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RESULTS OF TESTING THE AEDC 5-MW SEGMENTED ARC HEATER

Dennis D. Horn and St. George A. Brown
ARO, Inc.

PROPULSION WIND TUNNEL FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE

December 1974

Final Report for Period January 26, 1972 – November 28, 1973

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

The results of testing a nominal 5-MW segmented (constrictor channel type) arc heater are presented. The heater was operated at chamber pressures up to 104 atm with power inputs to nearly 3 MW using air as the test gas. Bulk enthalpies ranged from about 7000 Btu/lb at 26 atm to 4500 Btu/lb at 102 atm. The nozzle exit flow was surveyed with null-point calorimeters and pressure and enthalpy probes. Performance comparisons are made between

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20. ABSTRACT (Cont'd)

the segmented and Linde-type arc heaters. Detailed test and data summaries are presented. All testing was performed at the Arnold Engineering Development Center.

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PREFACE

The work reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 65802F. The results presented were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, Arnold Air Force Station, Tennessee. The work was performed from January 26, 1972, through November 28, 1973, under ARO Project Nos. PL3257, PF227, and PF427. The manuscript (ARO Control No. ARO-PWT-TR-74-72) was submitted for publication August 19, 1974.

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1.0 INTRODUCTION

In 1967, the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), contracted with Electro-Optical Systems, Inc. (EOS) to perform a study and develop an ultrahigh-pressure arc heater. The study was to encompass all requirements needed to produce a d-c electric arc heater that would operate at pressures up to 200 atm and at an enthalpy high enough to provide realistic simulation of the stagnation conditions on a reentry vehicle (Refs. 1 and 2). This effort resulted in the delivery of a constricted-channel, segmented arc heater to AEDC in November 1969 (see Fig. 1). The specific goal for this d-c arc heater was to heat air to 3830 Btu/lb bulk enthalpy at 200 atm with a power input of 5 MW. This heater was operated at AEDC for performance evaluation through June 1970, at which time development testing was terminated because of lack of funding. The test results are presented in Ref. 3.

The heater was extensively modified, and experimental efforts were resumed during Fiscal Year 1972 (FY 72). This modified arc heater is referred to throughout this report as the 5-MW Segmented Arc Heater (SAH). The specific objectives were to operate the heater on air at chamber pressures of 25, 50, 80, and 100 atm. Steady-state energy balances were obtained at nominal current levels of 400, 500, and 600 amp, and the effluent was surveyed with impact pressure probes, null-point calorimeters, and an enthalpy probe. In FY 73 and 74 the effort was extended to include operation of the heater at higher arc currents and enthalpies and to provide minor configuration changes for developing design criteria for a new heater. The results of these tests during Fiscal Years 1972, '73, and '74 are reported herein.

2.0 TEST APPARATUS AND PROCEDURE

2.1 ELECTRIC POWER AND OTHER UTILITIES

Electric power was supplied to the arc heater through a series of transformers and an ignitron rectifier. The characteristics of this d-c supply are shown in Fig. 2. Ballast resistance up to 9.3 Ω was added as necessary to improve arc stability. High pressure air (up to 4000 psia) was supplied by the AEDC von Kármán Facility (VKF) either from a storage bottle or directly from compressors, through a pressure control and metering station. Demineralized cooling water was supplied to the arc heater by two centrifugal pumps, each rated at 120 gal/min at 1200 psig.

2.2 INSTRUMENTATION

Strain gage transducers, thermocouples, voltage dividers, current transducers, and turbine-type flowmeters were sensors for the pressures, temperatures, arc voltage and current, and cooling water flows which were recorded on strip chart recorders for steady-state values; transient and redundant parameters were recorded on oscillographs. Air mass flow rate was measured using a choked venturi which was calibrated by flowing air into a tank and weighing on precision scales. Control room data were obtained from voltmeters, ammeters, autosyn gages, Simplytrol® meters, and strip chart recorders. Closed-circuit television was used to monitor the arc heater during operation.

Model instrumentation included a 0.25-in. nose radius (NR) null-point calorimeter, impact pressure probes, and an enthalpy probe; these were swept through the heater effluent consecutively using a five-position linear model injection system (Ref. 4). Model tips were positioned 0.1 in. downstream of the nozzle exit, and the sweep rate was approximately 25 in./sec. Model position was correlated to oscillograph records by the use of high-speed motion pictures and common timing pulses.

2.3 ARC HEATER

The 5-MW segmented arc heater used in this test was the constricted-channel device delivered by EOS and modified at AEDC. The constrictor channel segments were water-cooled copper rings, the water passage being formed by silver-brazing two copper rings together. The internal channel diameter was 0.934 in., and each segment was 0.187 in. wide. The initial configuration, which is shown in Fig. 3, consisted of 65 segments, including tapered segments at each end of the channel and an air injection ring at the upstream end (Fig. 4). The segments were electrically insulated by boron nitride (BN) spacers 0.081 in. thick.

A ring electrode was located at each end of the channel. A magnetic coil, encapsulated in plastic and consisting of eight turns of square copper tubing, formed the external part of each electrode ring assembly. The coils were electrically connected in series with the arc column; the polarity was selected to augment the air swirl and stimulate rotation of the arc termination on the electrodes. The heater was operated with reversed polarity throughout the test series; i. e., the anode was the upstream electrode. The axial distance between anode and cathode centerlines was from 19 to 20 in.

Four upstream segments were positioned between the anode and end plate assembly, each electrically insulated with boron nitride spacers. These segments, coupled with tangential air injection at the end plate liner, prevented arc attachment on the end plate. Two downstream segments provided a transition section for the flow entering the nozzle throat. The conical nozzle had a 0. 215-in. throat diameter and a 0. 400-in. exit diameter (Fig. 5). Air was introduced at the air injection ring and end plate liner in various ratios indicated in Tables 1, 2, and 3. Swirl direction for all air stations was clockwise looking downstream.

The addition of four upstream segments and a new nozzle design were the only configuration changes made preceding the testing reported herein. Subsequent modifications and configuration changes are covered in Section 3.0.

2.4 TEST PROCEDURE

2.4.1 Pretest Checkout

After it was verified that all air, water, and instrumentation connections were properly attached, the heater chamber was sealed by a flapper valve at the nozzle exit and connected to a vacuum system. The heater was checked for gas leaks with the pressure maintained at a level near 1 mm Hg. Test voltages were then applied to ensure that external insulation was adequate up to 12. 5 kv and that breakdown voltage with the heater evacuated was below 8 kv. Cooling water was supplied to the heater at the scheduled operating pressure and flow rate, and a leak check of all cooling components was performed. The water system was then secured, and routine instrumentation and auxiliary system preoperational procedures were completed. The vacuum was maintained throughout the pretest procedures. The regulated air supply was preset for the pressure required for the run, and the electrical leads were attached to the heater. The heater was then ready for operation.

2.4.2 Starting and Operating Procedures

The automatic sequencer for the arc heater system was activated, and the recording instruments were started. The transformer tap position was set for the scheduled power level. After checking the coolant flow interlocks, flow rates, regulated air pressure, heater vacuum, and power setting, the open-circuit voltage was applied to the heater electrodes. When breakdown occurred and current was established, the air valve was opened automatically using the signal from a current-sensing device. Time required from arc initiation to full pressurization was about 1.5 sec. Nearly 8 to 10 sec were required for coolant water temperatures to stabilize for an energy balance. Models were injected as required during heater operation. For a normal shutdown, power termination automatically closed the air valve. Then cooling water and other support systems were manually secured. The heater was started "on condition" for all runs, and conditions were not changed during any given run.

3.0 TEST DESCRIPTION AND RESULTS

3.1 RUN SUMMARY

Test summaries for the experimental effort are shown in Tables 1 through 6. Tables 1 and 4 are data summaries,and descriptive test summaries, respectively, for tests made during Fiscal Year 1972. Tables 2 and 5 are for Fiscal Year 1973, and Tables 3 and 6 are for Fiscal Year 1974.

3.1.1 Fiscal Year 1972

The heater was initially operated on January 26, 1972 (see Tables 1 and 4). Runs 1 and 2 resulted in some insulator damage near the anode. Subsequently, the air injection at the end plate was reduced, and Runs 3 through 15 were made without difficulty. Runs 3, 5, 8, 12, and 15 were short checkout runs to verify proper heater operation before steady-state energy balance runs were attempted. The heater was operated successfully for 15 to 20 sec on Runs 4, 6, 7, 9, 10, 11, 13, and 14, and energy balances were obtained. The flow was surveyed with a null-point calorimeter and a pressure probe on these runs. The heater was operated at nominal chamber pressures of 26 atm on Runs 4, 6, and 7; 53 atm on Runs 9, 10, and 11; and 80 atm on Runs 13 and 14. A predicted performance envelope based on these 8 runs is presented in Fig. 6. Runs 15 through 18 were at a nominal chamber pressure of 100 atm, although the heater was "on condition" long enough to obtain an energy balance only during Run 17.

3.1.2 Fiscal Year 1973

Runs 1 through 4 were made at arc current levels in the range from 650 to 700 amp to determine if additional enthalpy could be obtained at the higher currents. Run 1 was a checkout run; Run 2 was a successful energy balance run at 682 amp and a chamber pressure of 64 atm. A bulk enthalpy of 5886 Btu/lb was measured, and centerline enthalpy, based on pressure and calorimeter measurements, was 9400 Btu/lb. Efforts on Runs 3 and 4 to operate at 80 atm chamber pressure and high current resulted in successive failures of the base segment.

In order to alleviate this problem, a configuration change was incorporated into the cathode area of the heater (see Fig. 7). An air injection station was installed in place of the base segment, and an additional cathode assembly was installed. The upstream cathode assembly was used not as an electrode, but as a hightly cooled transition station between the downstream cathode and the air injection ring. Both spin coils were connected to augment arc rotation at the cathode. Runs 5, 6, and 7 were required to optimize the amount of air at the downstream injection station. Run 7 resulted in a successful energy balance at a chamber pressure of 46 atm and a current of 529 amp.

Various minor configuration changes were then made on Runs 8, 10, and 11 to provide design criteria data for a new heater design. The nominal condition for these runs was 50 atm and 500 amp. Run 7 was used as a base line for comparing the results of these configuration changes. Both the anode and cathode spin coils were disconnected for Run 8. This resulted in a moderately high erosion rate on the surface of both electrodes. Run 9 resulted in an external arc-over to the heater frame, but no damage occurred to the heater internally. The spin coils were reconnected in the normal manner for Run 10, and six pairs of adjacent segments on the upstream end of the constrictor channel were shorted together (see Tables 2 and 5) to determine if the width of the segments could be increased without causing shorting of the arc column along the wall. Run 10 was successful, and no evidence of arcing was found on the channel wall. Eight additional pairs of segments were shorted together for Run 11, resulting in considerable arcing (see Table

5). The voltage drop from anode to cathode is shown in Fig. 8 for Runs 7, 10, and 11. The effect of shorting segments is evident on Run 11.

Testing for Fiscal Year 1973 was then terminated because of water leakage problems at the silver solder joints of the channel segments. Repair with soft solder was unsatisfactory, and spare segments were not available.

3.1.3 Fiscal Year 1974

A complete new set of channel segments was installed at the beginning of this phase of testing. This set included 36 segments of the welded type and 15 segments of the silver-soldered type. The new welded segments were externally identical to the original segments, but the silver solder joint at the water passage was replaced with a welded joint. The new silver-soldered segments were 0.25 in. wide (1/16-in. wider than the original segments), and the silver solder joint was relocated to the outside diameter of the segment. This design diverted potential water leaks to the external portion of the arc heater.

