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RESULTS OF TESTING ULTRAHIGH PRESSURE ELECTRIC ARC HEATERS

H. F. Lewis, D. D. Horn, and J. B. Patton

ARO, Inc.

October 1970

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NOTICES

AEDC-TR-70-228

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FOREWORD

The test program reported on herein was sponsored by Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 64719F, Facility Technology.

The results of the test program presented in this report were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the AEDC, AFSC, Arnold Air Force Station, Tennessee, under Contract F40600-71-C-0002. The work was performed from July 1969 through June 1970 under ARO Project No. PL3008, and the manuscript was submitted for publication on August 26, 1970.

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This technical report has been reviewed and is approved.

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ABSTRACT

Results of testing three electric arc heaters designed by Electro-Optical Systems (EOS) are presented. Two of the heaters had power input ratings of 1 MW; one was designed for nitrogen and one for air operation. The third was rated at 5 MW for air operation. All three heaters were of segmented constrictor design for d-c operation. Operating experience and design information were gained from the 1-MW heaters. In their present form, neither is useful for ablation or aerodynamic tests because of unreliable operation and unsteady pressure and power outputs. The 5-MW heater was designed for 200 atm pressure and 3830 Btu/lb enthalpy. This goal was not achieved because of repeated failures and heater damage caused by electrical arc-overs. The best demonstrated performance by the 5-MW EOS heater was 6135 Btu/lb at 23 atm pressure. Some comparisons are made of the thermodynamic performance, component durability, and maintainability of the 5-MW EOS heater and a Linde heater of equal power rating. All testing was done at Arnold Engineering Development Center.

CONTENTS

APPENDIXES

I. ILLUSTRATIONS

Page

II. TABLES

NOMENCLATURE

B-Field	Magnetic field
D	Heater constrictor diameter, in.
d^*	Throat diameter of exit nozzle, in.
E	Arc voltage, v
h_o	Total enthalpy (bulk or mass-averaged value) of plasma jet, Btu/lb
i	Arc current, amp
L	Arc column length, in.
ℓ	Heater chamber length, in.
$\dot{m}$	Gas mass rate of flow, lb/sec
N_2	Molecular nitrogen, gas
p_o	Arc heater chamber pressure, atm (1 atm = 14.696 lb/in.^{2})
p_s	Gas supply pressure, atm (1 atm = 14.696 lb/in.^{2})
P_{GAS}	Net power to working gas, (P_{IN} - P_{LOSS}), kw
P_{IN}	Total power supplied to heater, kw
P_{LOSS}	Power lost to cooling water, kw
S.F.	Scale factor

t	Time, sec
η	Arc heater efficiency, 100 x (P_{GAS}/P_{IN}), percent

SECTION I
INTRODUCTION

In April 1967, Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), contracted with Electro-Optical Systems (EOS) to perform an Ultrahigh Pressure Arc Heater Study. The study was to encompass all areas needed to produce an electric arc heater (d-c) that would operate at a pressure of 200 atm and an enthalpy high enough to provide realistic simulation of the stagnation point conditions on a reentry vehicle. Most of the high-pressure, high-energy ablation tests have utilized the Linde- or Huels-type arc heater. Two such heaters have been operated at 200 atm pressure, but the enthalpy (bulk or mass-averaged value) has been only 2000 to 2400 Btu/lb. The 200-atm pressure capability was developed by personnel working independently at AEDC and McDonnell-Douglas Corporation (St. Louis) (Ref. 1).

Some of the limitations of the Linde-type arc heater are noted in Ref. 2:

1. The length of the arc cannot be controlled but is dependent on the operating parameters of pressure, mass flow rate, arc current, and constrictor diameter.

2. The arc length fluctuates because of self-magnetic effects, producing unsteady values of pressure and enthalpy.

3. The constrictor channel also serves as an electrode, which results in high electrode erosion.

4. Repeatability of test conditions is difficult to achieve because of the arc length fluctuations.

These four limitations were to be overcome by designing a constricted, segmented-channel arc heater with a fixed interelectrode distance, which would result in a "stretched" arc of greater length than a "natural-length" arc. A constricted, segmented-channel arc heater of given geometry, gas mass flow, and arc current would, therefore, produce a higher pressure and enthalpy than a Linde-type heater of the same geometry, operating with the same mass flow and current, because of increased power input with the "stretched" arc.

This design philosophy was used to design and test a 1-MW heater at EOS. Figures 1a and b (Appendix I) and Ref. 3 describe this heater, which was operated using nitrogen as the test gas. Maximum concurrent operating conditions of a pressure of 96 atm and an enthalpy of 5760 Btu/lb were demonstrated, at which time the EOS power supply limit was reached.

A heater of 1-MW power rating, similar to the one tested at EOS, was designed by EOS and tested at AEDC. The original version of this heater was initially operated on nitrogen; then it was modified and operated using air. The results of these tests are discussed in this report.

After the demonstration run with nitrogen of 96 atm and 5760 Btu/lb, additional analytical and design work was done by EOS (see Ref. 2), with the specific goal of producing a d-c arc heater capable of supplying air at 200 atm and 3830 Btu/lb (bulk or mass-averaged value) with a power input of 5 MW. The heater was delivered to AEDC in November 1969, and this report is primarily concerned with presenting the results of operational testing and modifications to this 5-MW heater through the month of June 1970. Development testing was terminated at this time for lack of a sponsor and necessary funding.

SECTION II
TEST APPARATUS

2.1 ELECTRIC POWER AND OTHER UTILITIES

Electric power was supplied to the arc heater through a series of transformers and an ignitron rectifier, as shown in the diagram in Fig. 2. High-pressure air (up to 4000 psia) was supplied by the AEDC von Kármán Facility (VKF) either from a storage bottle or directly from a compressor, through pressure control and metering stations. Nitrogen (up to 4000 psia) was supplied from a storage bottle. Demineralized cooling water was supplied to the arc heater by two centrifugal pumps, each rated at 120 gpm at 1200 psig. Helium gas, used for arc initiation, was supplied from K-bottles.

2.2 INSTRUMENTATION

Pressures, temperatures, and cooling water flows were read from a recording oscillograph; strain-gage transducers, thermocouples, thermistors, and turbine-type flowmeters were sensors for these variables. Redundant systems were provided for temperature and flow measurements. Arc current and voltage were measured by use of current sensors and voltage dividers, respectively. Air mass flow was measured using venturi flowmeters; these flow measuring devices were calibrated by flowing air to a tank and weighing on precision scales and were always operated in the choked condition. Control room readout was made using voltmeters, autosyn gages, Simplytrol® meters, and analog-to-digital converters. Closed-circuit television was used to monitor the arc heater during operation.

2.3 1-MEGAWATT HEATERS

As stated in the Introduction, the first EOS arc heater tested at AEDC was a segmented, constricted channel heater similar to the original demonstration heater tested at the EOS facility. This heater was initially operated with nitrogen at AEDC, then modified and operated with air. The nitrogen version is shown in section in Fig. 3a, and by a photographic view in Fig. 3b. Tungsten was used for the cathode and copper for the anode. Constrictor channel segments were made with a water-cooled copper inner ring silver-brazed to a copper outer ring. The segments were electrically insulated by boron-nitride spacers. Air was injected into the heater just downstream of the cathode. The air ports were oriented so that the flow had a clockwise (looking downstream) swirl. Figure 3c is a cutaway photograph showing the copper holder and tungsten insert that make up the cathode. A solenoid coil, encapsulated in plastic, was used to spin the anode termination of the arc, and the magnetic field was oriented so as to augment the clockwise air swirl. The coil, which is coaxial with the anode, is made up of 8 turns of square cross section copper tubing and is shown in Fig. 4. The coil was powered by a d-c source independent of the main power supply.

The 1-MW nitrogen heater was modified so that is could be operated with air. This modification consisted of removing the entire cathode and end plate shown in Fig. 3a, adding 12 channel segments and a spin-coil, ring-anode assembly, plus a new end plate and air injection arrangement. The constrictor column diameter was 0.934 in., the axial distance between the electrodes was 5.501 in., and the exit nozzle throat diameter was 0.111 in. In contrast to the nitrogen heater, the air heater was run with reversed polarity; i.e., the upstream electrode was the anode and the downstream electrode was the cathode. The resulting configuration was almost identical with that of the 5-MW air heater, which is described in Section 2.4. A photograph of the 1-MW air heater, mounted on the test stand and ready for operation, is shown in Fig. 5. Also shown is a flapper valve whose function will be described later.

2.4 5-MEGAWATT HEATER

A section drawing of the 5-MW arc heater is shown in Fig. 6a. This heater is similar to the 1-MW air heater, except that there are 65 insulated channel segments versus 20 for the 1-MW heater. The constrictor column diameter was 0.934 in., the axial distance between electrodes was 17.561 in., and the throat diameter of the exit nozzle was 0.215 in. The electrodes are similar, with the upstream electrode being the anode and the downstream electrode the cathode. Spin coils are coaxial with each electrode so as to rotate the electrode arc column terminations, augmenting air swirl. Cooling water for the nozzle, electrodes, channel segments, and the back plate is supplied from two manifolds (see Fig. 6c). Figure 6b is a view of the disassembled heater, illustrating the complexity of construction. Front, side, and rear views of the assembled heater are shown in Figs. 6c, d, and e. The assembled heater mounted on the test stand with power leads connected is shown in Figs. 6f and g.

2.5 PROCEDURE FOR STARTING AND OPERATING HEATERS

2.5.1 Checkout Procedures

After verifying that all gas, coolant, and instrumentation connections were properly attached, a measurement of the resistance between the various components was made. The values obtained were checked to determine if they were within the allowable range. Ideally, the goal was to have an infinite resistance between adjacent components; also, between components and the heater frame, which was grounded. In practice, this goal cannot be achieved; therefore, a practical working standard which specified a minimum resistance of 20,000 ohms between adjacent components was adopted. However, the resistance between any heater component and ground was always very large (>1 megohm). The main power supply was electrically floating during heater operation.

