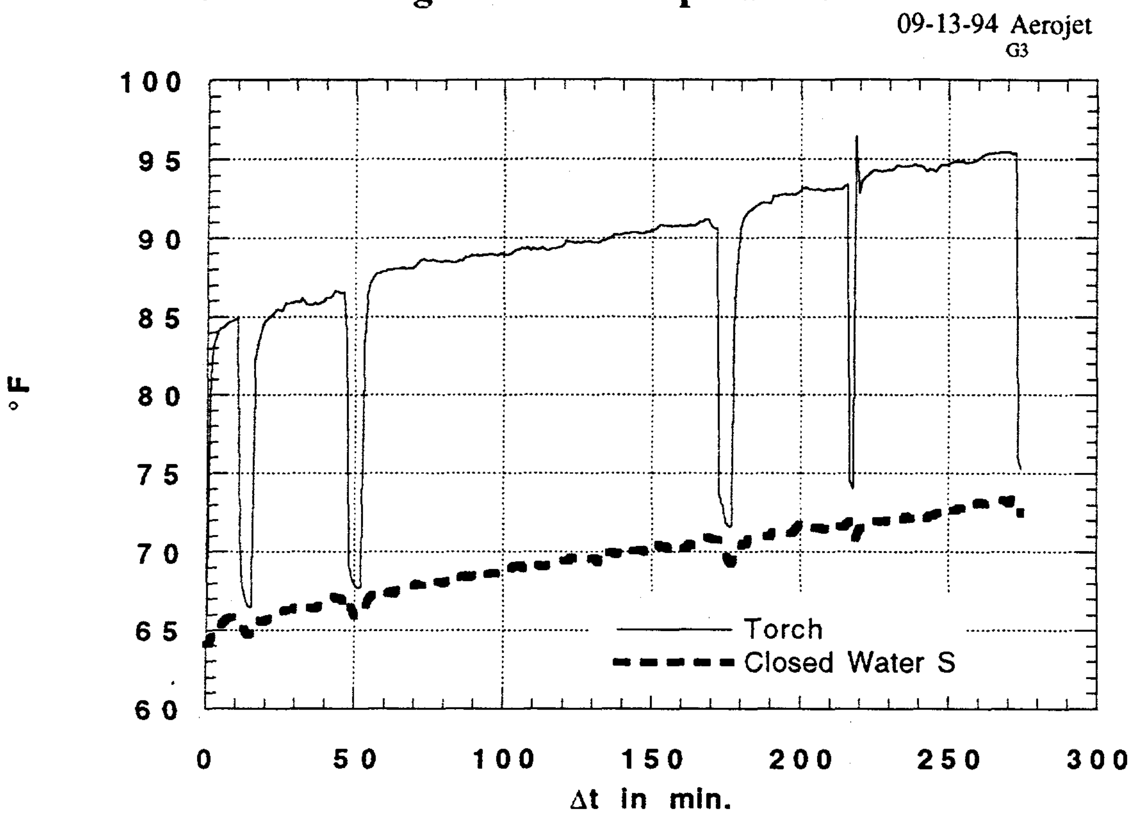
Torch Voltage and Current



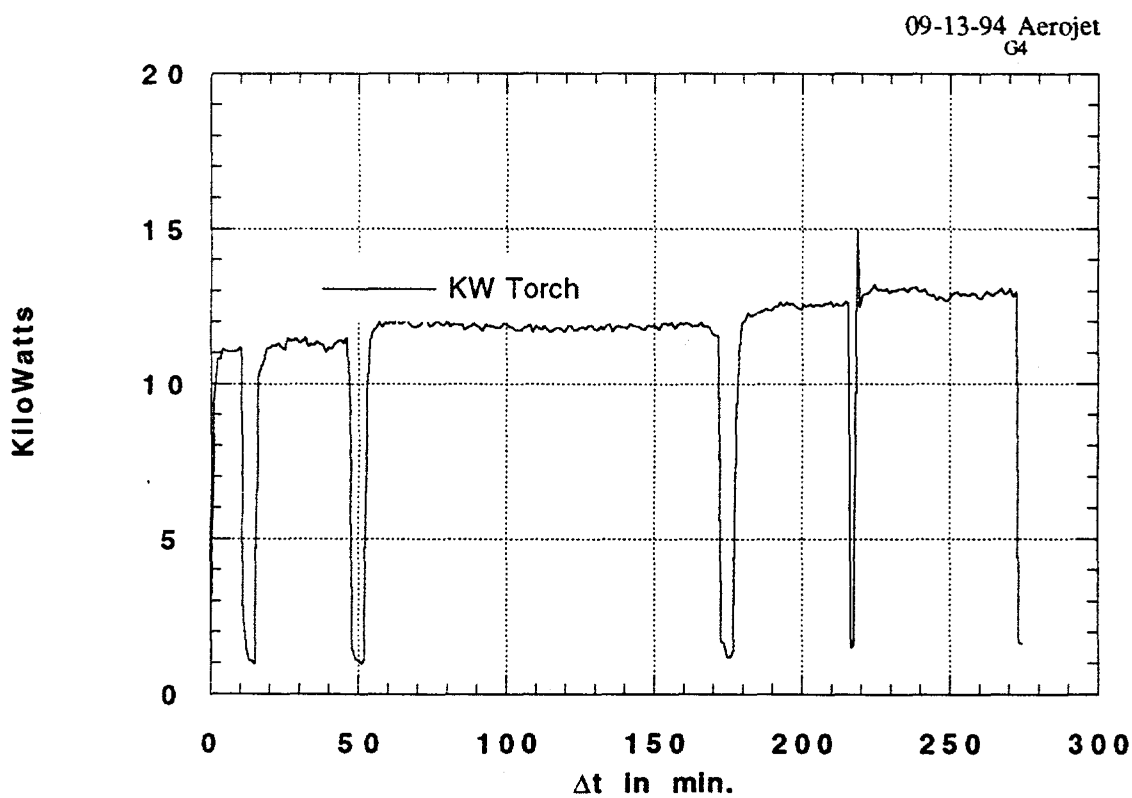
KiloWatts Into Torch



Torch Cooling Circuit Temperature

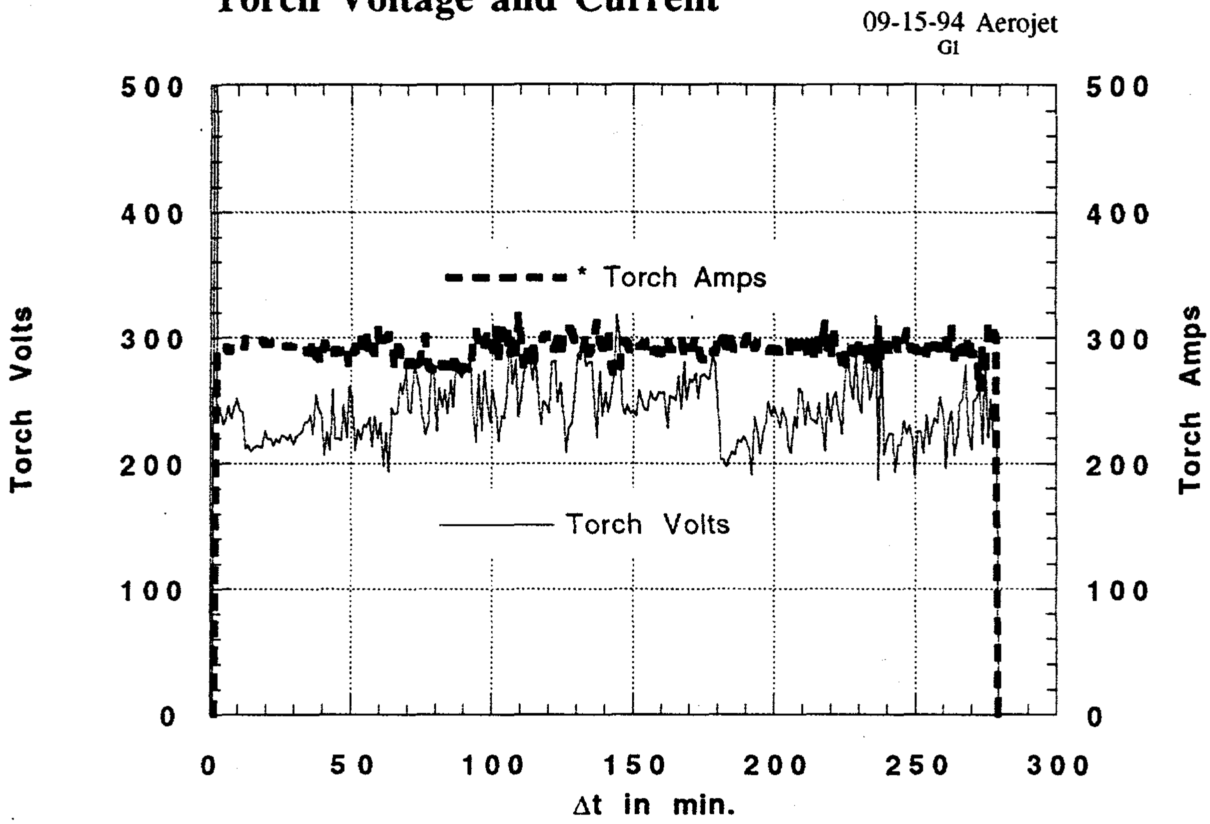


KiloWatts Removed by Torch Cooling Circuit