Eleven runs were made during Fiscal Year 1974 (Tables 3 and 6). Five runs were made at a nominal chamber pressure of 50 atm, two runs at 75 atm, and four runs at 100 atm. Arc current was nominally 550 amp for all runs except Run 5 (an air line failure caused low chamber pressure and high current). The flow was surveyed with a boundary-layer pressure probe and null-point calorimeter to determine the nozzle exit pressure and enthalpy profiles. On later runs an enthalpy probe and an impact pressure probe having the same geometry as the enthalpy probe were installed to further instrument the nozzle flow conditions.

The heater was initially operated to verify proper functioning with the new segments installed. A chamber pressure of 50 atm was selected because several previous heat balance runs were successful at this pressure level. The heater operated successfully on Run 3 for 21.1 sec at a chamber pressure of 52.9 atm.

Next the heater was operated at 75 atm pressure. After a successful checkout run, a burn-through in the channel occurred on the attempted energy balance run. Rather than continue with the 75-atm level, operation was extended to 100 atm because this was the area of primary interest.

The remaining four runs were made at a nominal pressure of 100 atm. Runs 8, 9, and 10 were of short duration to optimize the heater operation. The flow was surveyed with instrumented models on all four runs although a heat balance was obtained on Run 11 only. This run was a 13.9-sec run at 101.5 atm. After 12 sec of operation a burn-through occurred in the channel approximately 8 segment positions from the anode. The run was of sufficient duration to obtain an energy balance prior to the failure. The three separate channel failures which occurred during FY 74 each involved segments of the welded construction, and the last failure occurred in a normally cool region of the heater. Therefore, some cooling passage deficiency peculiar to the welded design was suspected.

3.2 ARC HEATER DATA

3.2.1 Enthalpy

Enthalpy based on data from the energy balance, pressure and calorimeter profiles, and the enthalpy probe are presented in Fig. 9. The bulk enthalpies resulting from energy balances are shown in Fig. 9a. The line through the data represents the bulk enthalpy obtained for the highest current runs at each pressure level. The centerline enthalpy values represented by the line through the data in Figs. 9b and c were 50 percent higher for the data based on the null-point calorimeter and 10 percent higher for the enthalpy probe when compared to the bulk enthalpy line in Fig. 9a.

3.2.2 Segment Heating Load

Typical segment heat load profiles are presented in Fig. 10. Cooling water temperature rise was measured at various locations along the channel and was used to determine the heating load on the segments. Both total segment heat-transfer rates and wall heat fluxes are shown in Fig. 10. In general the heat loads were highest in the downstream half of the channel. Current densities in the channel varied from 120 to 154 amp/cm^2 for the runs shown. The effects of both arc current and chamber pressures on segment heat losses are evident from these data.

3.3 MODEL DATA

Pressure profiles of the nozzle exit flow are shown in Fig. 11 for chamber pressures of 26, 54, and 102 atm. A boundary-layer probe containing a high response pressure transducer was used to measure these stagnation point pressures. The pressure profiles were generally "flat" across the major portion of the nozzle flow for all pressure levels.

Enthalpy profiles of the exit flow are presented in Fig. 12 for these same runs. These profiles were calculated utilizing the Fay-Riddell theory, the pressure profile data from Fig. 11, and heat-transfer measurements made with a null-point calorimeter probe. The centerline enthalpies were generally 50 percent higher than measured bulk values (see Fig. 9). The profiles show very little centerline "peaking" at these pressure levels. A typical enthalpy profile measured with the enthalpy probe (Ref. 4) is shown in Fig. 13 for 102 atm chamber pressure. The centerline enthalpies were generally 10 percent higher than measured bulk values (see Fig. 9).

Observations from motion pictures made during model traverses indicated the flow to be steady and free of debris. Oscillograph voltage traces substantiated the steady flow characteristics. Models showed no evidence of contamination from the jet, even when the arc was terminated while a model was in the flow.

3.4 COMPARISON OF PERFORMANCE IN SEGMENTED AND LINDE-TYPE ARC HEATERS

The enthalpy of the segmented arc heater as a function of chamber pressure is compared with the Linde-type heaters in Fig. 14. The lines shown represent the best performance obtained by both heaters (i. e., only the high current operation). Both the centerline enthalpy (determined from calorimeter data) and bulk enthalpy for the segmented heater were 65 percent higher than for the Linde-type arc heater. While this is a significant increase over the existing heaters in performance, the following facts must be pointed out:

1. The segmented heater is in a developmental stage, and the increased performance should be verified with an operational heater configuration.
2. The data for the Linde-type heater used in Fig. 14 were based on a larger heater with a 0.375-in.-diam throat although 1-MW Linde heaters generally show no higher performance.
3. It is reasonable to expect that with additional development effort the performance of the segmented-type heater can

be further improved. The Linde-type heater, on the other hand, is a mature design, and significant improvements in performance are unlikely.

4.0 CONCLUDING REMARKS

During the series of tests described in this report, a segmented arc heater was operated at chamber pressures up to three times higher than previously reported for this type of heater. No inherent difficulties were encountered which would prevent operation at chamber pressures greater than 100 atm. Segment failures were confined to the welded type and did not represent a general overheating problem within the channel. Wall heat fluxes up to 6000 Btu/ft^2-sec were measured without segment failure. Increases in enthalpy up to 65 percent over the Linde-type heater were measured for pressure levels below 100 atm. Nozzle exit profiles, both pressure and enthalpy, were basically flat, with very little centerline peaking. The effluent was observed to be clean and to have relatively steady intensity. Much experience was gained in the operation of the segmented heater at high pressures, and valuable hardware improvements and configuration optimizations were accomplished.

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1. Richter, R. "Ultrahigh Pressure Arc Heater Studies (Phase III)." AEDC-TR-70-106 (AD866965), March 1970.
2. Richter, R. "Ultrahigh Pressure Arc Heater Studies." AEDC-TR-69-180 (AD59053), September 1969.
3. Lewis, H. F., Horn D. D., and Patton, J. B. "Results of Testing Ultrahigh Pressure Electric Arc Heaters." AEDC-TR-70-228 (AD875516), October 1970.
4. Horn, D. D. "Ablation Testing for Tasks 3, 4, and 5 of the Reentry Systems Environmental Protection (RESEP) Program in the AEDC 5-Megawatt Arc Heater Test Unit." AEDC-TR-68-154 (AD837841), August 1968.

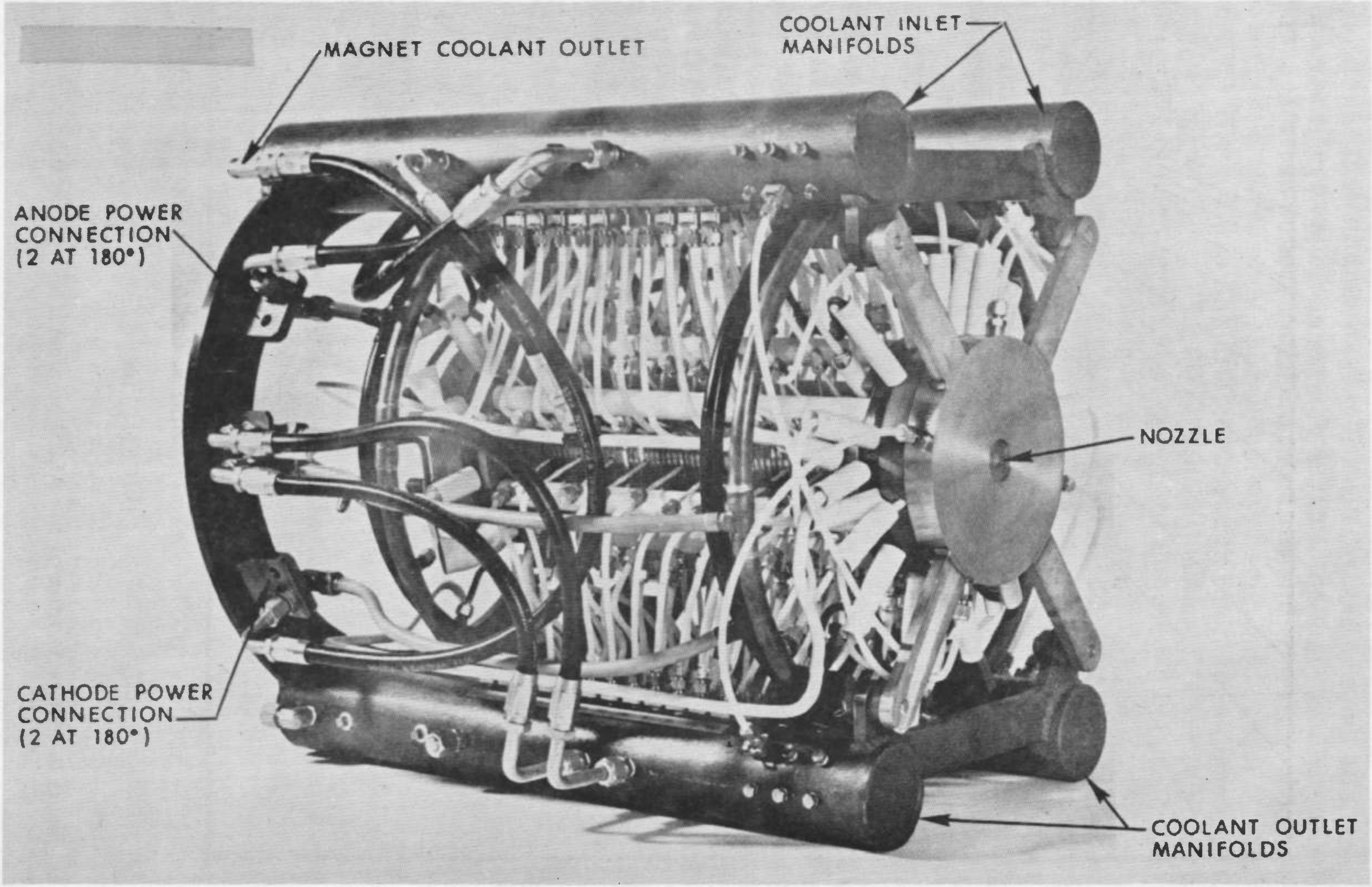


Figure 1. High pressure arc heater (front view).