Cooling water was supplied to the heater at the scheduled operating pressure and flow rate, and a leak check of all cooling system components was made. If there were no leaks, the cooling water was turned off, and a voltage check was made to determine if the heater would withstand the open-circuit voltage required for starting without external or internal arc-over occurring. This check was made with the heater chamber at atmospheric pressure.

Next, the heater chamber was sealed by the flapper valve (Fig. 6f) and evacuated to a pressure less than 10 psfa to check for gas leaks. Then, with the heater still connected to the vacuum system, helium flow was initiated and adjusted so that the breakdown or arcing voltage across the heater electrodes was established and was below the external arcing voltage. Electrical leads were attached to the heater, the auxiliary systems were actuated and checked out, and the heater was then ready for operation.

2.5.2 Starting and Operating Procedures

The automatic sequencer for the arc heater system was activated, and the recording instruments started. Transformer tap position (see Fig. 2) was set for scheduled power, and the heater chamber was evacuated to less than 10 psfa. After checking the coolant flow interlocks, the working gas inlet pressure, coolant flows, and power setting, the helium flow was initiated. Open-circuit voltage was applied to the heater electrodes, and when current flow began, a valve was triggered which allowed the test gas (air or nitrogen) to flow to the heater. When the arc was established, the helium flow was manually shut off. Several seconds of operation were allowed for pressures, temperatures, etc., to reach a steady state so that performance data could be recorded. For a normal shutdown, the automatic sequencer was deactivated, which interrupts power, test gas, and cooling water after preset intervals of time have elapsed.

During heater operation, the gas flow and power input can be changed, if required. This allows starting at relatively low pressure and power levels, and increasing to required levels. This is standard operating procedure when heater operation above 20 atm pressure is required.

2.6 HEATER SYSTEM PROTECTIVE DEVICES

Necessary safety devices were provided to protect the arc heater in case of component failure during a run. The standard interlocks which must be satisfied to initiate the arc were water flows (both high and low), helium flow, and coil power. If any of these parameters changed beyond specified limits during the run, the arc power was automatically terminated.

During the test period, two additional protective devices were incorporated. One was a holding-circuit which prevented the arc power from reestablishing and causing possible damage if the arc heater current terminated for any reason during a run. The other device (see Fig. 7) was an arc voltage transfer system, installed to limit the open-circuit voltage and provide protection to the heater if the arc should blow out during the run. When the voltage reached a pre-set level, the current path would transfer through the protective device, and a current sensor at the device activated the rectifier shorting circuit and terminated the power to the heater.

SECTION III
TEST RESULTS

Tables I and II (Appendix II) are test run logs which give heater inputs and outputs, plus other information, for the 1-MW and 5-MW arc heaters. Tables III and IV describe the damage incurred, if any, during each heater run and list the system electrical configuration for each run. Tables V and VI are for Runs E17 and E18, giving the sequence of events leading to arc-overs and heater damage. These tables are based on galvanometer traces and surveillance camera film data. Table VII gives operating data for the 5-MW EOS and Linde heaters.

3.1 SURVEY OF HEATER DAMAGE AND SUBSEQUENT MODIFICATIONS

During the course of testing the EOS 1-MW and 5-MW arc heaters, some component damage occurred, as is to be expected during development tests. Most of the damage was caused by electrical "arc-overs" (arcing which follows paths other than the operating path from anode to cathode through the constrictor channel), which may have been triggered by a gas or water leak, or other cause. By examining heater and auxiliary system components after arc-over occurred, it was possible in every case to determine the path traveled by the arc. Consequently, modifications to heater and auxiliary system components were made with confidence. A run-by-run survey of arc heater damage, if any, and systems modifications, if any, follows.

3.1.1 1-MW Nitrogen Heater

A description of this heater is presented in Section 2.3 and Fig. 3. The first test run (Run E1) (see Table III) was a 113-sec run with no failure. Run E2 had a total time of 409 sec, also without failure. This was the longest run made with any of the three EOS heaters. Run E3 was a 43-sec run, terminated by an arc-over which severely damaged the cathode end of the heater. Figures 8 and 3c show the extent of the damage; Fig. 8a shows the cathode plate; Figs. 8b and 3c show virtual destruction of the cathode; and Fig. 8c shows the destroyed gas injection ring. Some moderate damage was sustained by the anode (Fig. 8d) and the first two segments downstream of the anode (Figs. 8e and f). Run E3 was the last run made with the 1-MW nitrogen heater. A total of 565 sec of run time was logged for the three runs made with this heater.

3.1.2 1-MW Air Heater

A total of seven runs were made with the 1-MW air heater; two runs (E4 and E8) were unproductive because of early arc-overs. The 3-in. air line insulator installed during all runs prior to Run E4 was found to be inadequate and was replaced by a 12-in. insulator (Fig. 6g) prior to Run E5. A total run time of 330 sec was logged with this heater (see Table III). The heater was disassembled after Run E7. No damage was evident other than normal erosion, although after 159 sec of run time (E4 through E7), "normal erosion" is at best only a relative term meaning that the heater had suffered no catastrophic damage and was operational. Run E9 was terminated by an arc-over from the cathode to the cathode spin coil. A section of the spin coil was destroyed (see Fig. 9), and the coil was repaired before the next run was made. Prior to Run E10, two changes were made: first, a holding circuit (see Section 2.6) was installed; second, four 10-in.-diam by 0.010-in.-thick Mylar® insulating sheets were installed, one on each side of the two spin coils. Run E10, the final run made with the 1-MW air heater, was a 2-min run during which no major damage occurred.

3.1.3 5-MW Arc Heater

The 5-MW and 1-MW arc heaters were very similar, differing mainly in the number of insulated column segments, having 65 and 20, respectively. In addition, the spin coils of the 5-MW heater were polarized (see Table IV) so that the resulting arc termination rotations augmented the air swirl. Also, the voltage transfer device, described in Section 2.6 and Fig. 7, was installed prior to Run E11, the first attempted run with the 5-MW heater. Mylar insulating sheets were installed on each side of the spin-coil sections, as with the 1-MW air heater, for arc-over protection.

Figures 10a and b show the anode and air injection configurations used during the 5-MW tests. For Runs E11 through E15, the configuration shown in Fig. 10a was used, with air being injected through the conical-shaped end plate insert. Because of excessive erosion to the tapered segments downstream of the anode (Fig. 10c), the anode downstream corner, and the first insulating spacer downstream of the anode, it was concluded that the arc attached to the anode corner (Fig. 10a) and then arced from segment to segment along the tapered segments. In addition to the damage, this kind of arc-path pattern resulted in more energy loss to the cooling water and, therefore, lowered heater efficiency.

The voltage transfer device prevented possible heater damage during starting attempts for Runs E11 and E12. Because of a rectifier malfunction, excessive open-circuit voltage was impressed on the heater, but no damage occurred. The rectifier was repaired and adjusted, and no further trouble of this nature was experienced.

Run E13 was a normal run of 20 sec duration. Run E14 was terminated by an arc-over from the cathode through the Mylar sheet to the downstream base segment after 2.50 sec of operation. The damage is shown in Fig. 11.

A major change was made in the arc heater electrical system prior to Run E15; the electrode spin coils were grounded by the d-c power supply, a source independent of the main power supply. Consequently, a large difference in potential could exist between an electrode and its coaxial spin coil. It was believed that this situation had caused or contributed to previous arc-overs; therefore, the spin coils were connected in series with the electrodes so that essentially no potential difference existed between electrode and spin coil.

During Run E15, before the anode and air injection configurations were changed, a hot spot developed at the downstream base segment, and the hot gas burned through the base segment (Figs. 12a and 13a). The cathode spin coil also sustained slight damage (Fig. 12b). This is the only case of major damage not caused by an electrical arc-over. As a result of the base segment burnthrough, both base segments were redesigned (see Figs. 13a and b). Both segments were provided with more coolant flow and better thermal protection. In addition, the upstream base segment was provided with air injection ports (Fig. 13b); this was done to prevent the arc from attaching to the anode downstream corner (Fig. 10a). Also, the shape and diameter of the anode were changed (Fig. 10b) to aid in moving the location of the arc attachment point.

Run E16 was the first run with the changed anode and air injection configurations. This was a 25-sec run at low pressure, about 23 atm. After the run, the heater was inspected, and no damage was evident. Also, it appeared that the arc had attached to the anode in a normal manner, indicated by the unbroken line in Fig. 10b.

The objective of the last two runs, E17 and E18, was to attain an arc chamber pressure of 100 atm. Neither run was successful. Run E17 produced a pressure of 70 atm but was terminated after 14 sec by an internal arc-over that severely damaged the end plate and end plate insert (Fig. 14a). The anode was also damaged (Fig. 14b). Apparently, the arc first transferred from the anode to the end plate insert, then along the wall back to the anode, as shown by the dashed lines in Fig. 10b. Finally, the arc burned through the end plate insert and took an external path to the cathode. Table V gives a probable sequence of events for Run E17, based on postrun heater inspection, galvanometer traces, and surveillance camera film.

Run E18, the last 5-MW run, again resulted in severe damage from an internal arc-over. During this run, the arc termination again apparently transferred from the anode to the end plate insert, then along the wall back to the anode, as occurred in Run E17. Also, a piece of insulating material blocked the exit nozzle throat for several seconds, resulting in nozzle destruction. The damage is shown in Figs. 15a and b.