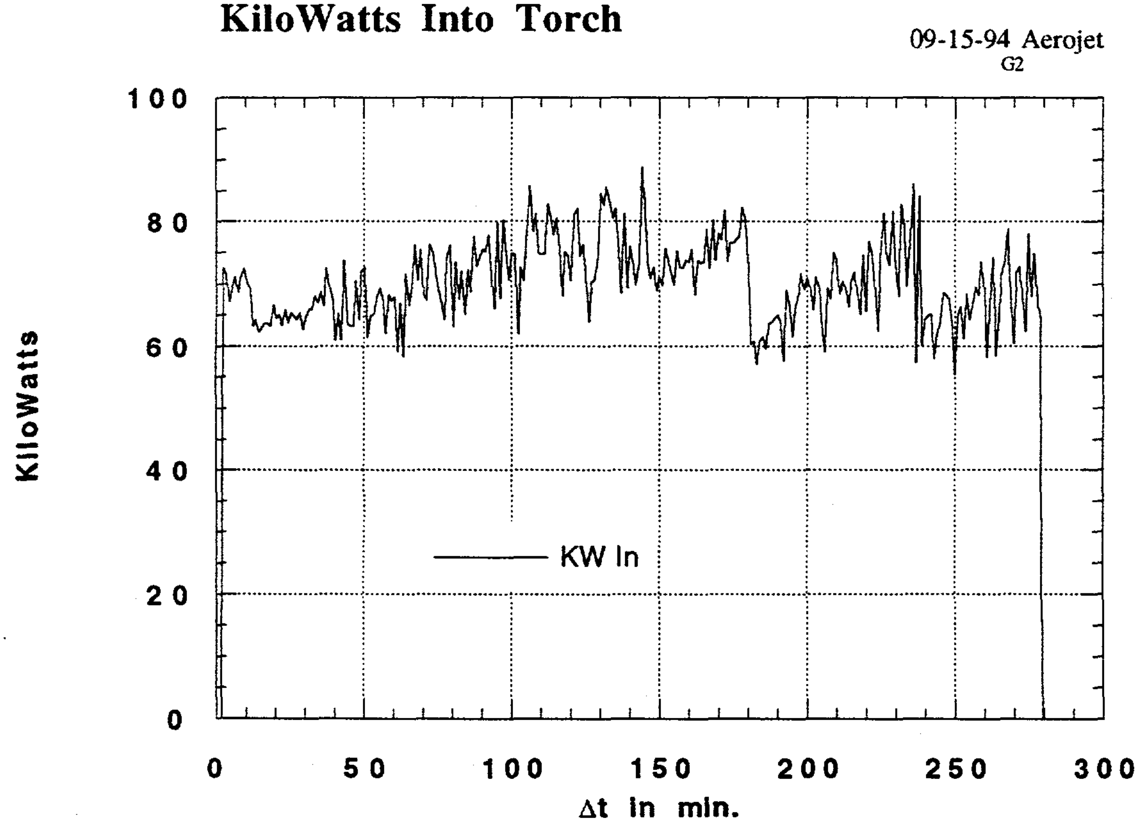


1/4 Scale Data Summary		
	Run Date: 9/15/94	
	Customer: Aerojet	
	Work Order #: 9094 0268	
Material: Slag in Tub		Video Tape #: N/A
Furnace Configuration: Normal		Video Start: N/A
Type of Feedstock: N/A		Supply Gas: N2
Estimated Electrode Hours: 4Hrs 15Min		Operators: rl pw
Remarks: N2 injection Platelette Electrode		
Run the rest of Day		Results: Continued testing electrode,very little noticeable wear.