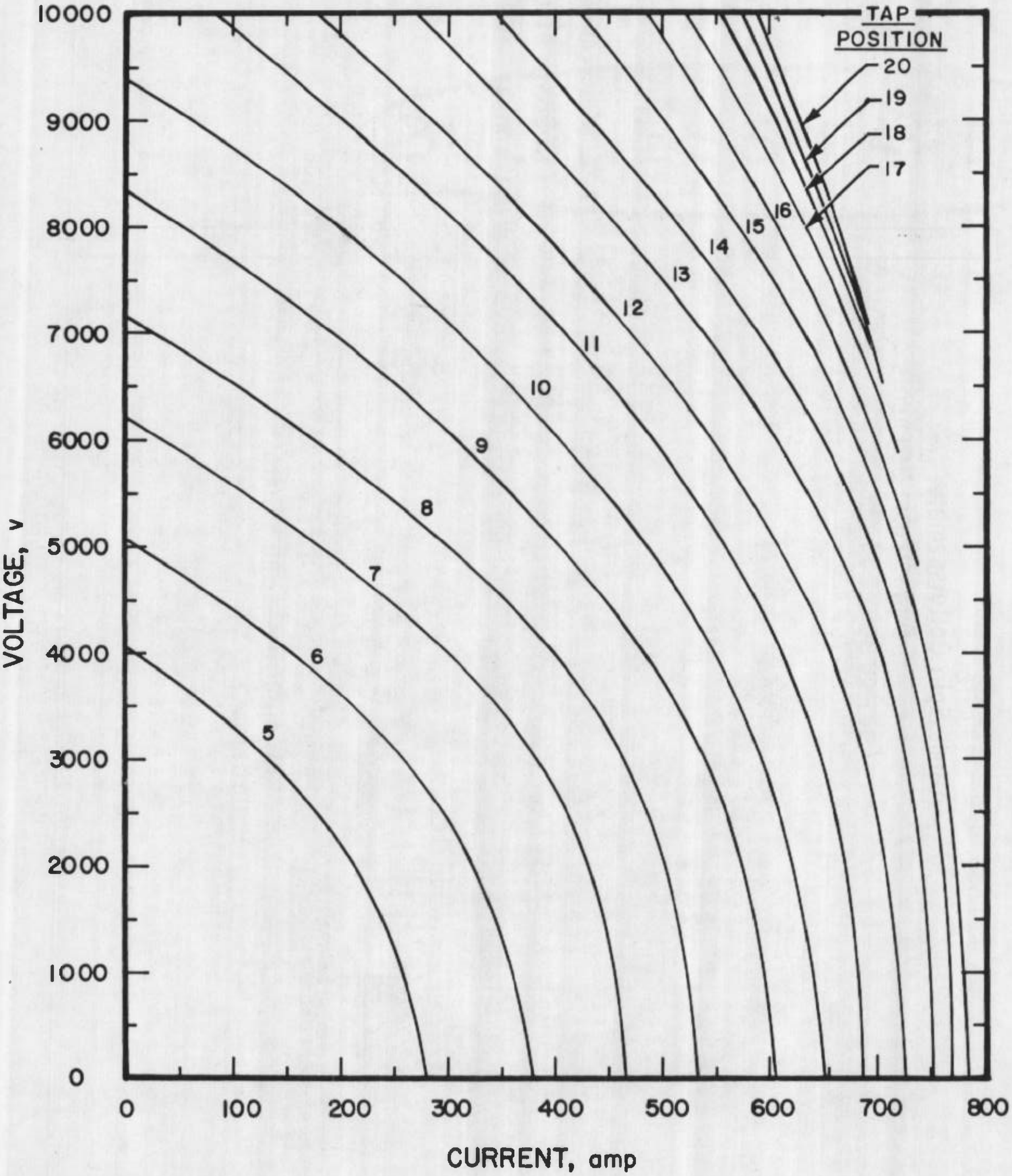


Figure 2. Characteristics of the AEDC nominal 5-MW power supply.

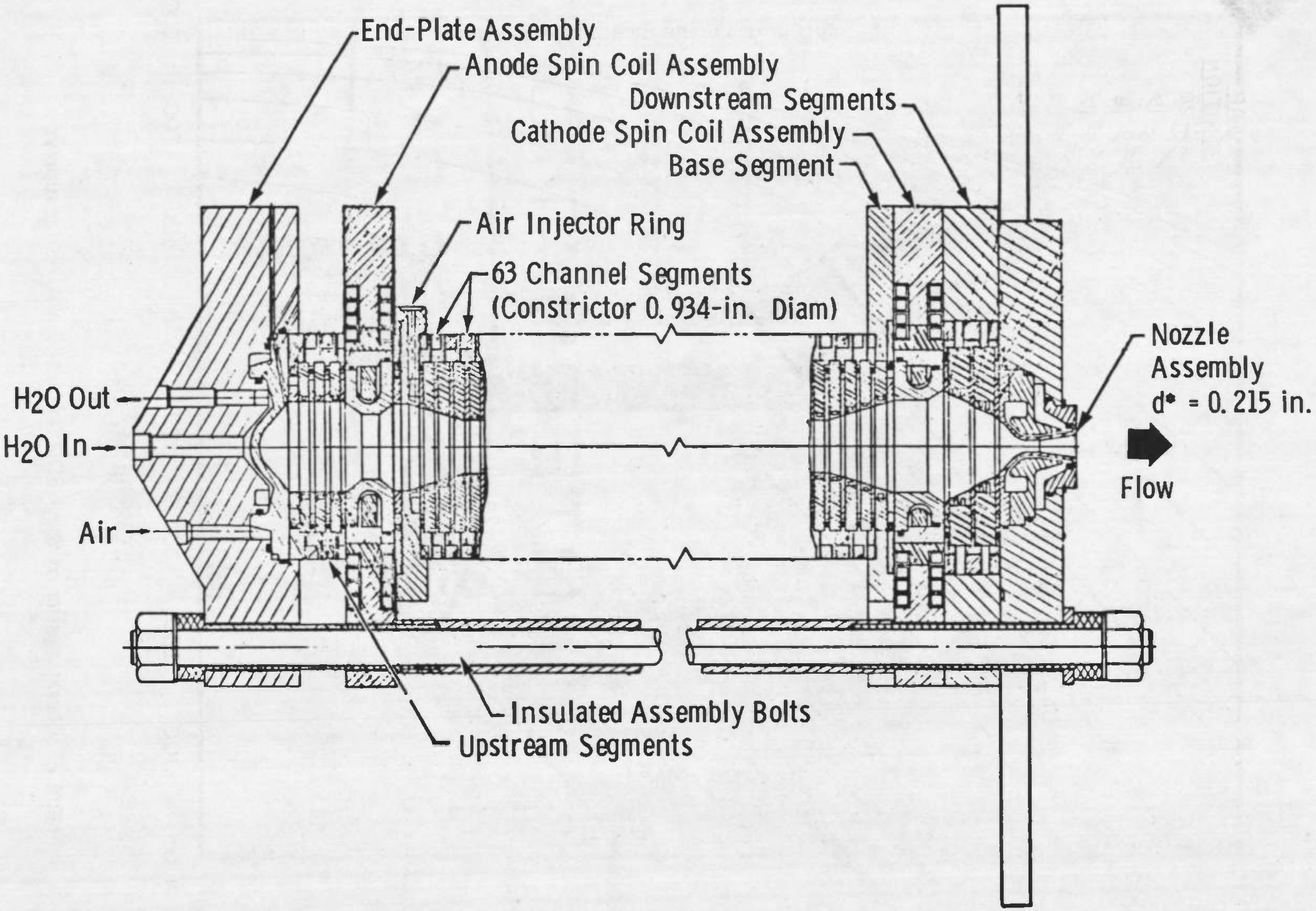


Figure 3. 5-MW segmented air arc heater.

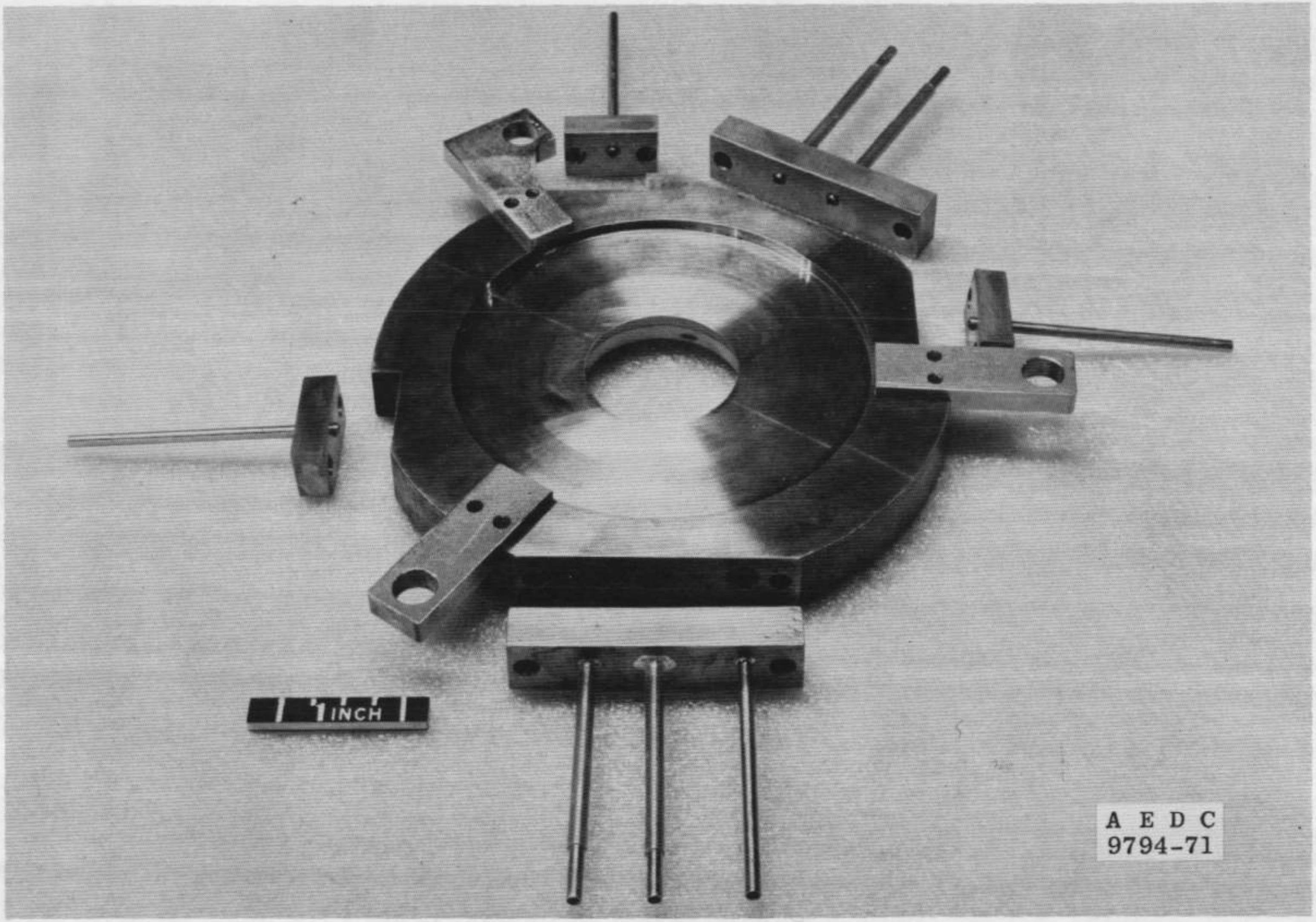


Figure 4. Upstream air injection ring.