Changing the air injection location was beneficial for low-pressure operation but seemingly resulted in transferring the arc from the anode to the end plate insert during high-pressure operation.

Throughout the tests, the erosion and cracking of the boron nitride insulators was a problem; other and better insulating materials are needed if the heater is to operate in the 100- to 200-atm region.

It seems apparent that some redesign, perhaps extensive in character, plus additional testing, is necessary to demonstrate the operational capability of the EOS 5-MW arc heater in the 100- to 200-atm pressure regime.

3.2 ARC HEATER PERFORMANCE

3.2.1 EOS Heaters

The primary goal of testing the EOS heaters was to determine if the 5-MW heater would produce concurrent thermodynamic conditions of 200 atm pressure and 3830 Btu/lb enthalpy, using air as the test gas. This goal was not achieved: (1) because the time required to repair damaged heater components reduced the time available for test runs, and (2) because of the rapidity with which damage occurred during the last two scheduled high-pressure runs (E17 and E18). Run E17 produced the highest pressure, about 70 atm, but cooling water temperatures did not stabilize, and full programmed airflow and power could not be reached before damage occurred; therefore, no accurate value of enthalpy could be determined.

Figure 16 and Tables I and II show the thermodynamic performance of the EOS heaters. The 1-MW air heater performance is relatively well documented from 10 to 85 atm pressure. On the other hand, there are only four data points at greater than 10 atm pressure for the 1-MW nitrogen heater and two for the 5-MW heater. The 1-MW nitrogen and 5-MW air heaters produced higher enthalpies than the 1-MW air heater, for the same arc chamber pressure. It is believed that the change in the anode and air injection configurations after Run E15 (see Section 3.1.3) accounted for most of the difference in enthalpy between the two 5-MW data points. During Run E13, the arc path was probably as shown in Fig. 10a, which resulted in higher losses and, therefore, lower enthalpy than was achieved during Run E16 (Fig. 16b). Maximum enthalpies achieved were as follows: 7920 Btu/lb at 20.5 atm for the 1-MW operating on nitrogen gas, 7145 Btu/lb at 8.8 atm for the 1-MW heater with air, and 6135 Btu/lb at 22.8 atm for the 5-MW heater with air. Values of enthalpy were calculated from an energy balance method, as specified by ASTM Standard E341-68T (see Ref. 4).

3.2.2 Comparison of Performance Characteristics of EOS and Linde 5-MW Heaters

Enough data are not available for a credible comparison of the thermodynamic performance of the 5-MW EOS and Linde N4000 heaters. The available data are shown in Fig. 17, and all that can be said is that the EOS heater produced 35-percent higher enthalpy (6100 versus 4500 Btu/lb) at 23 atm pressure than the 100-atm version of the Linde heater. Although the EOS design point projects an enthalpy 80 percent greater than that achieved by the improved 200-atm version of the Linde N4000 heater, there is nothing to be concluded by extrapolating the EOS performance to 200 atm.

3.2.3 Variations in Pressure and Energy Level, 1-MW EOS Heaters

The orifices used for measuring arc chamber pressure were located on the first segment downstream of the electrode nearest the exit nozzle (see Figs. 8e and 3a). This location was used for all nitrogen runs and for all air runs through Run E7. However, these orifices were often partially blocked by pieces of molten metal or insulating material. Therefore, for Runs E8 and E9, the inlet air supply pressure was used as an indication of arc chamber pressure. Voltage and current variations, and therefore enthalpy and pressure variations, should ideally be of small amplitude and high frequency for best simulation of steady-state conditions. Figures 18a and b show these variations for the EOS 1-MW nitrogen and air heaters (see also Table VII). Jets exhibiting large-amplitude, low-frequency fluctuations in power (enthalpy) and pressure are not acceptable either for ablation or aerodynamic tests. The arc current trace for the nitrogen heater (Fig. 18a) displays the rectifier ripple frequency of 360 Hz superimposed on the operating frequency of about 23 Hz. A mean current value, i = 450 amp, with peak-to-peak variation of ±23 amp (2.6 percent of mean value); mean voltage, E = 680 v, with peak-to-peak variation of ±350 v (25.8 percent of mean value); and mean arc chamber pressure, p_o = 21.2 atm, peak-to-peak value of 2.0 atm (9.4 percent of mean value) are shown. The 1-MW air heater (Fig. 18b) shows improvement over the nitrogen heater, with peak-to-peak variations expressed as percent of mean values as follows: arc current, 2.0 percent; arc voltage, 12.3 percent; and inlet air supply pressure, 4.4 percent. The reduction in pressure variation for Run E9 was probably caused by the damping effect of the heater air manifold (Fig. 10a) and inlet orifices because the supply pressure, rather than the arc chamber pressure, was recorded. Heater cavity geometry, gas mass flow, rectifier output characteristics, and arc instabilities are some of the factors contributing to jet fluctuations.

3.2.4 Comparison of Variations in Pressure and Energy Level, 5-MW EOS and Linde N4000 Heaters

The chamber pressure measuring orifice for the EOS heater is located at the apex of the conical-shaped, end plate insert (Fig. 10). For the Linde N4000 heater, this orifice is located on the face of the front shell seal (see Fig. 19). Figures 18c and d and Figs. 18e and f, show, respectively, the current, voltage, and chamber pressure fluctuations for EOS and Linde heaters. The data shown in Fig. 18 are summarized in Table VII. The EOS heater exhibits less variation of arc current and voltage, with higher cyclic rates, than does the Linde N4000. However, the reverse is true for arc chamber pressure, with respect to variation about the mean value only, although it is believed that the measuring orifice location exerts a considerable influence on pressure data and their variation. Based on these limited data, it appears that the EOS heater effluent jet is potentially more steady than the Linde N4000 jet at low pressure.

3.3 COMPARISON OF COMPONENT DURABILITY AND HEATER MAINTAINABILITY, 5-MW HEATERS

Component durability of the EOS heater is poor; this must be qualified by saying that the heater is in an early stage of development and that durability could probably be improved as development progresses. However, it is believed that insulating material must be developed to withstand the thermal and mechanical stresses of 100- to 200-atm operation. The Linde N4000 heater has proved durability, having been operated routinely at 100 atm for many runs without destruction of any component (see, e.g., Ref. 5).

Maintainability includes time and costs involved in: (1) disassembling and assembling the heater, (2) fabricating spare parts, (3) installing in the test area and making all necessary utility and instrumentation connections, and (4) checking out for operation. Figures 6 and 19 show assembly drawings, exploded views, and installation photographs for the EOS and Linde heaters, respectively. Maintenance experience with both units at AEDC has shown that (1) assembly of the EOS heater requires about twice the time as assembly of the Linde heater, (2) fabrication of spares for the EOS heater is more expensive because of close tolerances and the use of special equipment; e.g., a brazing furnace, (3) installation of the EOS heater in the test area requires more time because of the number and complexity of connections, and (4) checking out the EOS heater requires two to three times the time expended on the Linde heater, mainly because of the greater number of gas and water seal inspections and tests and the much greater number of electrical checks that must be made. This experience points up the need for changes in the EOS heater design to improve maintainability of the unit.

SECTION IV
CONCLUDING REMARKS

Of the two EOS 1-MW heaters tested, the nitrogen model produced higher enthalpy than the air model in the 10- to 20-atm pressure region. The variation in arc chamber pressure and power exhibited by the two 1-MW heaters makes them unacceptable for use in ablation or aerodynamic testing. However, the two 1-MW heaters were less prone to electrical arc-overs than the 5-MW EOS heater, primarily because of the lower operating voltage.

The EOS 5-MW heater did not achieve the design goal of 200 atm and 3830 Btu/lb because of repeated failures and severe damage caused by electrical arc-overs. It did, however, produce about 35 percent more enthalpy than the 100-atm version of the Linde heater at 23 atm and was somewhat "smoother" in operation. Existing insulating material must be improved, or new material developed, if the heater is to operate in the 100- to 200-atm pressure region. The EOS heater is more complex mechanically and more costly to maintain, by a factor of 2, than is the Linde heater. It is evident that extensive redesign and additional testing is required before a full assessment of the EOS heater can be made.