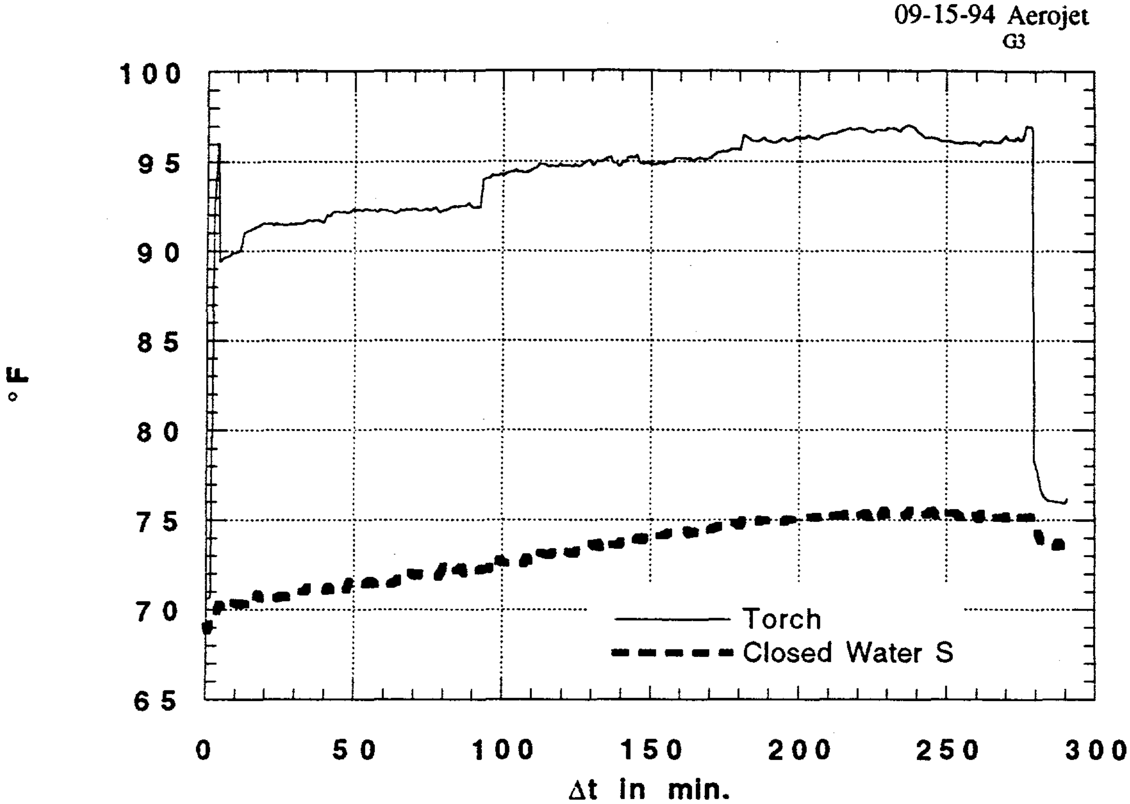
Torch Voltage and Current



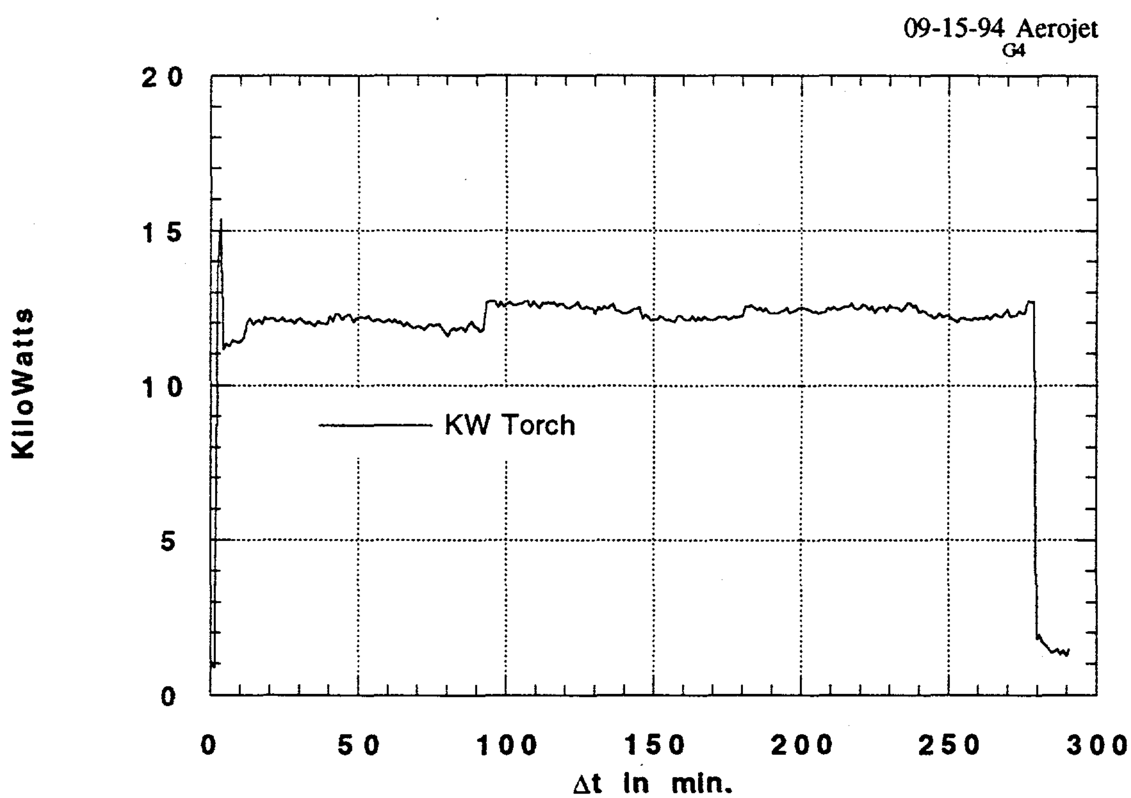
KiloWatts Into Torch



Torch Cooling Circuit Temperature



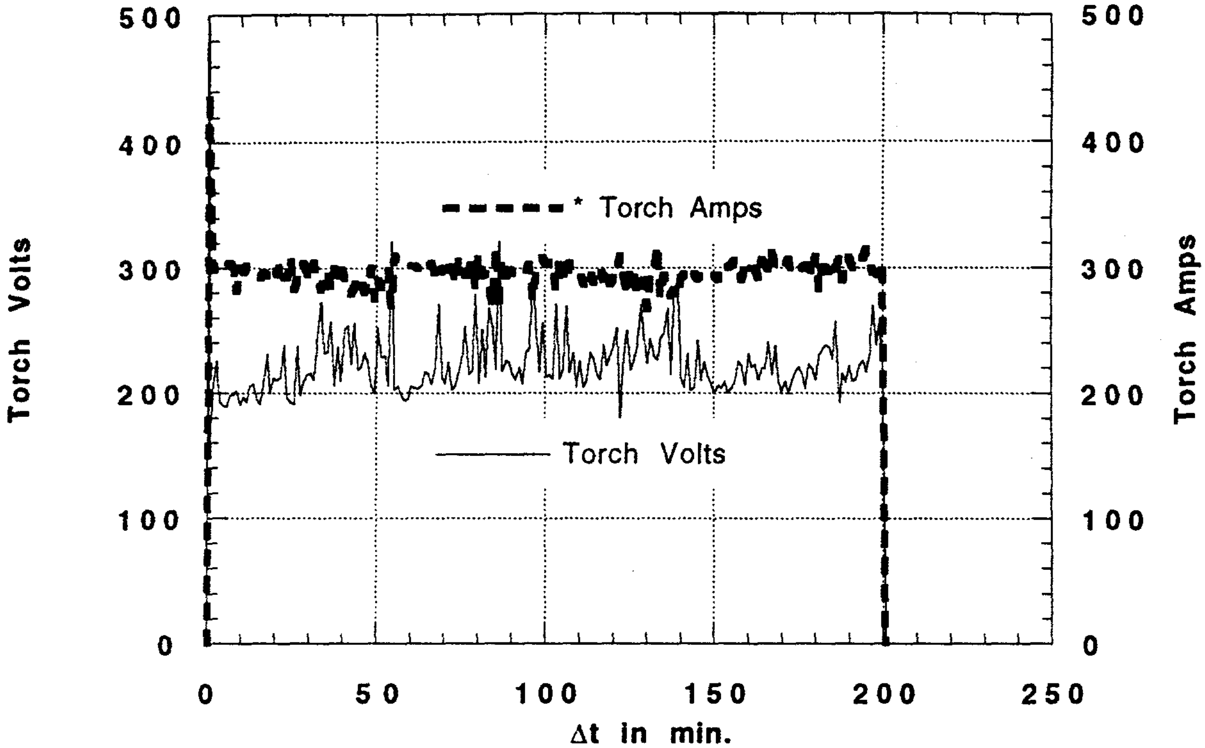
KiloWatts Removed by Torch Cooling Circuit



1/4 Scale Data Summary		
	Run Date: 9/16/94	
	Customer: Aerojet	
	Work Order #: 9094 0268	
Material: Slag in Tub		Video Tape #: N/A
Furnace Configuration: Normal		Video Start: N/A
Type of Feedstock: N/A		Supply Gas: N2
Estimated Electrode Hours: 8Hrs 25Min		Operators: R.Lampson
Remarks: N2 injection Platelette Electrode		
Run the rest of Day		Results: No problems to speak of.