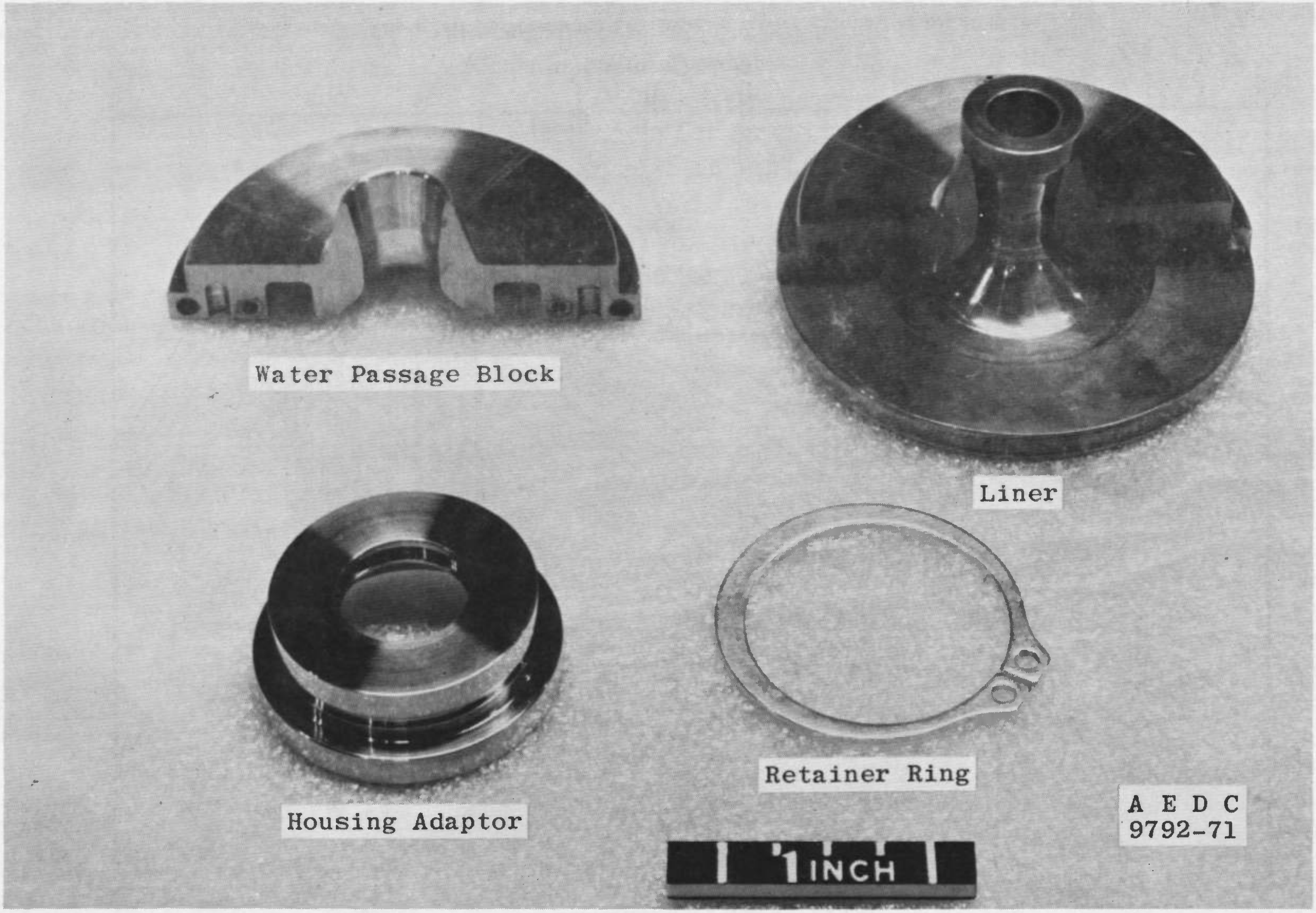


Figure 5. Nozzle throat liner and water passage blocks.

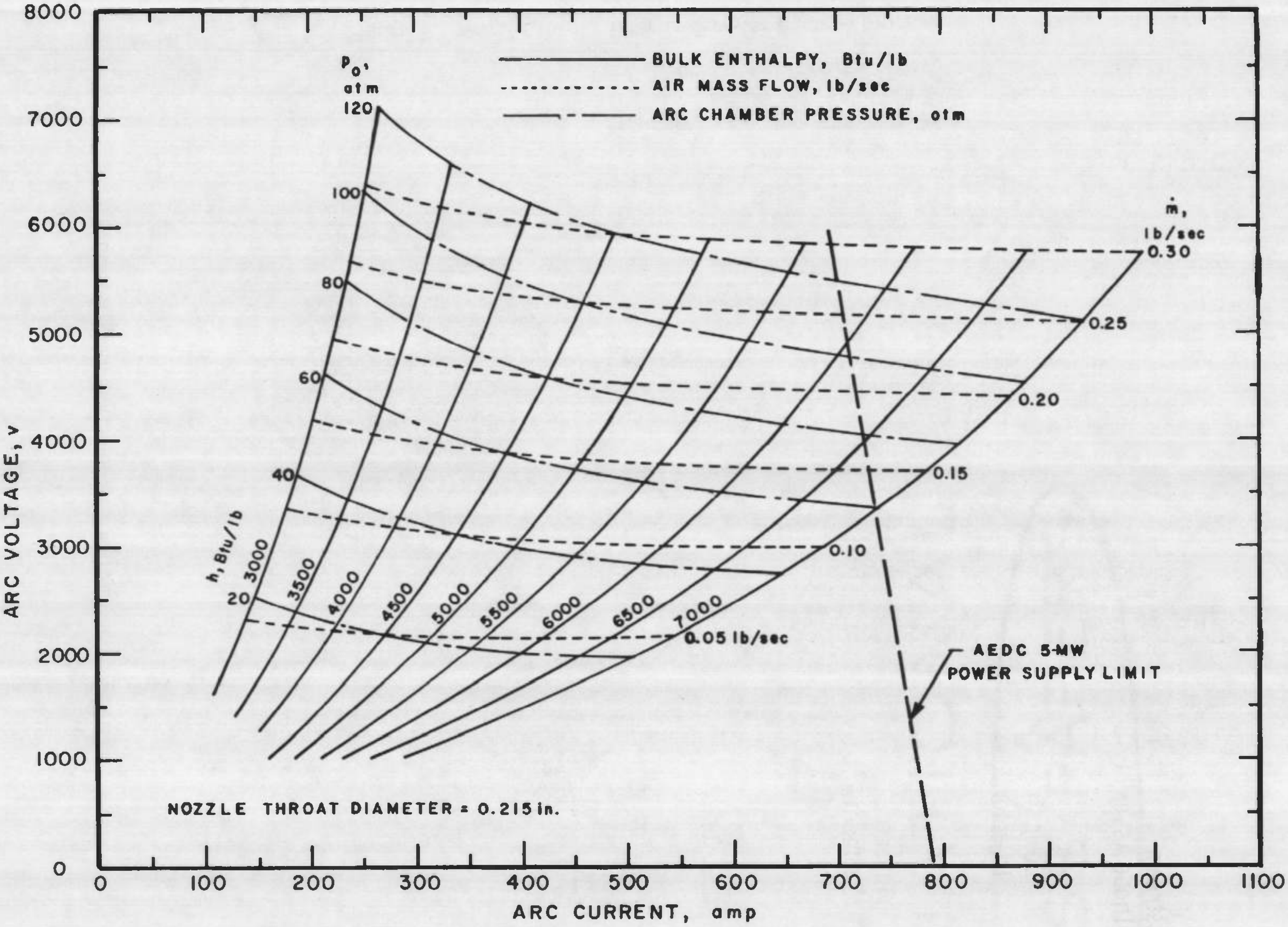


Figure 6. Predicted performance envelope — 5-MW segmented arc heater.

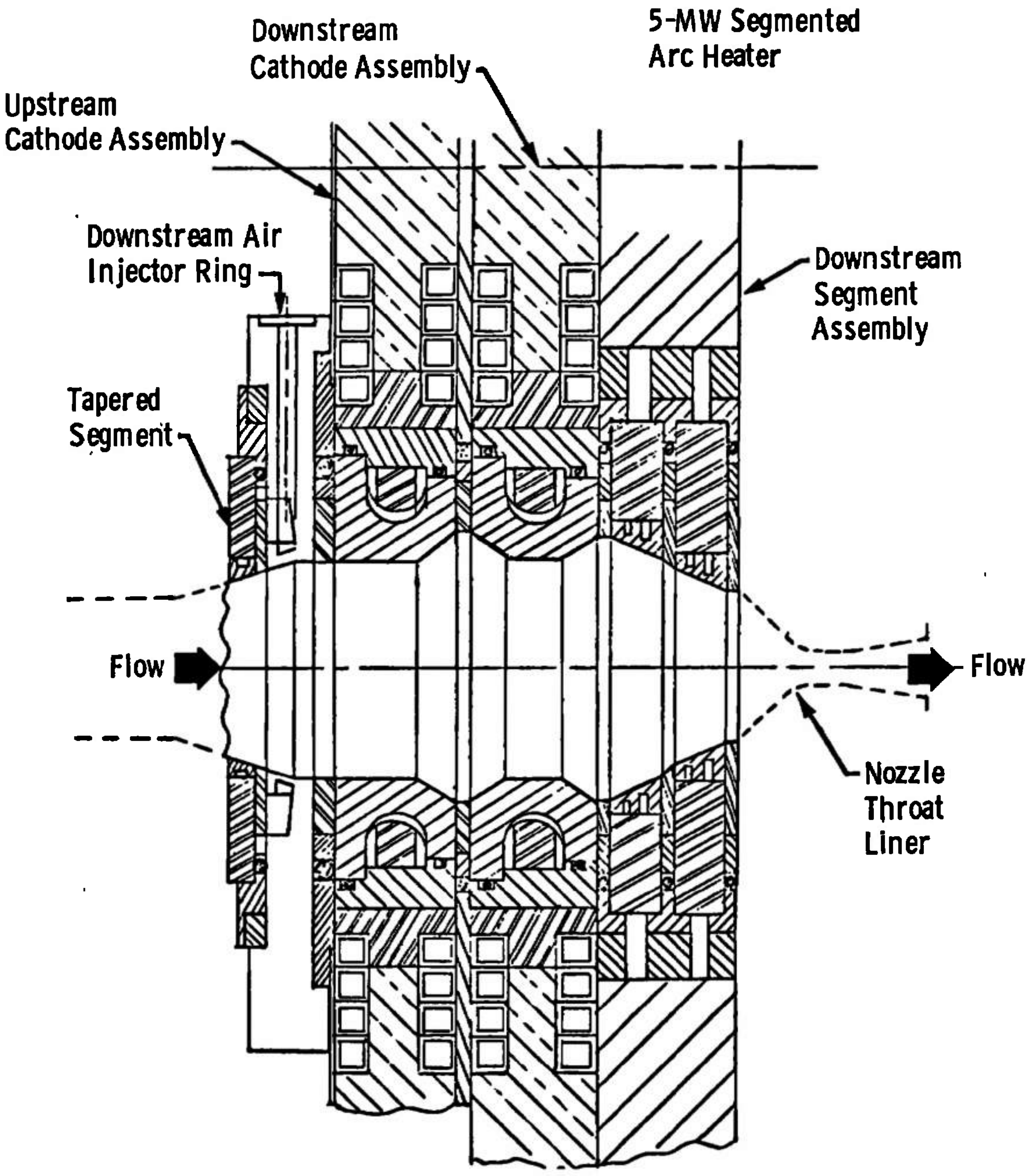


Figure 7. Downstream air injection modification.