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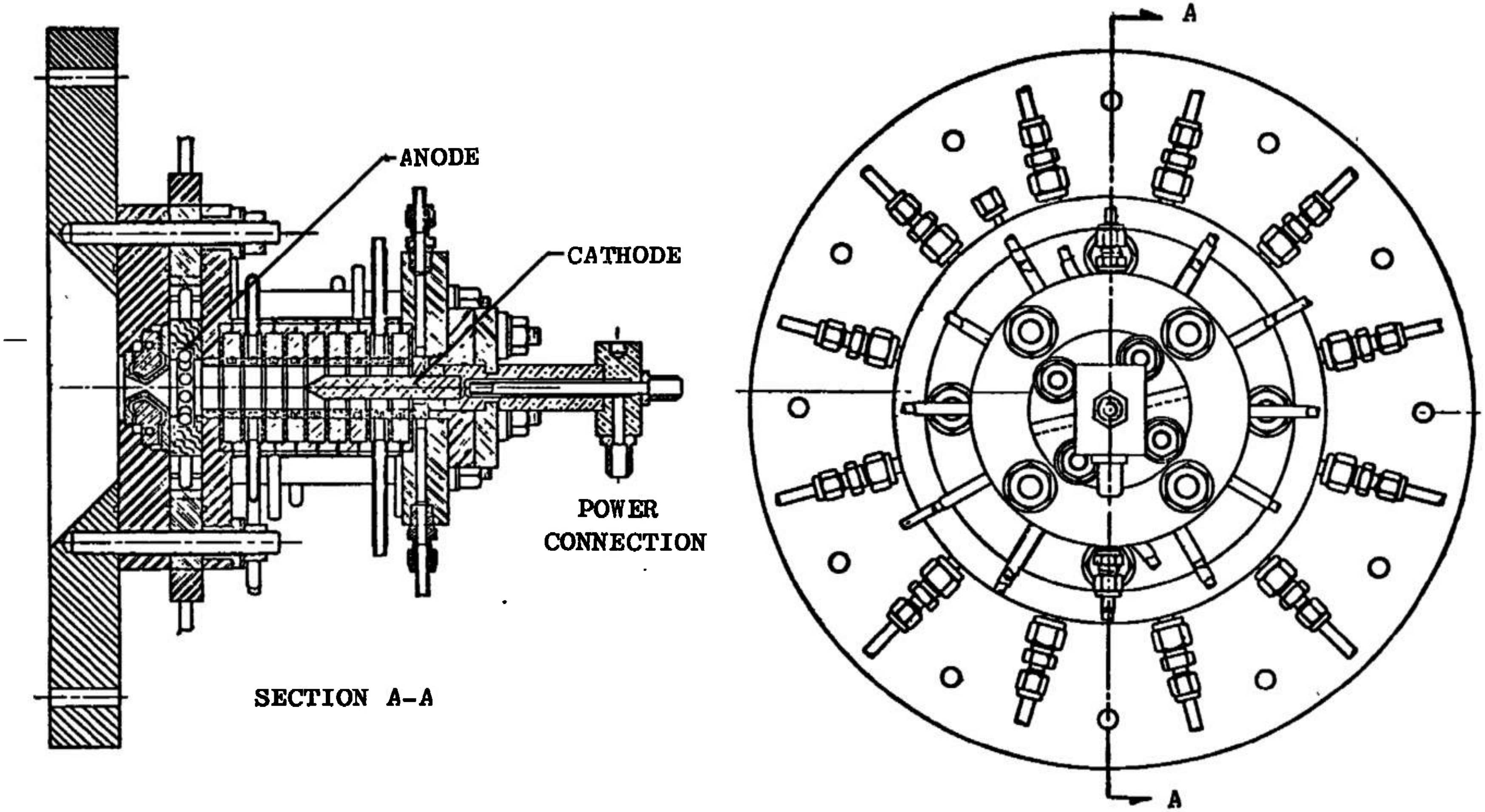
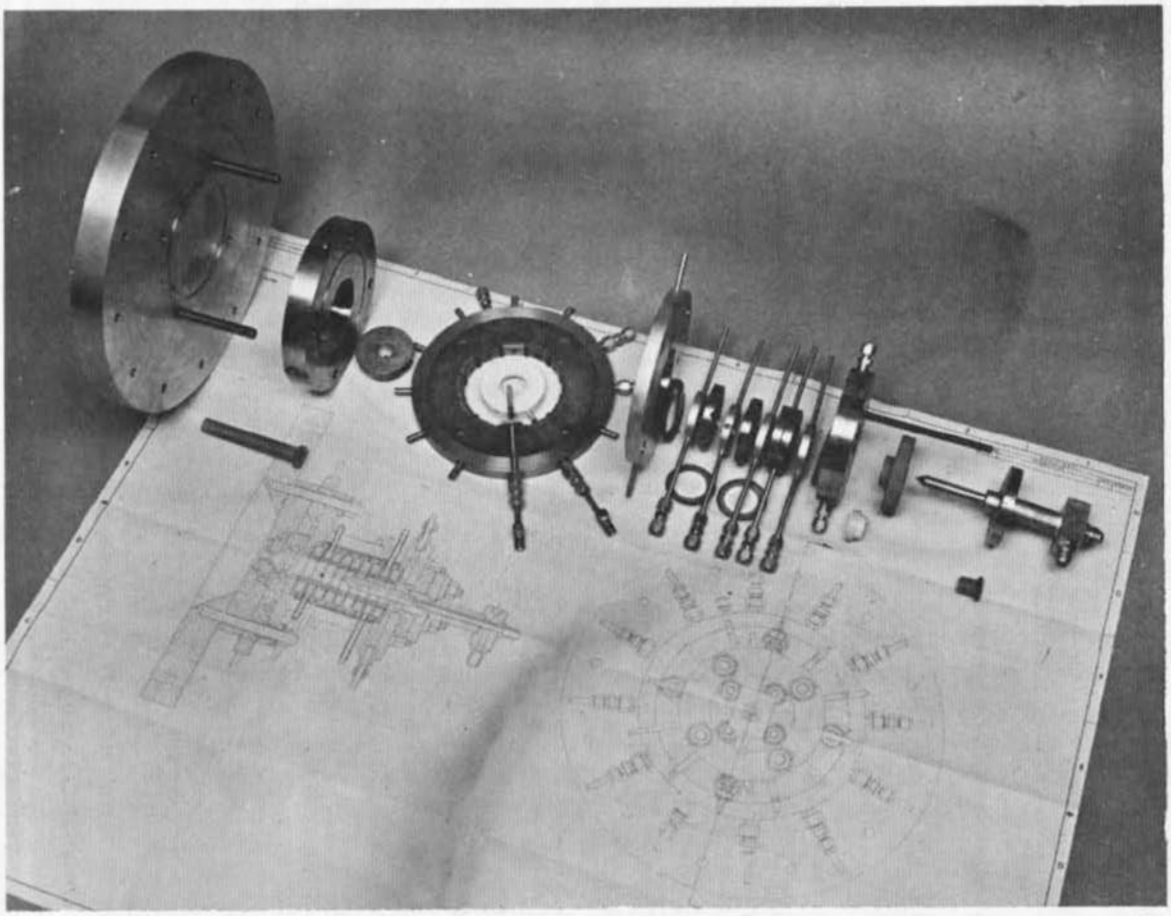
APPENDIXES
I. ILLUSTRATIONS
II. TABLES