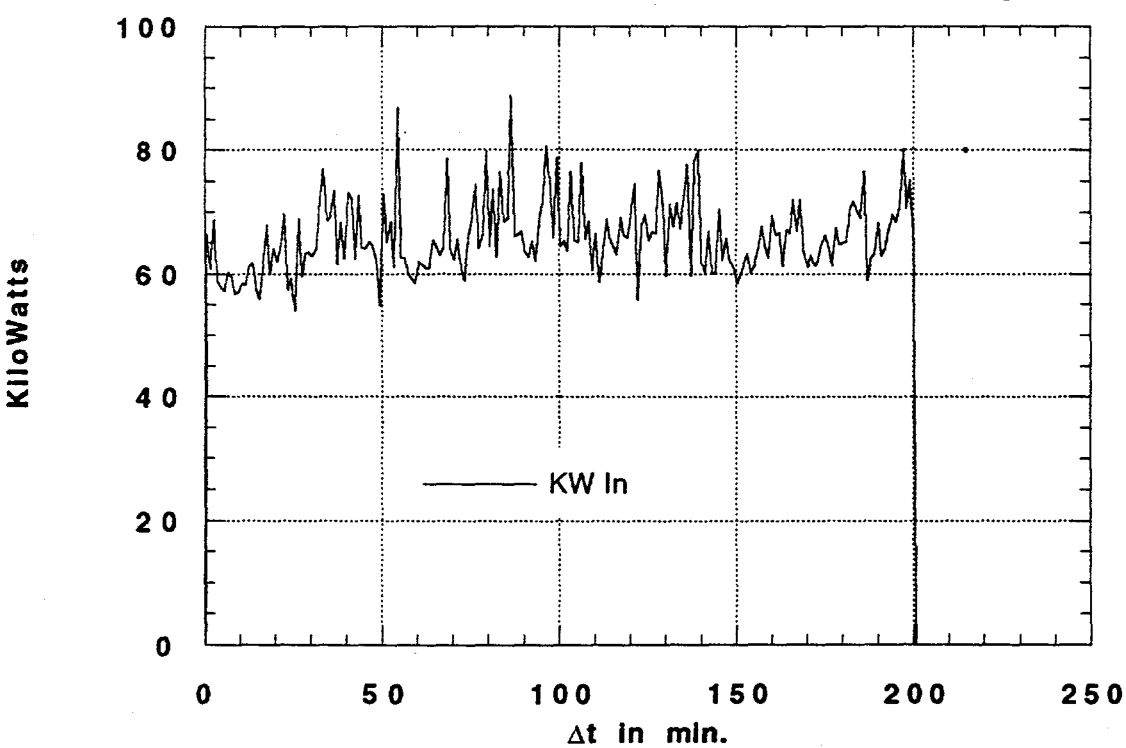
Torch Voltage and Current

09-16-94 Aerojet
G1

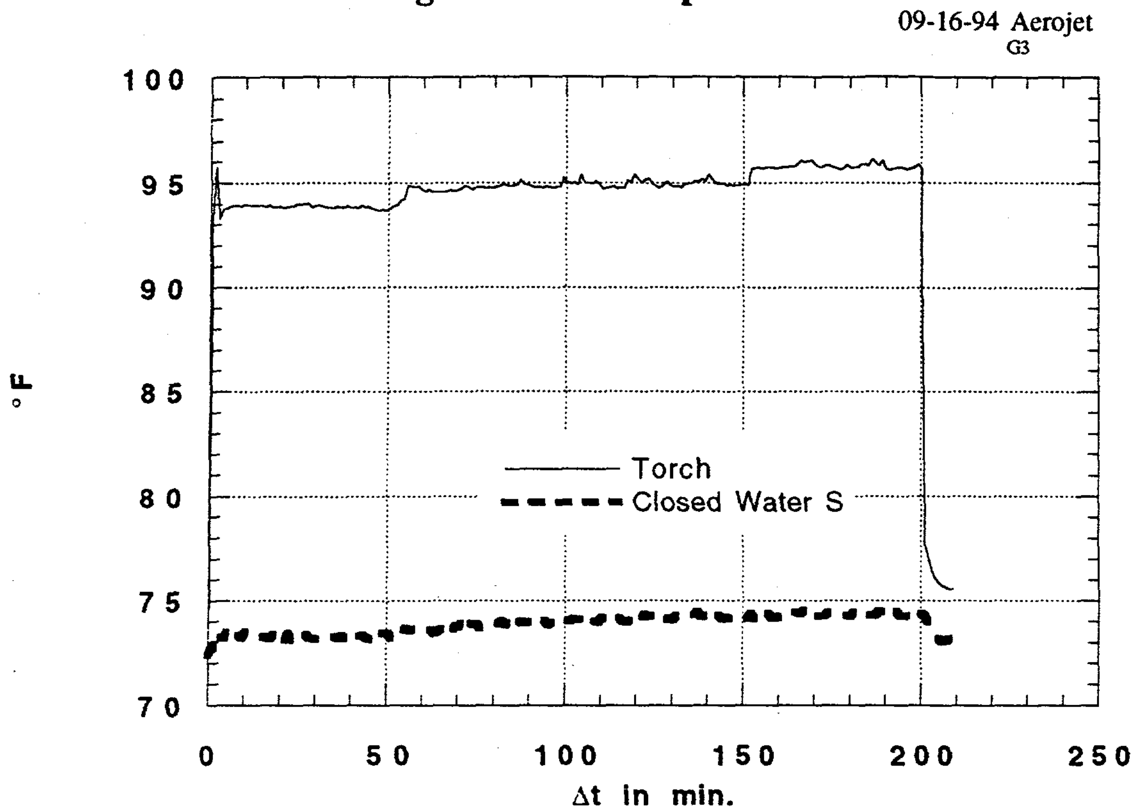


KiloWatts Into Torch

09-16-94 Aerojet
G2



Torch Cooling Circuit Temperature



KiloWatts Removed by Torch Cooling Circuit