TEST AA042 FY73

SYM.	RUN	Po	V	I	SEG. PAIRS SHORTED
○	7	46 atm.	3016 V.	529 amps	NONE
□	10	51 atm.	3215 V.	524 amps	6
△	11	51 atm.	3380 V.	512 amps	14

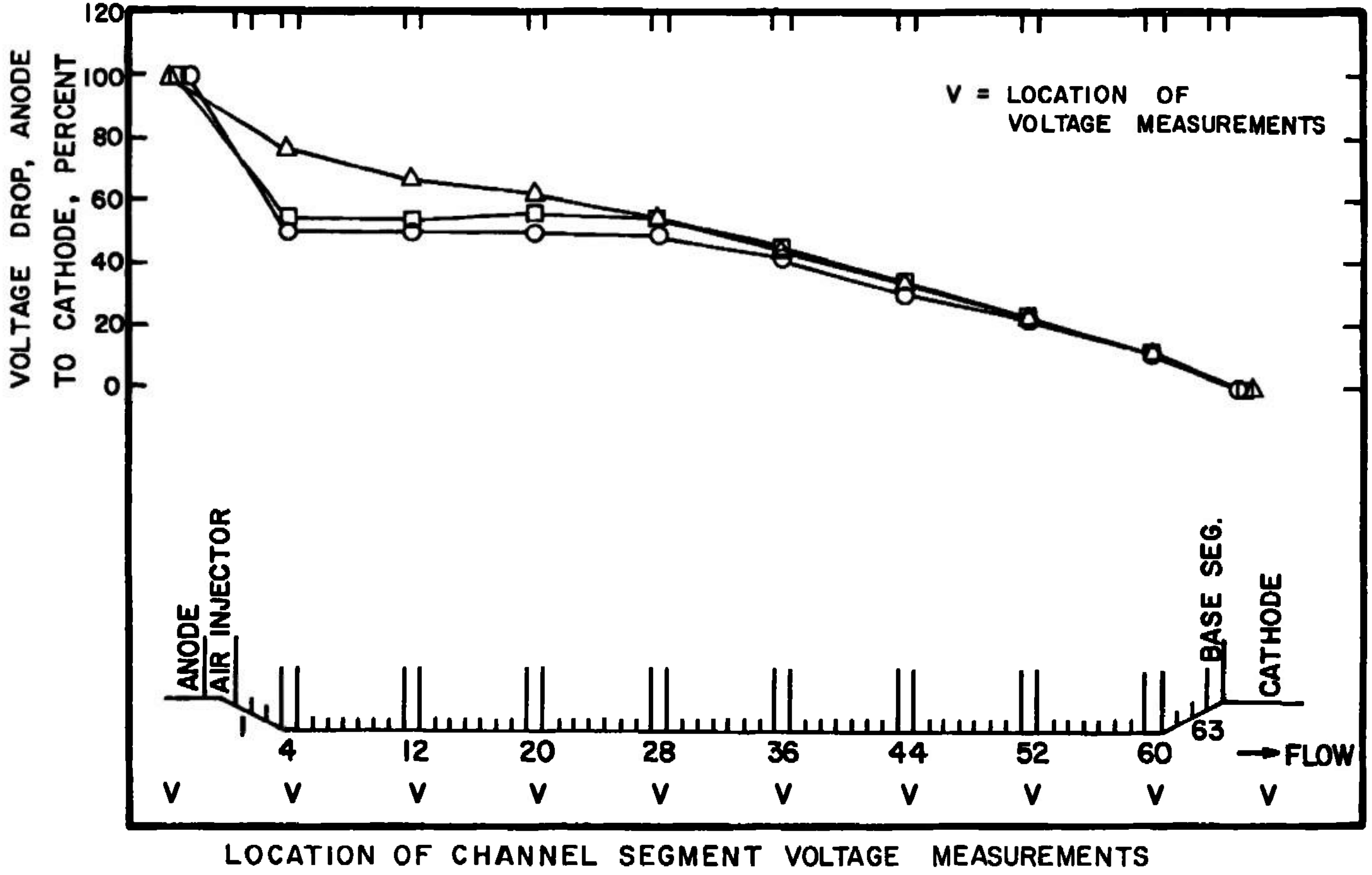
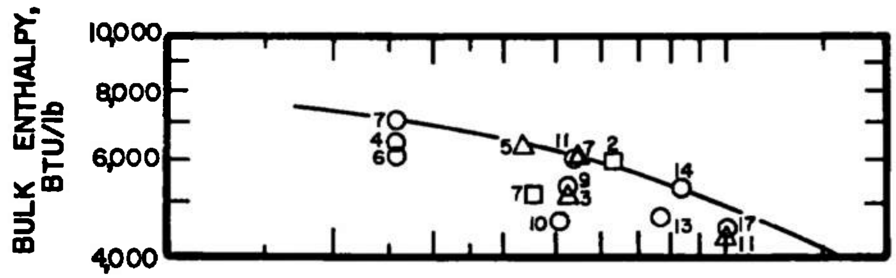


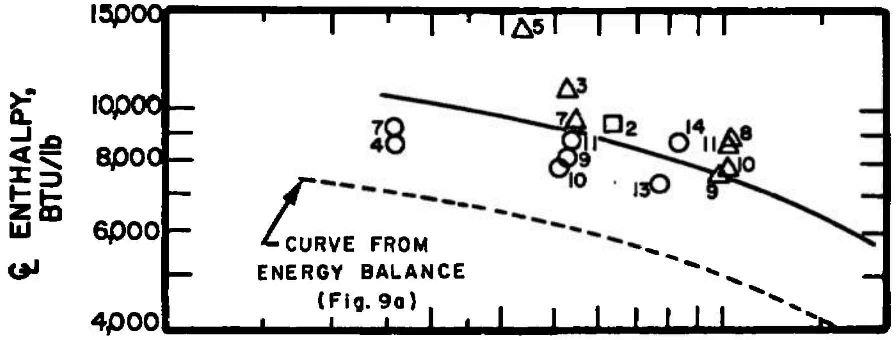
Figure 8. Channel voltage profile measurements.

SYM.	FY
○	72
□	73
△	74

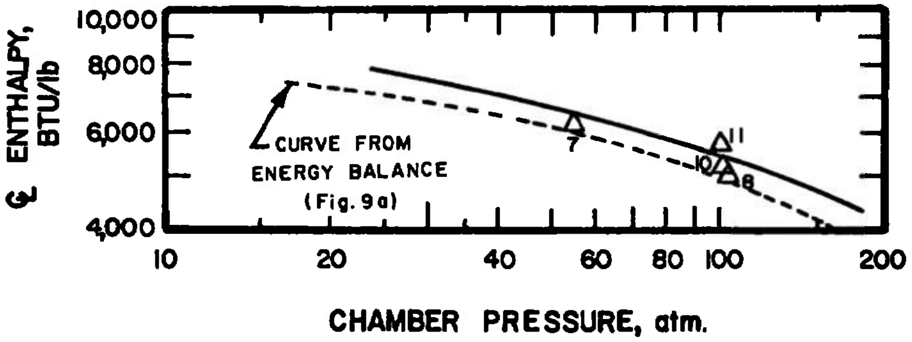
NUMBERS CORRESPOND TO RUN NUMBERS IN TABLES 1, 2, and 3.



a. Energy balance



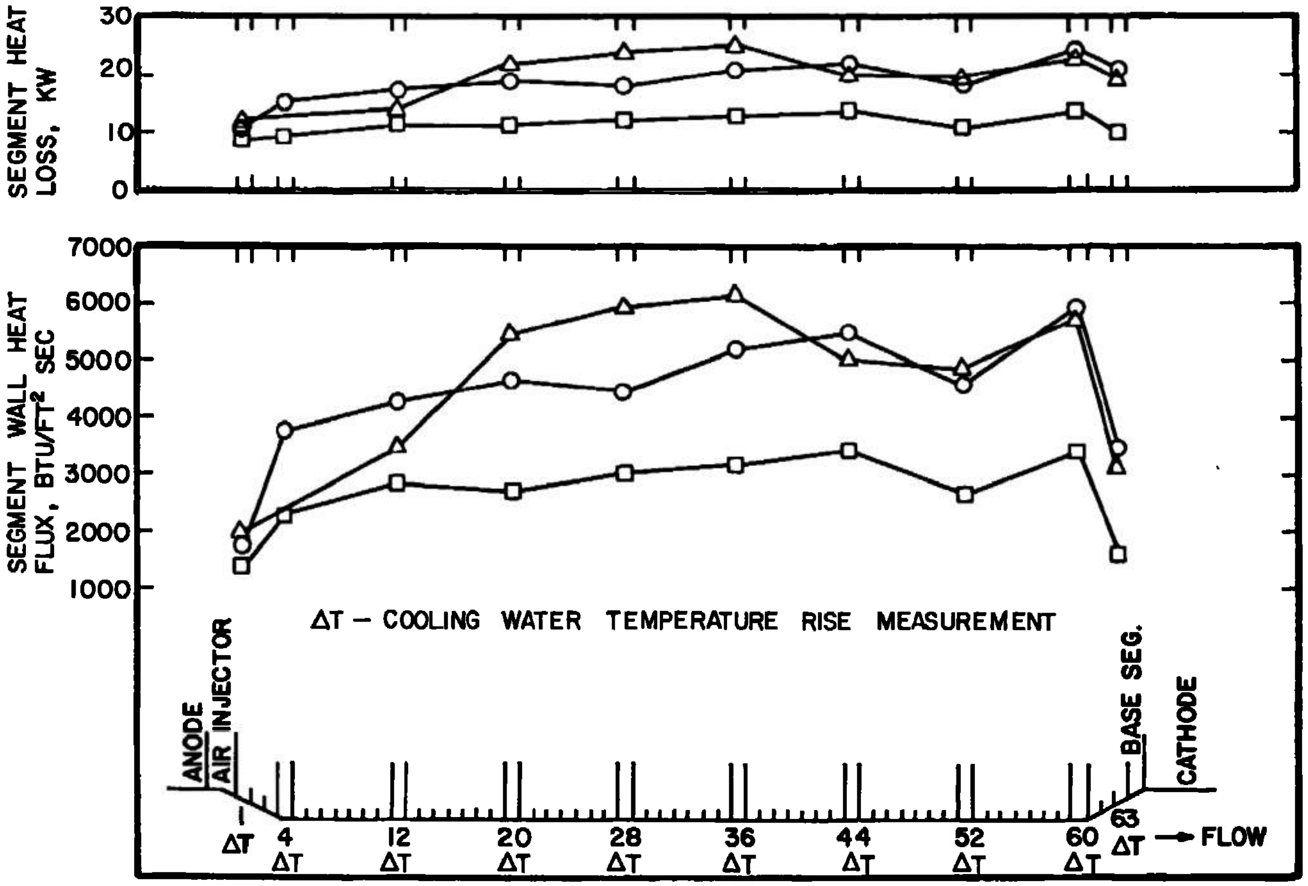
b. Calculated enthalpy based on pressure and calorimeter data



c. Enthalpy probe

Figure 9. Segmented arc heater enthalpy data.

SYM	TEST	RUN	Po	I	POWER IN	I/CM^2
○	AA042	2	64 atm	682 amps	2.42 MW	154
□	AA042	7	46 atm	529 amps	1.60 MW	120
△	AA044	11	102 atm	554 amps	2.76 MW	125



LOCATION OF CHANNEL SEGMENT MEASUREMENT

Figure 10. Channel segment heat loss and wall heat flux profiles.