a. Drawing
Fig. 1 Original EOS Segmented 1-MW d-c Arc Heater, Nitrogen Operation



b. Photograph of Components
Fig. 1 Concluded

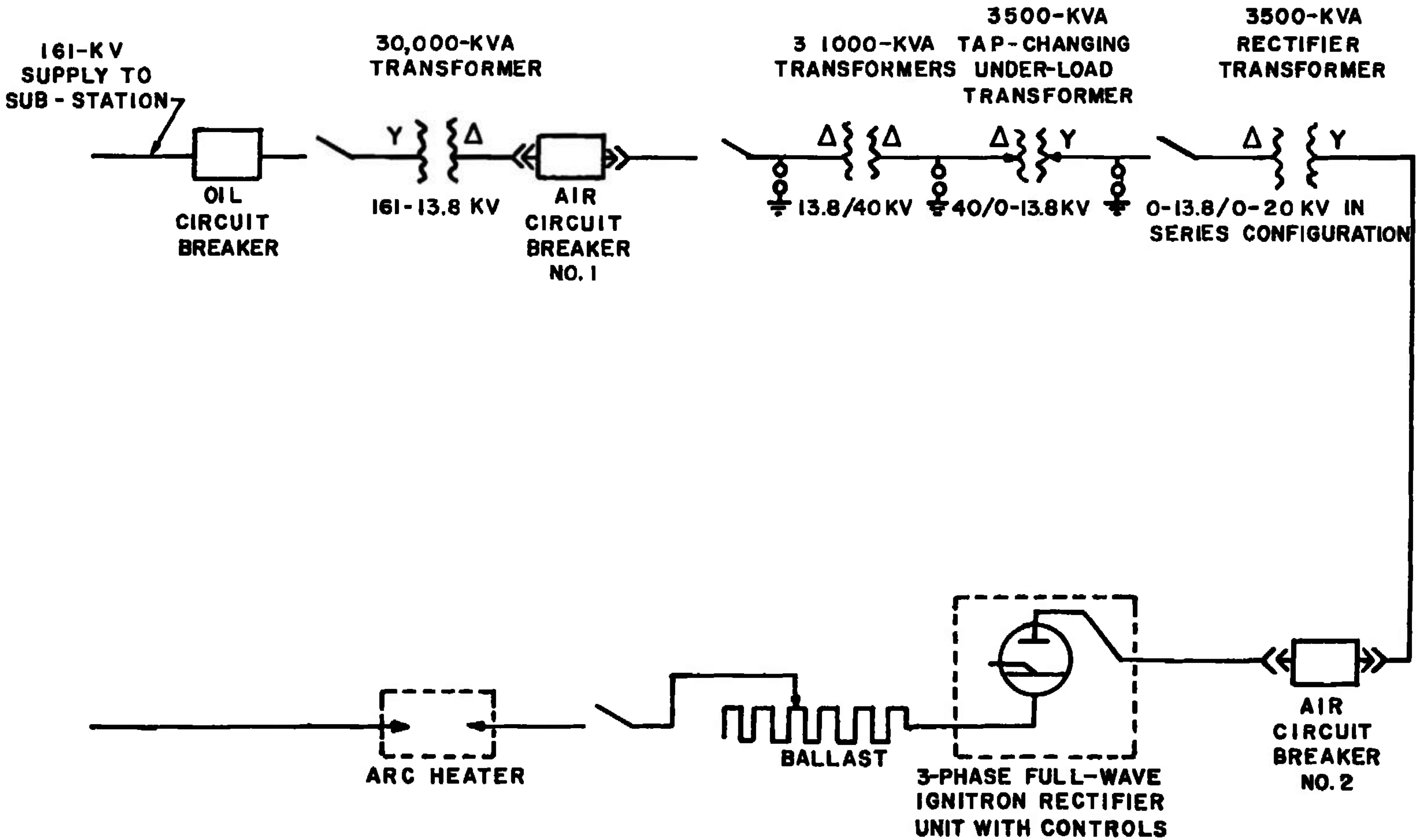
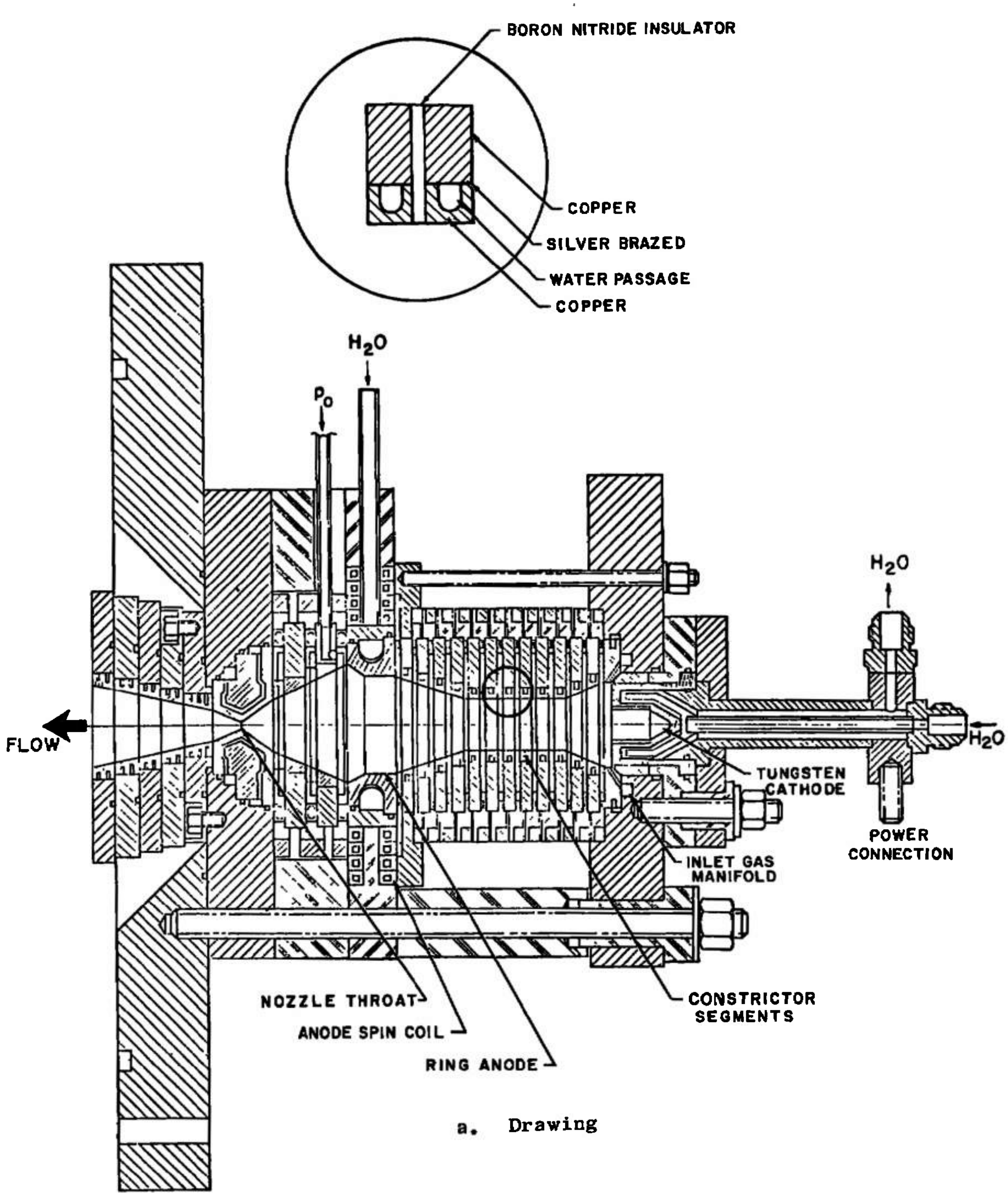
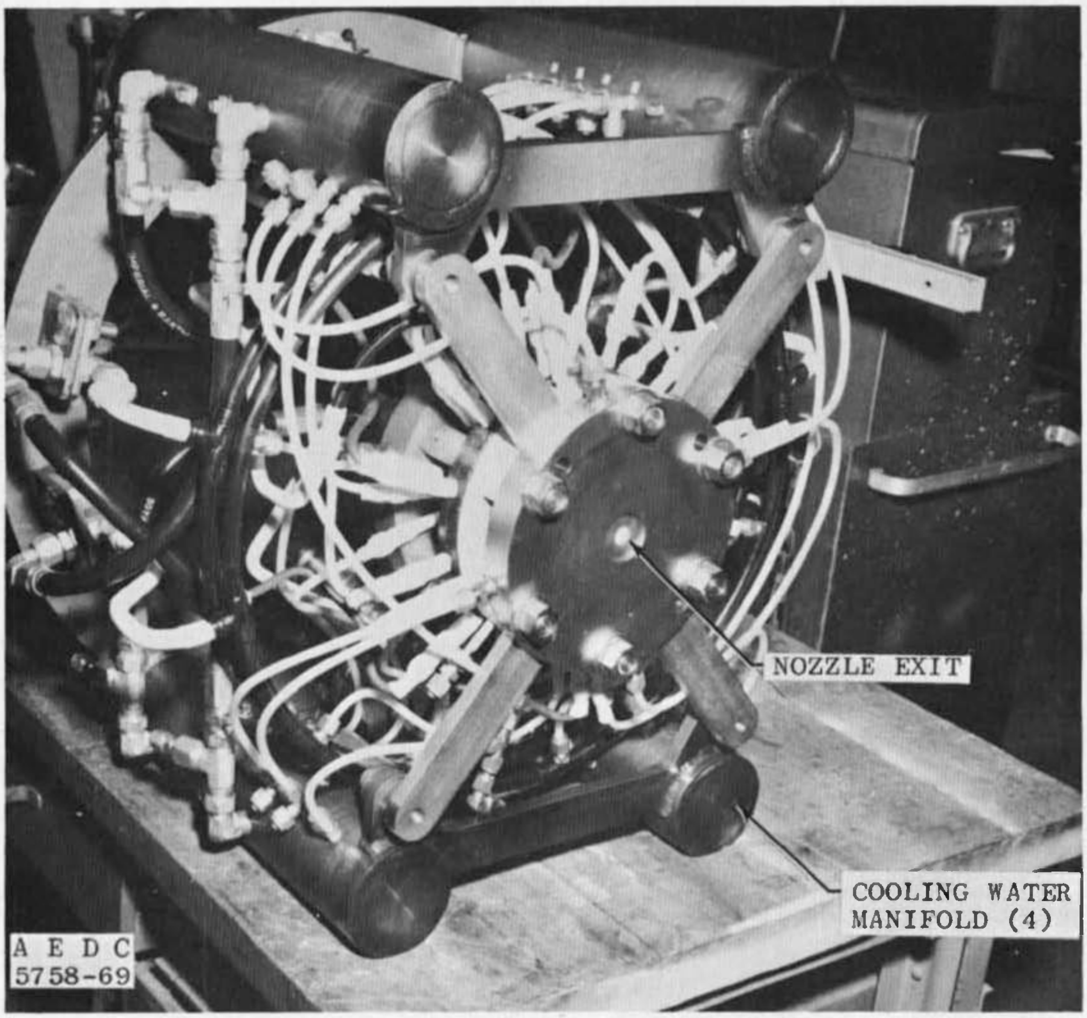


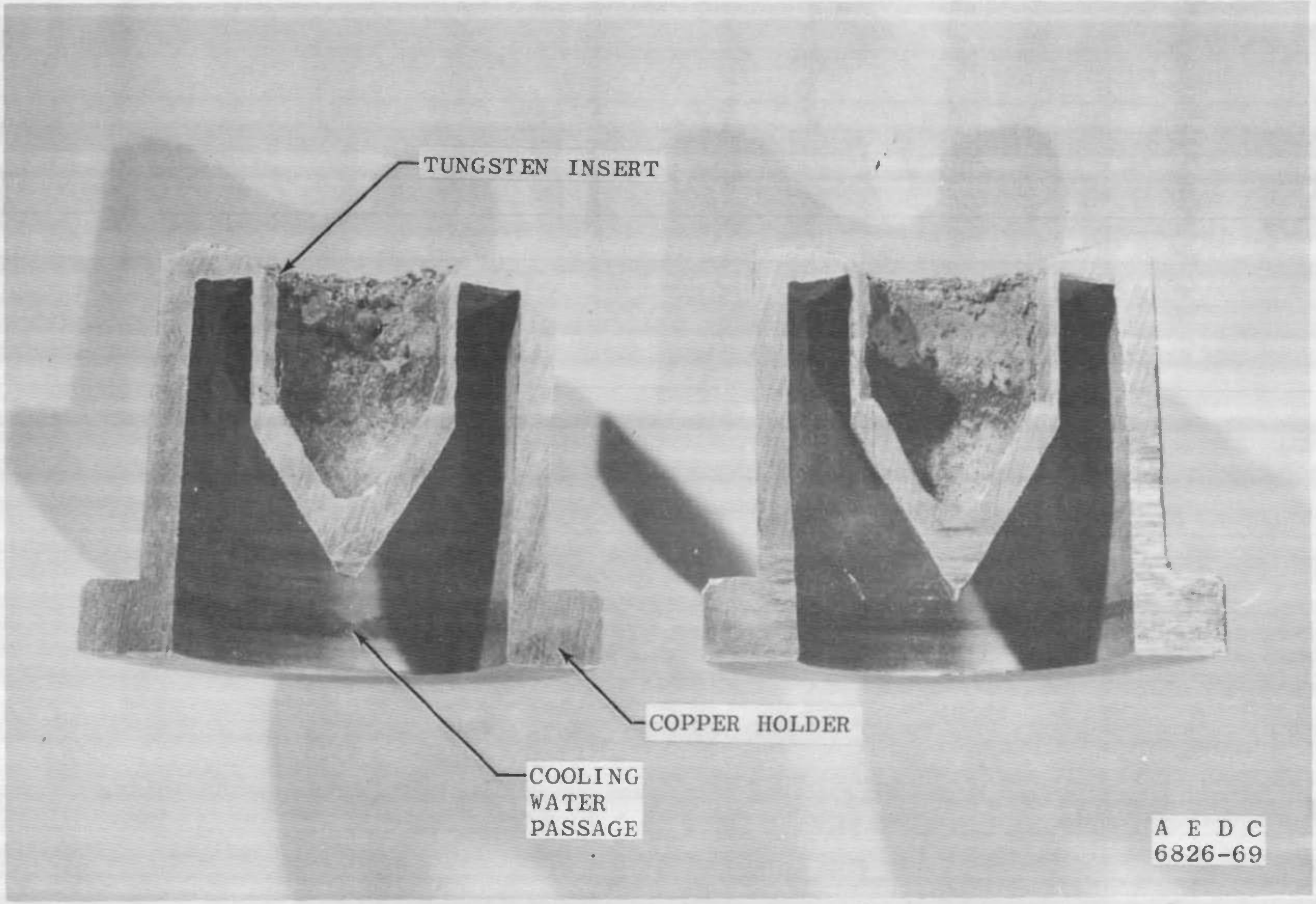
Fig. 2 Main Power Supply Line Diagram



a. Drawing
Fig. 3 EOS 1-MW Nitrogen Arc Heater Operated at AEDC



b. Assembled Heater, Discharge End View
Fig. 3 Continued



c. Cataway View of Cathode (Damaged)