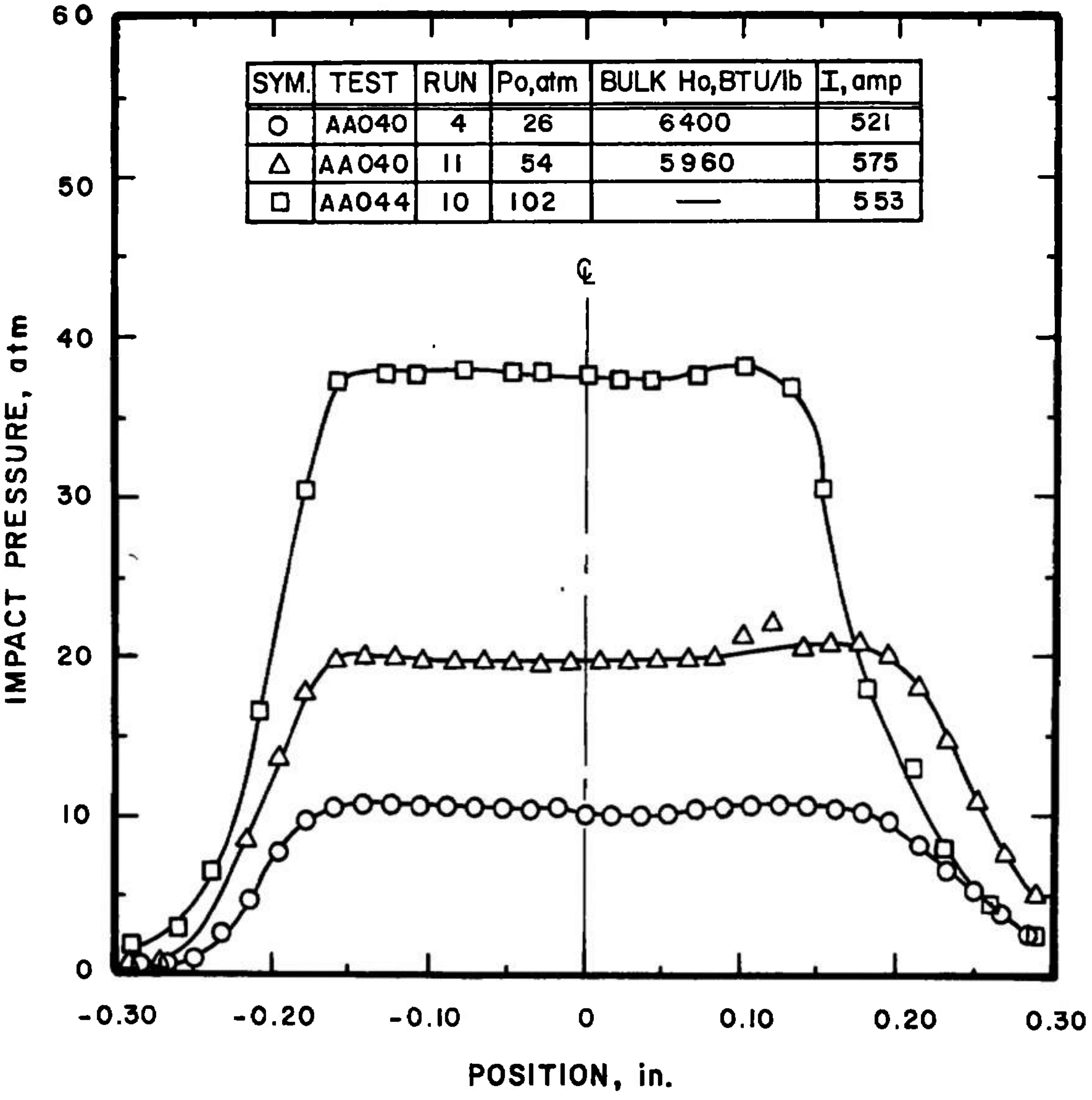
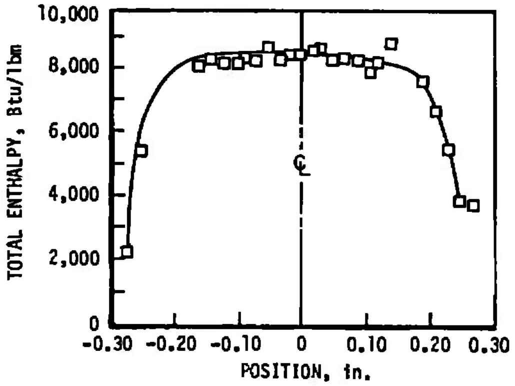
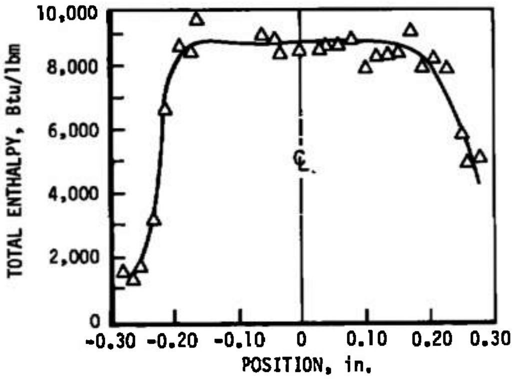


Figure 11. Nozzle exit pressure profiles.

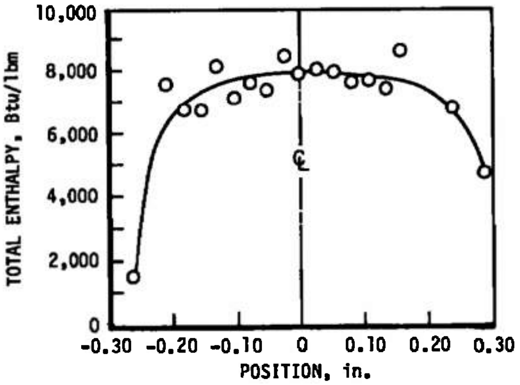
SYM	TEST	RUN	P_0, atm	BULK H_0, Btu/lb	I, amps
□	AA040	4	26	6400	521
△	AA040	11	54	5960	575
○	AA044	10	102	--	553



a. 26-atm chamber pressure



b. 54-atm chamber pressure



c. 102-atm chamber pressure

Figure 12. Nozzle exit enthalpy profiles (based on heat-transfer measurements).

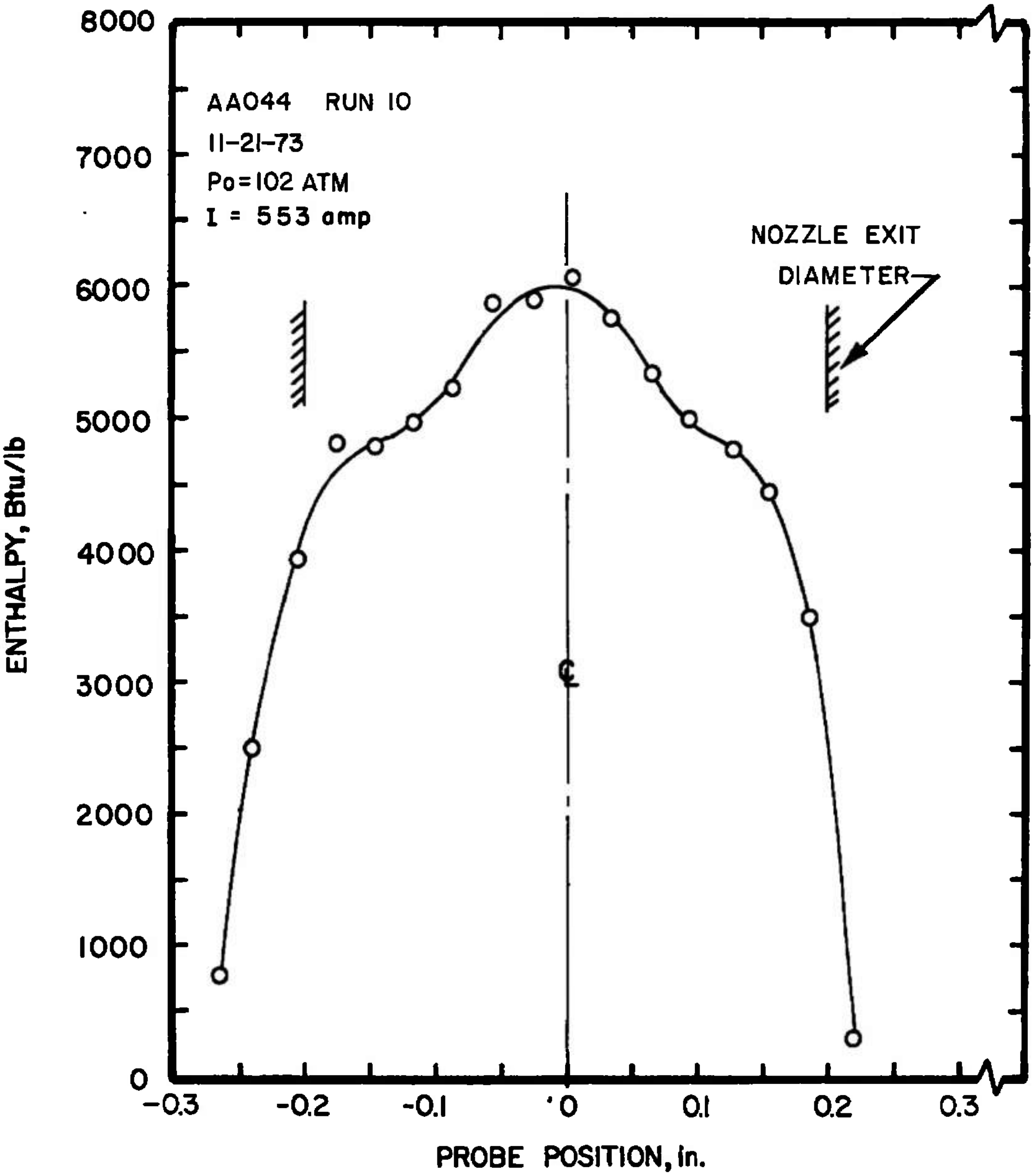
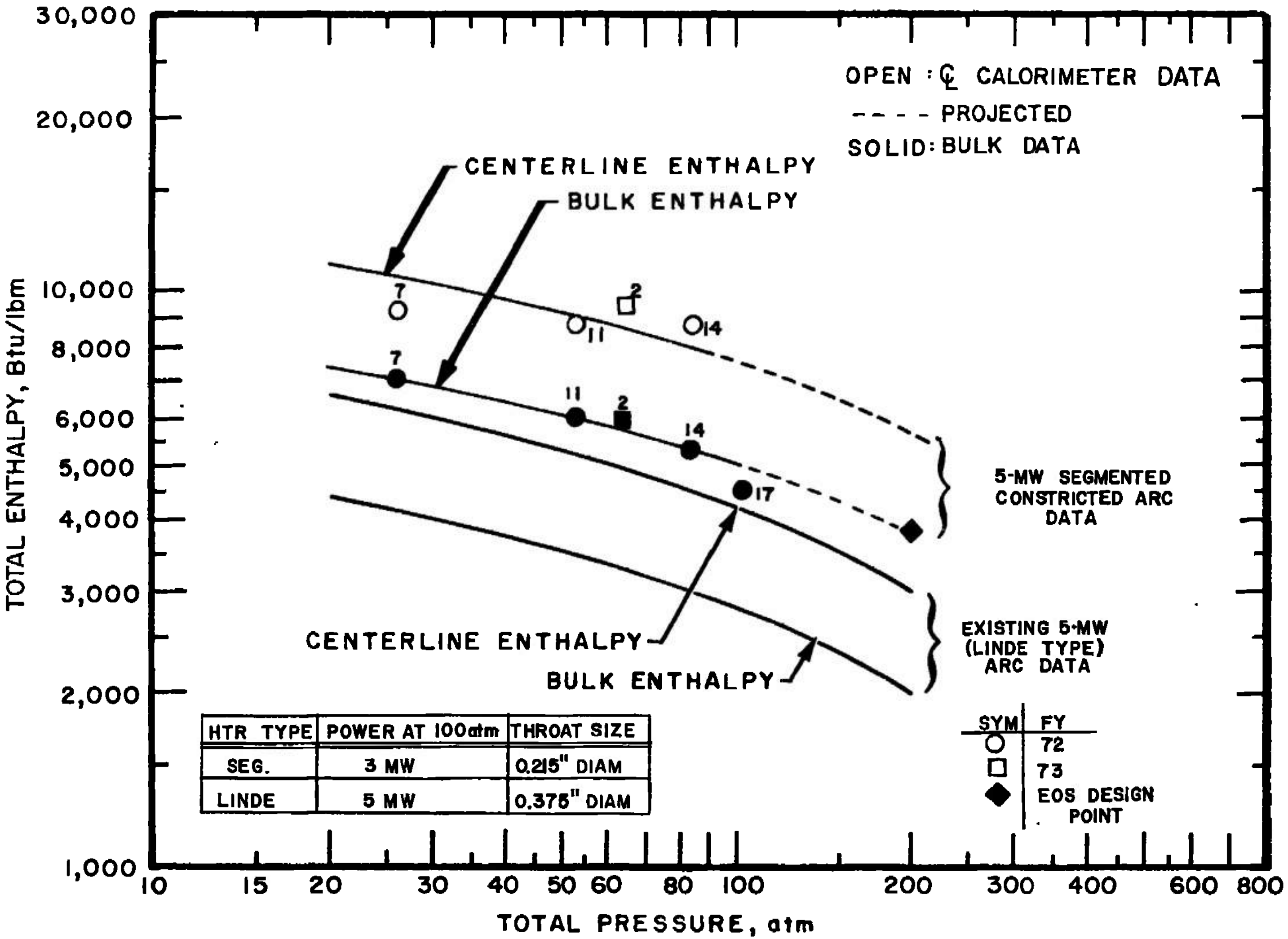


Figure 13. Enthalpy profile at 102-atm chamber pressure.