Fig. 3 Concluded

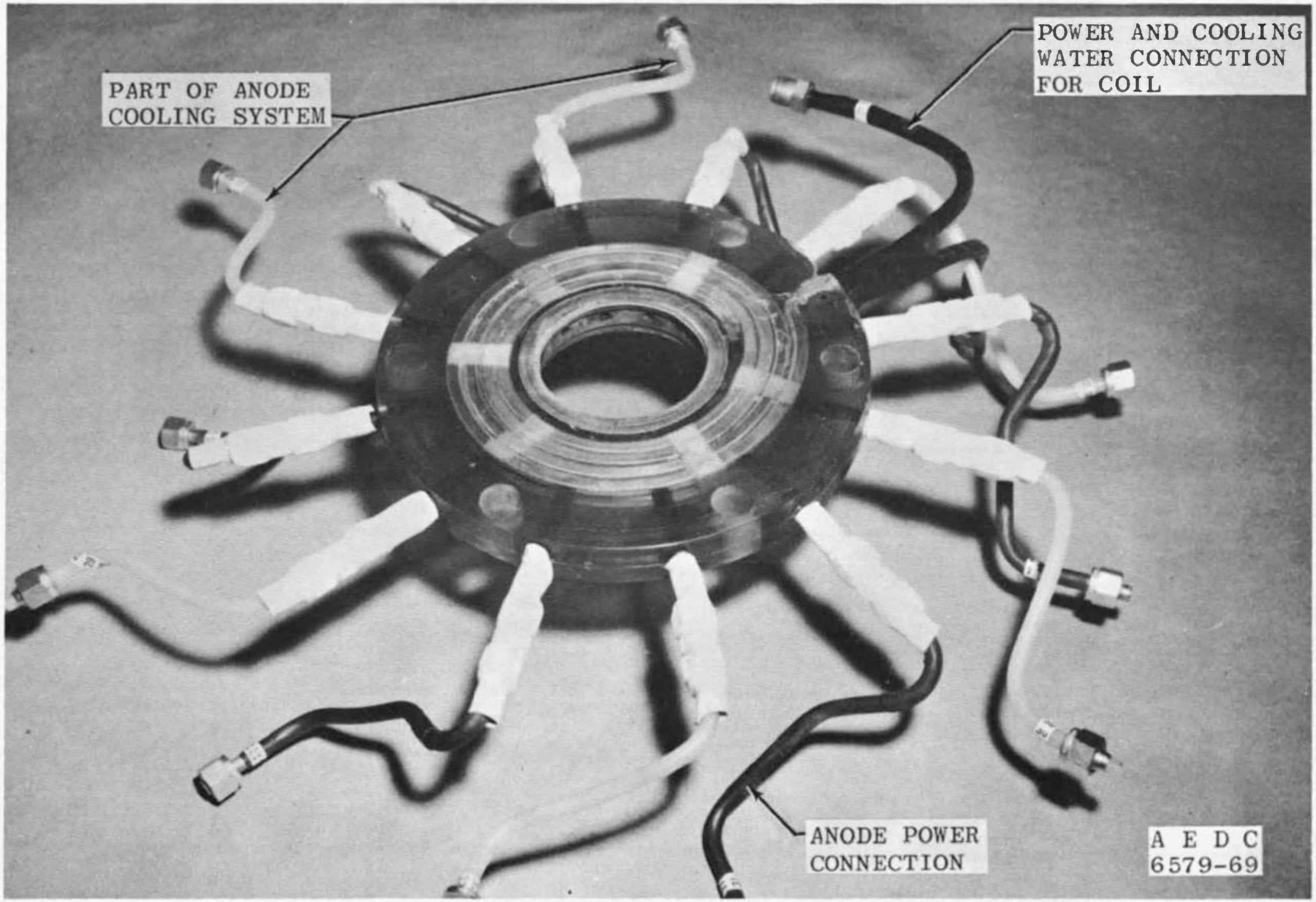


Fig. 4 Spin Coil Used on 1-MW Heaters

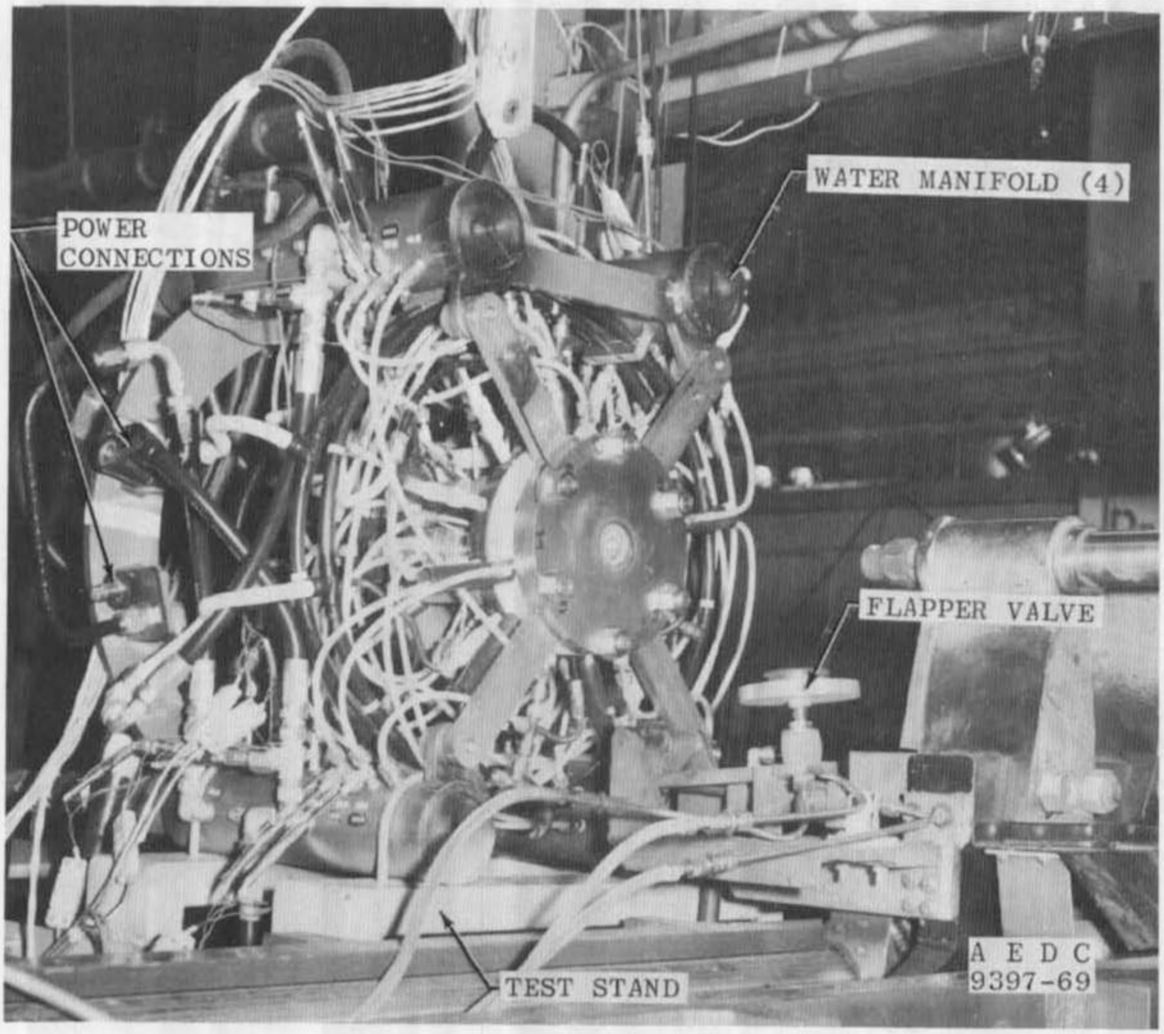
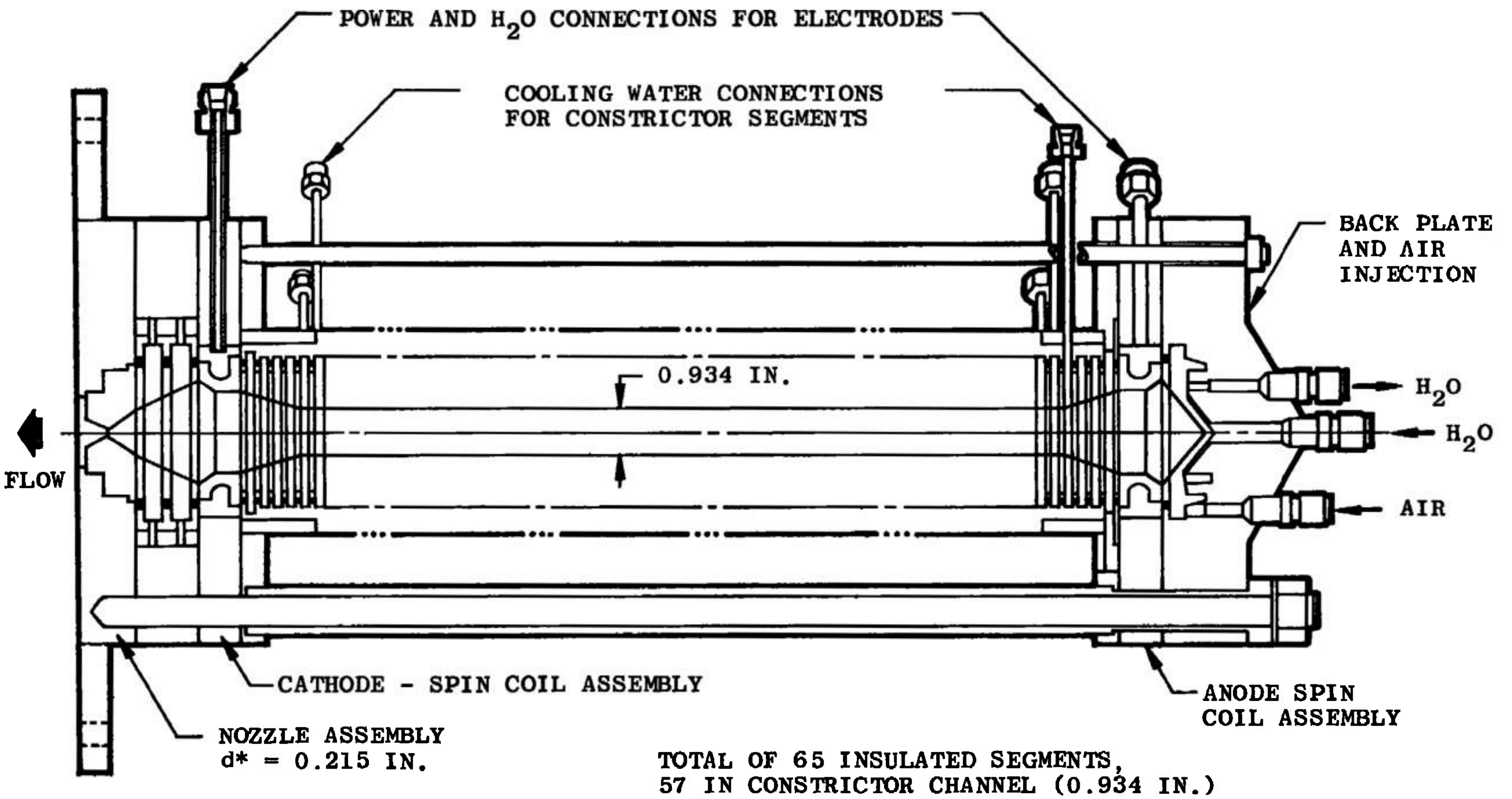
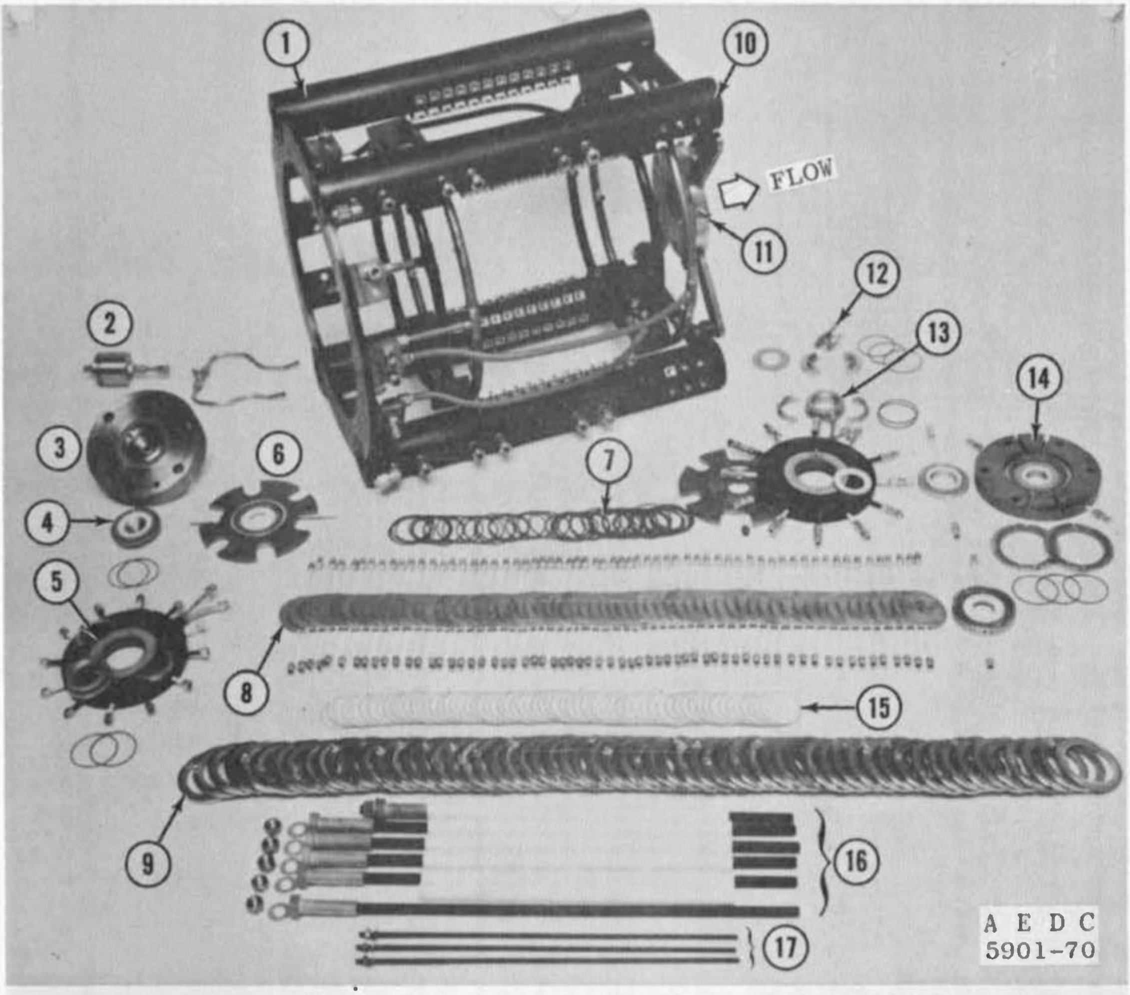