HTR TYPE	POWER AT 100atm	THROAT SIZE
SEG.	3 MW	0.215" DIAM
LINDE	5 MW	0.375" DIAM

Figure 14. Comparison of segmented arc performance with present 5-MW arc heater capability at AEDC.

Table 1. Fiscal Year 1972 Data Summary

Test AA040			Arc Heater Data					Model Data			
Run	Date	Run Time, sec	V, v	I, amp	$\dot{m}$, lb/sec	Bulk H_o, Btu/lb	p_a, atm	℄p_t, atm	℄$\dot{q}_{cw}$, Btu/ft^2-sec	℄h, Btu/lb	Remarks
1	1-26-72	1.5	1847	533	0.050	-	21.5	-	-	-	Air Ratio 1:1*. Insulator erosion.
2	2-11-72	5.5	1934	526	0.051	-	25.4	-	-	-	Air Ratio 1:1. Insulator damage.
3	2-19-72	4.0	2050	524	0.055	-	26.5	-	-	-	Air Ratio 3.5:1. Arc attachment good.
4	2-21-72	18.7	2090	521	0.055	6403	29.3	10.0	7200	9600	Air Ratio 3.5:1. Arc attachment good.
5	2-24-72	3.1	2050	441	0.057	-	25.9	-	-	-	Air Ratio 3.5:1. Arc attachment good.
9	2-29-72	15.3	2080	427	0.058	9024	26.0	9.9	-	-	Air Ratio 3.5:1. Arc attachment good.
7	3-02-72	18.0	2120	591	0.055	6989	26.2	10.5	8000	9200	Air Ratio 3.5:1. Arc short of optimum.
8	3-07-72	3.0	3330	477	0.120	-	52.4	-	-	-	Air Ratio 3.5:1. Arc attachment good.
9	3-09-72	14.9	3300	475	0.120	5326	53.2	20.3	9700	8100	Air Ratio 3.5:1. Arc attachment good.
10	3-23-72	19.3	3360	370	0.121	4589	51.0	19.4**	9100	7900	Air Ratio 3.5:1. Arc attachment good.
11	3-27-72	15.0	3300	575	0.116	5963	53.7	19.7	10300	8700	Air Ratio 3.5:1. Arc short of optimum.
12	3-30-72	4.0	4180	462	0.177	-	72.1	-	-	-	Air Ratio 3.5:1. Arc slightly longer than optimum.
13	4-03-72	16.0	4230	477	0.187	4993	77.6	29.9	11000	7300	Air Ratio 3.5:1. Arc attachment good.
14	4-05-72	15.0	4495	561	0.192	5270	94.4	31.5	13000	8700	Air Ratio 3.5:1. Arc attachment good.
15	4-20-72	4.1	4920	472	0.248	-	95.2	-	-	-	Air Ratio 3.5:1. Arc slightly longer than optimum.
16	4-26-72	10.0	5250	461	0.267	-	101.1	-	-	-	Air Ratio 3.5:1. Arc attached to upstream segment and caused segment failure after 2-sec run time; external arc occurred after 9-sec run time.
17	5-01-72	20.1	4830	602	0.290	4449	102.0	-	-	-	Air Ratio 3.5:1. Arc attachment longer than optimum; gas leak occurred between cathode and downstream segment after 12 sec.
18	5-24-72	3.0	4700	582	0.252	-	100.7	-	-	-	Air Ratio 3.5:1. Nozzle throat failed after 2.5 sec.

*Air Ratio of Air Injection Ring to End Plate
**Estimated

Table 2. Fiscal Year 1973 Data Summary

Test AA042			Arc Heater Data					Model Data			
Run	Date	Run Time, sec	V, v	I, amp	$\dot{m}$, lb/sec	Bulk H_o, Btu/lb	p_o, atm	¢p'_t, atm	¢$\dot{q}_{cw}$, Btu/ft^2-sec	¢h, Btu/lb	Remarks
1	9-14-72	4.5	3370	683	0.135	-	59.7	-	-	-	Cathode erosion severe; Air ratio 3.5:1.
2	9-25-72	17.1	3544	682	0.136	5886	63.9	24	12400	9400	Cathode erosion moderate; Air ratio 7:1.
3	9-29-72	3.0	3910	693	0.196	-	-	-	-	-	Base segment burned through, Air ratio 3:5:1.
4	10-17-72	2.7	4090	658	0.196	-	75.6	-	-	-	Base segment burned through, Air ratio 3:5:1.
5	11-10-72	4.2	3190	553	0.118	-	48.4	-	-	-	Downstream air injection; Air ratio 7:2:1*; Some arc attachment to nozzle.
6	1-11-73	4.2	3410	600	0.14	-	55.5	-	-	-	Downstream air injection; air ratio 20:6:1. Minor arc attachment to downstream segments.
7	1-17-73	12.0	3016	529	0.112	5140	46.3	-	-	-	Downstream air injection; air ratio 48:14:1. Arc attachment optimized at this condition. (Air ratio remained the same for remainder of runs.)
8	1-26-73	4.0	3503	507	0.118	-	48.6	-	-	-	Both spin coils disconnected; electrode erosion moderately high.
9	2-01-73	-	-	-	-	-	-	-	-	-	External arc-over.
10	2-02-73	4.3	3215	524	0.118	-	50.5	-	-	-	Same configuration as Run 7; 6 channel segment pairs shorted, arc attachment good.
11	2-08-73	4.1	3380	512	0.118	-	51.0	-	-	-	Same configuration as Run 7; 14 channel segment pairs shorted; strong evidence of arcing at walls of channel segment 1 through 26 and 46 through 63.

*Air Ratio of Upstream Air Injection Ring:
End Plate: Downstream Air Injection Ring.

Table 3. Fiscal Year 1974 Data Summary

Test AA044			Heater Data						Model Data					
Run	Date	Run Time, sec	V, v	I, amp	$\dot{m}$, lb/sec	Bulk H_o, Btu/lb	P_o, atm	P_t', B. L. Probe, atm	℄$\dot{q}_{cw}$ Calorimeter, Btu/ft^2-sec	℄h Calculated, Btu/lb	P_t' C2 Press. Probe, atm	℄h C4 Enthalpy Probe, Btu/lb	Remarks
1	9-26-73	4.6	3115	557	0.115	-	49.5	-	-	-	-	-	New air ring at end of channel. New welded and silver-soldered segments. Air ratio 20:8:1.
2	10-04-73	4.6	3145	550	0.115	-	50.5	-	-	-	-	-	Channel air ring removed; air to old downstream tapered ring; Ratio 48:14:1.
3	10-10-73	21.1	3285	543	0.123	5084	52.9	16.9	12,800	10,800	-	-	Same as Run 2.
4	10-17-73	4.3	4160	580	0.181	-	77.5	-	-	-	-	-	Air Ratio 48:19:1.
5	10-25-73	14.4	3050	635	0.10**	6340**	43.9	7.84	11,000	14,000	-	-	Air line to air ring broke at 2.9 sec. Air ratio 20:8:1 prior to line breaking.
6	11-01-73	10.8	4325	562	0.181	-	76.5	-	-	-	-	-	Configuration same as Run 5. Burn-through channel at 2.9 sec.
7	11-07-73	14.4	3460	525	0.120	6025	55.4	18.2	11,300	9,500	19.6	6250	Air ratio 48:14:1; four models injected.
8	11-12-73	4.8	5150	570	0.255	-	104.1	34.5	14,000	8,800	38.8	5000	Air 48:19:1; four models injected; burn-through channel at 4 sec.
9	11-16-73	4.2	4900	555	0.255	-	99.3	34.5	13,200	7,600	38.4	-	Air same as Run 2, moved S.S. segments downstream.
10	11-21-73	4.6	4950	553	0.261	-	102.0	34.6	12,800	7,800	37.7	5300	Air ratio changed 20:10:1; four models injected.
11	11-28-73	13.9	4980	554	0.253	4256	101.5	31.3	13,200	8,600	37.4	5750	Air ratio 20:10:1; four models injected; burn-through channel at 12 sec.

*Air Ratio of Upstream Air Injection Ring: End Plate.
Downstream Air Injection Ring
**Estimated

Table 4. Descriptive Test Summary for Fiscal Year 1972, Test AA040

Run	Objective	Configuration	Results
1	Short shakedown run at 25 atm, 500 amp.	Initial configuration shown in Fig. 3; four upstream segments and new nozzle configuration installed.	BN insulators near anode severely eroded by cold air; arc attachment OK; silver-solder joint leaking in downstream segment No. 1.
2	Repeat of Run 1.	Same as Run 1, except fused silica insulator installed downstream of anode and two Synthane® insulators were installed immediately upstream of anode. Stud bolt insulators were installed at nozzle and cathode end of heater.	Fused silica insulator broke into several pieces and scattered throughout heater. Arcing occurred between anode and air injector ring. The Synthane insulators were charred but not damaged. Surface tracking on upstream segments near anode; all segments leak-checked OK.
3	Repeat of Run 2 to correct arc attachment location.	Replaced fused silica insulator with BN. A 0.067-in.-diam orifice was installed in air line to end plate to reduce upstream air flow.	Heater operation was satisfactory, with arc attachment on downstream taper of anode and near upstream edge of cathode. Segments were free of arc tracks and water leaks.
4	Steady-state energy balance run at nominal 25 atm and 525 amp.	Same as Run 3.	Arc attachment and general condition of heater were good. A null-point calorimeter was swept through the flow 0.1 in. downstream of the nozzle exit; a 0.25-in.-NR graphite model was injected into the flow to measure centerline stagnation pressure.

Table 4. Continued

Run	Objective	Configuration	Results
5	Checkout run at nominal 25 atm and low current.	Same as Runs 3 and 4.	Arc attachment and general condition of heater were good. No water in heater after run.
6	Energy balance run at 25 atm and low current.	Same as Runs 3, 4, and 5.	Arc attachment was optimized for this condition. Heater ran well for 16 sec and the calibration models were injected.
7	Energy balance run at nominal 25 atm and high current.	Same as Runs 3, 4, 5, and 6.	In general the run was satisfactory and the calibration models were injected into the flow. Anode arc attachment was downstream of the optimum location. The heater was dry inside after run, but the air injection ring and a tapered segment had pinhole leaks at the silver solder joint.
8.	Checkout run at nominal 50-atm chamber pressure and 500 amp current.	Same as Runs 3, 4, 5, 6, and 7.	Arc attachment nearly optimized. Heater was dry and in good condition after run.
9	Energy balance run at same condition as Run 8.	Same as Runs 3, 4, 5, 6, 7, and 8.	Arc attachment and general condition of heater good. Calibration models injected which included in addition to the null-point calorimeter and graphite pressure model, a fast response copper pressure probe to obtain a nozzle exit pressure profile.
10	Energy balance run at nominal 50 atm and reduced current.	Same as Runs 3, 4, 5, 6, 7, 8, and 9.	Same as Run 9.
11	Energy balance run at nominal 50 atm and 600 amp.	Same as Runs 3, 4, 5, 6, 7, 8, 9, and 10.	Same as Runs 9 and 10 except arc shorter than optimum.

Table 4. Continued

Run	Objective	Configuration	Results
12	Checkout run at nominal 80 atm.	Same as Runs 3 through 11 except a new cathode liner installed with the angle of the tapered surface modified to allow replacement of the tapered BN insulator downstream of the cathode with a straight insulator.	Heater ran satisfactorily; arc longer than optimum. No water in heater after run.
13	Energy balance run at same conditions as Run 12.	Same as Run 12.	Heater ran well for 15 sec and three models were injected (same as Runs 9, 10, and 11). Arc attachment nearly optimized.
14	Energy balance run at nominal 80 atm and increased current.	Same as Runs 12 and 13.	Same as Run 13. Found water leaks in four segments during post check.
15	Checkout run at nominal 100-atm chamber pressure and 475-amp current.	Same as Runs 12, 13, and 14.	Heater run was satisfactory; arc slightly longer than optimum. Found water leaks in silver solder joints of three segments during post inspection. No evidence of arc tracking or overheating on any segments.
16	Energy balance run at same condition as Run 15.	Same as Runs 12 through 15.	Arc attached to the first upstream segment (next to anode), and it burned through after 2 sec of heater operation. Then an external arc occurred at 9 sec caused by water spraying on the outside of the heater. Minor external damage occurred to hoses, insulators, and thermocouples. Internal damage was confined to the segment that failed and adjacent insulators. The models were not injected.

Table 4. Concluded

Run	Objective	Configuration	Results
17	Energy balance run at nominal 100-atm chamber pressure and 600-amp current.	Same as Runs 12 through 16.	Arc was longer than optimum. Heater ran satisfactorily for 12 sec; then gas leak occurred between cathode liner and first downstream segment. Damage was confined to the cathode and downstream segment assemblies. An energy balance was obtained prior to failure, but models were not injected.
18	Repeat of Run 17.	Same as Runs 12 through 17.	Heater reached full chamber pressure of 100 atm; however, after 2.5 sec of operation the nozzle throat liner failed causing sudden decrease in chamber pressure. The other components of the heater were undamaged.

Table 5. Descriptive Test Summary for Fiscal Year 1973, Test AA042

Run	Objective	Configuration	Results
1	Checkout run at nominal 60-atm chamber pressure and 700 amp current.	Same as FY72 Test AA040 Runs 12 through 18; new nozzle liner.	Heater ran satisfactorily; however, severe cathode erosion occurred and some arc attachment on the base segment was evident. Found small water leaks (silver solder joint) in 4 segments after the run.
2	Energy balance run at same conditions as Run 1.	Same as Run 1 except an 0.0465-in.-diam orifice installed in air line to end plate.	Condition of heater was good after the run; however, cathode erosion was moderately severe. Five models were injected, including two null-point calorimeters, one boundary-layer pressure probe, one 0.25-NR teflon ablation model, and one graphite centerline pressure model.
3	Energy balance run at nominal 80 atm and 700-amp current.	Original 0.067-in.-diam orifice installed in air line to end plate (configuration same as Run 1).	Burned through base segment after 3 sec of heater operation; cathode erosion severe on upstream end. Suspect arc attachment to base segment caused failure. Other component damage was minor.
4	Energy balance run at 80 atm and 600-amp current.	Same as Run 3 with new base segment replacement and other damaged components.	Same as Run 3; base segment failure at 1.5-sec run time.

Table 5. Continued

Run	Objective	Configuration	Results
5	Checkout run at 50 atm, 550 amp with downstream air injection.	Downstream air injection ring and dual cathode installed (see Fig. 7). The 0.067-in.-diam orifice remained in air line to end plate; the 0.0465-in.-diam orifice was installed in air line to downstream air ring. Both cathode coils were hooked in series with the arc current but only the downstream cathode liner served as an electrode.	Arc attachment was evident at the nozzle throat and exit indicating a "blown" arc. Other heater components looked normal. Excessive downstream air rate caused the extended arc.
6	Checkout run at 60 atm and 600 amp with reduced downstream air injection.	Same as Run 5 except 0.028-in.-diam orifice installed in downstream air injection supply line.	Cathode arc attachment slightly downstream of optimum, indicating still somewhat excessive amount of downstream air. All heater components were satisfactory; however several silver-solder joints were leaking in the channel segments (soft solder had melted from previous repair). No spare segments were available that had not been repaired with soft solder.
7	Energy balance run at 50 atm and 500 amp with further reduction in downstream air injection.	Same as Run 6 except 0.018-in.-diam orifice installed in downstream air injection supply line.	Heater ran smoothly at this condition; the air ratios appeared to be optimized as well as the arc attachment locations. The nozzle throat liner was measured and found to be enlarged (average throat diameter was 0.223 in.). The erosion was caused by the blown arc on Run 5.

Table 5. Continued

Run	Objective	Configuration	Results
	The remaining runs in FY73 were made to determine various minor configuration changes on the arc heater operation. The nominal condition for these runs was 50 atm and 500 amp. Run 7 served as a baseline for comparison.		
8	Checkout run without spin coils.	The magnotic spin coils at the anode and cathode were disconnected; otherwise heater configuration was the same as Run 7.	The heater ran satisfactorily and arc length was unchanged; however, the surface erosion of both electrodes was moderately severe.
9	Checkout run with six adjacent pairs of channel segments shorted.	Same as Run 7 except the following pairs of segments immediately downstream of the upstream air ring were shorted together: 1-2, 3-4, 5-6, 7-8, 9-10, and 11-12.	External arc occurred upon current initiation caused by breakdown of standoff insulator on anode buss. The heater did not draw current internally, and vacuum checked good after run. External damage minor.
10	Same as Run 9.	Same as Run 9.	Arc attachment was nearly optimized, and arc tracking was not evident on any channel segments (including the ones shorted together). No detrimental effect of the segment shorting was established. There was some moisture in the heater after the run.

Table 5. Concluded

Run	Objective	Configuration	Results
11	Checkout run with 14 adjacent pairs of channel segments shorted.	Same as Run 10 with these additional segments shorted together: 13-14, 15-16, 17-18, 19-20, 21-22, 23-24, 25-26, and 27-28. A 0.011-in.-diam starting wire was used to provide lower breakdown voltage.	Arc length appeared short of optimum probably due to arc shorting along channel wall. Moderately severe arc tracking occurred between adjacent unshorted segments on upstream end of channel down through segment 28. The next 20 segments had only slight evidence of tracking on the surface. The remaining 16 segments had increasing amounts of tracking toward the downstream end of the channel. The overall damage was negligible and part of the tracking may have been caused by the starting wire. Traces of the wire were evident inside the heater. There was moisture again from the repaired segments.

Table 6. Descriptive Test Summary for Fiscal Year 1974, Test AA044

Run	Objective	Configuration	Results
1	Short run at nominal 50-atm chamber pressure and 525-amp current with a new set of channel segments and a column air injection ring.	Basic heater configuration same as Test AA042, Run 6 (see Figs. 3 and 7). New channel segments were installed as follows (upstream to downstream): 13 welded segments, 15 silver-soldered segments, 23 welded segments; then a new 0.934-in.-diam channel air injection ring was installed with 0.028-in.-diam orifice in the air supply line. Standard tapered segments were located at each end of above channel configuration. Downstream air was not injected at the downstream air injection ring. The 0.067-in.-diam orifice was in the air line to the end plate.	Run was satisfactory, anode arc attachment was optimized, cathode attachment slightly upstream of optimum. Surface arc tracking occurred on approximately 12 welded segments upstream of the channel air injection ring. Found water leaks in five new welded segments after run.
2	Same as Run 1, but without channel air ring.	Same as Run 1, except the 0.934-in.-diam channel air injection ring was removed and the downstream air injection ring supplied with air through a 0.018-in.-diam orifice.	The 4-sec run was good; the arc attachment was optimized, and no evidence of water leaks was found in the channel.

Table 6. Continued

Run	Objective	Configuration	Results
3	Energy balance run at nominal 50 atm and 525 amp.	Same as Run 2.	Heater ran satisfactory for 21 sec with arc attachment on electrodes optimized. External water line broke at 15 sec run time and showered heater; however, no external arcing occurred. Heater was dry inside after run; however, pressure checking revealed 10 welded segments were leaking at weld joints. A calorimeter and pressure model were swept through the exit flow.
4	Short run at nominal 75 atm, 550 amp.	Same as Runs 2 and 3, except 0.0785-in.-diam orifice installed in air line to end plate.	The heater ran satisfactorily with no visible evidence of water in heater after run. Anode attachment location was optimized; cathode attachment was primarily on upstream cathode with severe arcing between the cathodes at BN insulator surface.
5	Energy balance run at nominal 75 atm and 550 amp.	Same as Run 4 except 0.028-in.-diam orifice in air line to downstream air ring.	Heater ran for 14 sec and two instrumented models were injected; however, at 3 sec the air line to the upstream air injection ring broke and chamber pressure dropped to 44 atm. Heater ran satisfactorily; however, anode arc attachment was on downstream end of anode liner.
6	Same as Run 5.	Same as Run 5.	Chamber pressure reached 76 atm; however, after 2.9 sec a burn-through occurred in the downstream set of welded channel segments. The damage was confined to that portion of the channel where the burn-through occurred. Cause was probably a water passage restriction in the segment that failed.

Table 6. Continued

Run	Objective	Configuration	Results
7	Same as Run 3 with enthalpy probe model installed.	Same as Runs 2 and 3.	Excellent run; arc attachment optimized, no segments leaking after run. Four instrumented models swept through the flow: one calorimeter, one enthalpy probe, and two pressure probes.
8	Short run at nominal 100-atm chamber pressure and 550 amp.	Same as Runs 2 and 3 except 0.0785-in.-diam orifice in air line to end plate.	Heater ran normally for 4 sec, then 0.5 sec before shutdown a welded channel segment in the downstream welded set failed. Again the failure was attributed to a restriction in the water passage of the segment that failed. Moderate erosion occurred between cathodes, which indicated the arc was attaching to the upstream cathode. Anode attachment was optimum. Four models were swept through the flow prior to failure.
9	Short run at nominal 100 atm, 550 amp with minor configuration changes.	Same as Run 8 except the 15 silver-soldered segment set was moved downstream 18 segment positions and the cathodes were shorted together electrically.	Arc attachment on both anode and cathode upstream of optimum; the heater run was satisfactory; however, the surfaces of several segments on the downstream end of the channel appeared to have experienced high heating rates.
10	Short run at same conditions as Run 9 with air injection ratios changed.	Same as Run 9 except 0.028-in.-diam orifice installed in air line to downstream air injection ring and 0.089-in.-diam orifice installed in air line to end plate.	Heater ran without problems and four models were injected into the flow. The anode arc attachment was slightly upstream of optimum; the cathode attachment was shared by both liner surfaces; however, the upstream liner had more erosion. No water in heater after run, and channel segments were satisfactory.

Table 6. Concluded

Run	Objective	Configuration	Results
11	Energy balance run at 100 atm and 550 amp.	Same as Run 10.	Heater ran for 14 sec, and 4 models were injected; however, after 12 sec a burn-through occurred five segment positions downstream from upstream end of straight portion of channel. Again, the segment was of welded construction and located in a relatively cool area of the heater. The arc attachment was optimized. Run time was sufficient prior to segment failure to obtain an energy balance.

NOMENCLATURE

℄_h	Centerline enthalpy, Btu/lb
$\text{℄}p'_t$	Centerline pressure at model stagnation point, atm
$\text{℄}\dot{q}_{cw}$	Centerline cold wall heat flux, Btu/ft^2-sec
d^*	Nozzle throat diameter, in.
H_o	Bulk enthalpy, Btu/lb
I	Arc current, amp
$\dot{m}$	Air mass flow rate, lb/sec
p_o	Chamber pressure, atm
V	Arc voltage, v

Abbreviations

BL	Boundary layer
BN	Boron nitride
NR	Nose radius
SS	Silver solder