Fig. 5 1-MW Air Heater Mounted on Test Stand

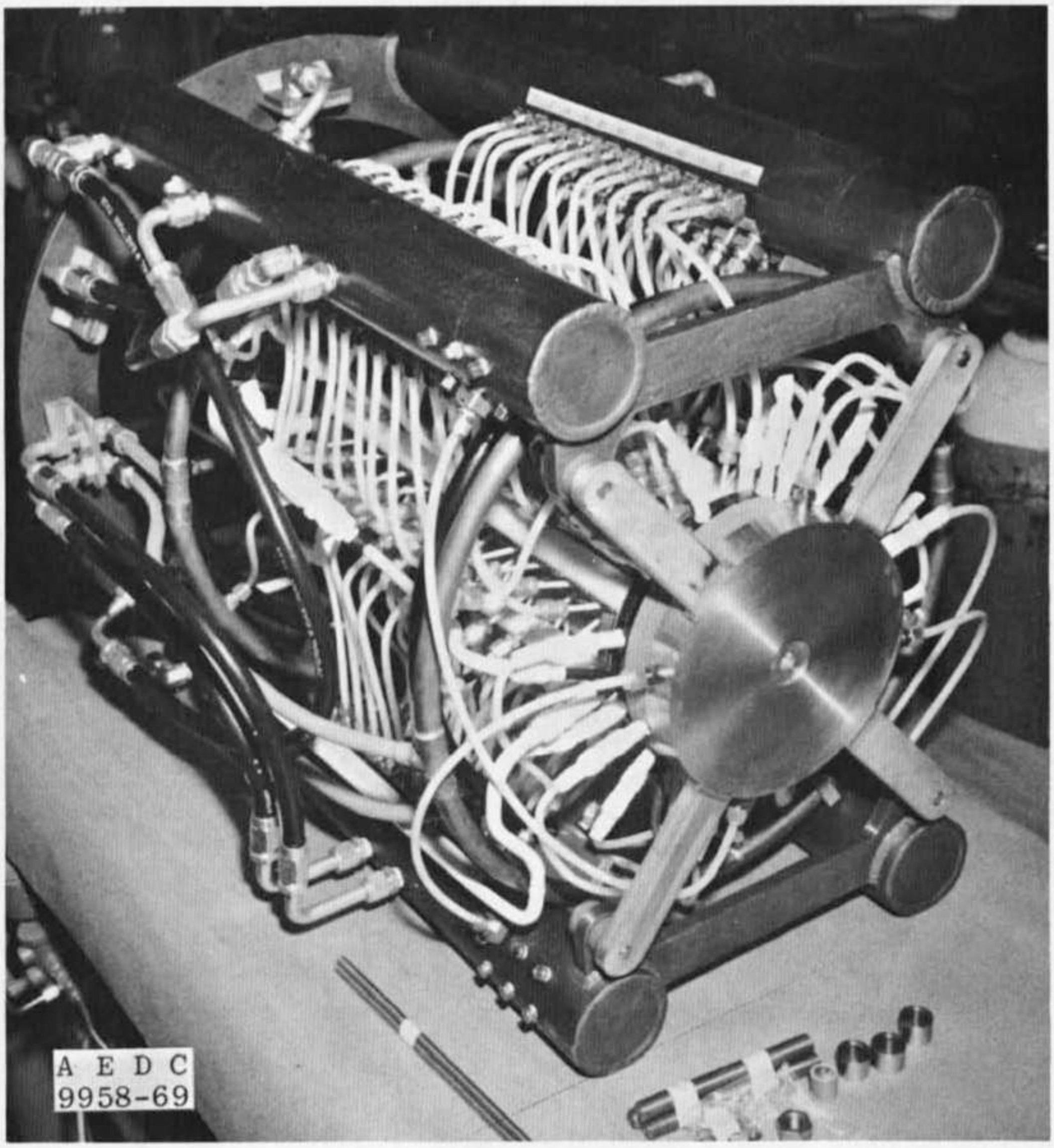


a. Drawing
Fig. 6 5-MW EOS Air Arc Heater

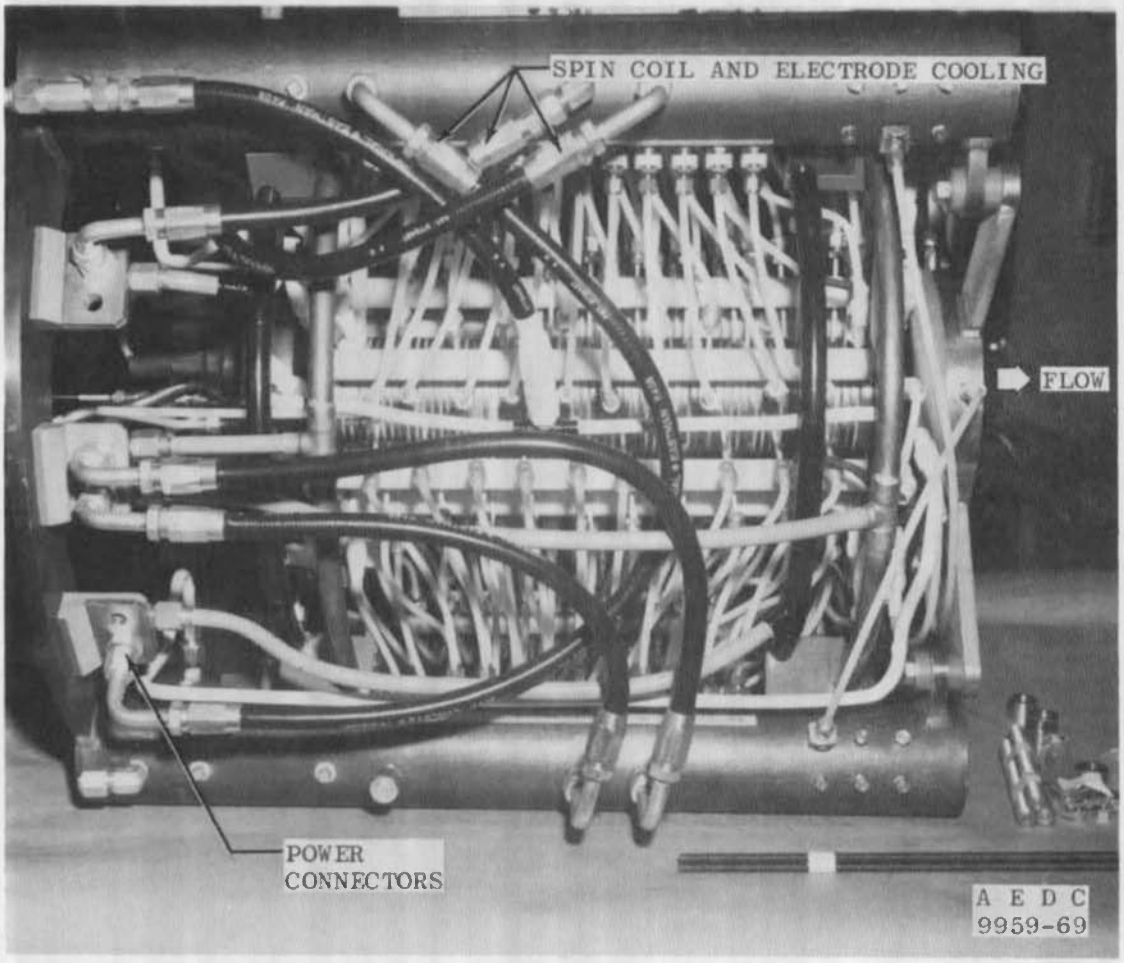


1. HEATER FRAME (1)
2. AIR LINE INSULATOR (1)
3. END PLATE (1)
4. END PLATE INSERT (1)
5. SPIN COIL (2)
6. BASE SEGMENT (2)
7. O-RINGS
8. SEGMENTS
9. T-RINGS
10. WATER MANIFOLD (4)
11. NOZZLE PLATE (1)
12. NOZZLE (1)
13. ELECTRODE (2)
14. SPACER RING (1)
15. COLUMN INSULATORS
16. TIE BOLTS (6)
17. ASSEMBLY BOLTS (3)

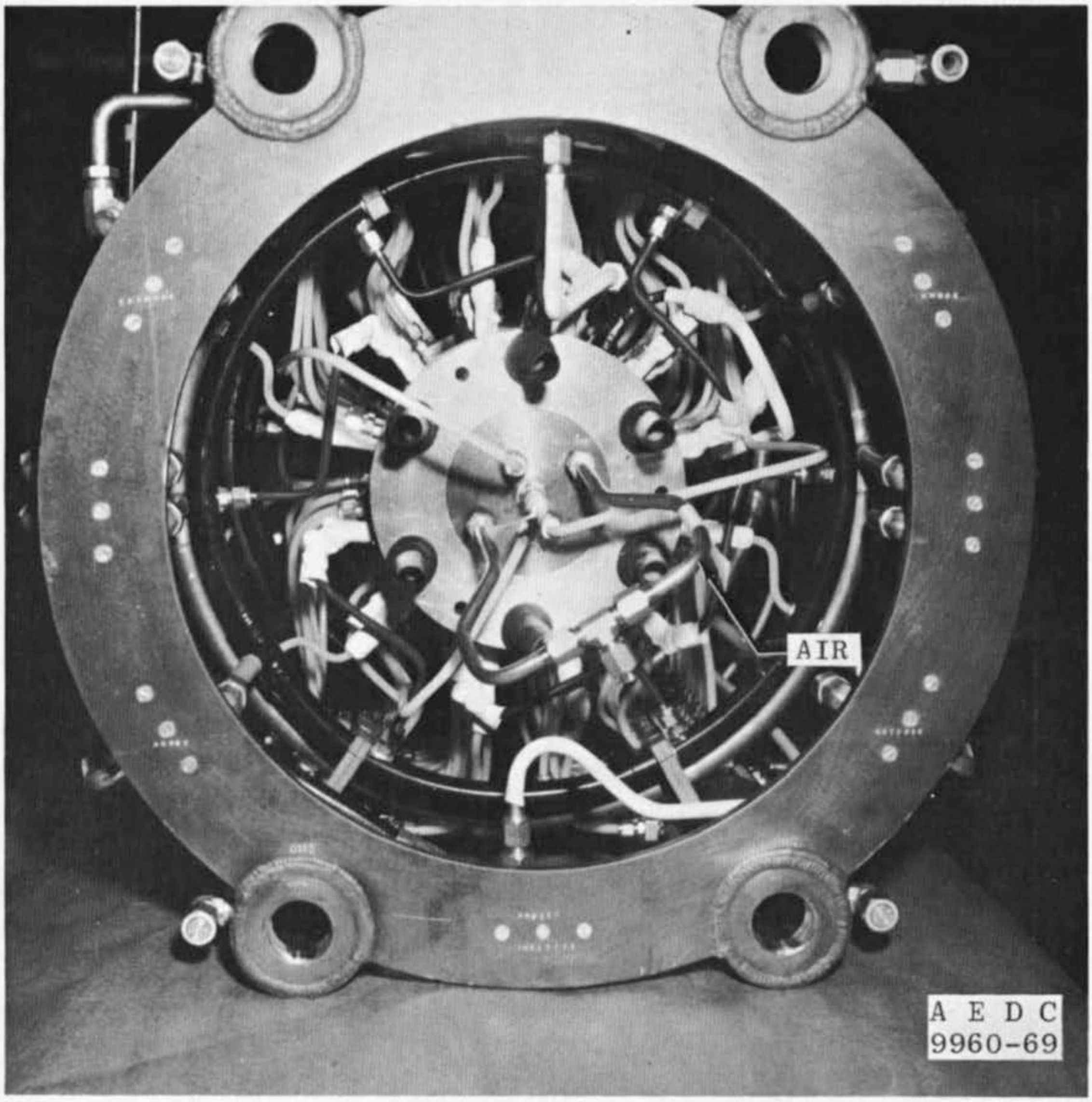
b. Exploded View
Fig. 6 Continued



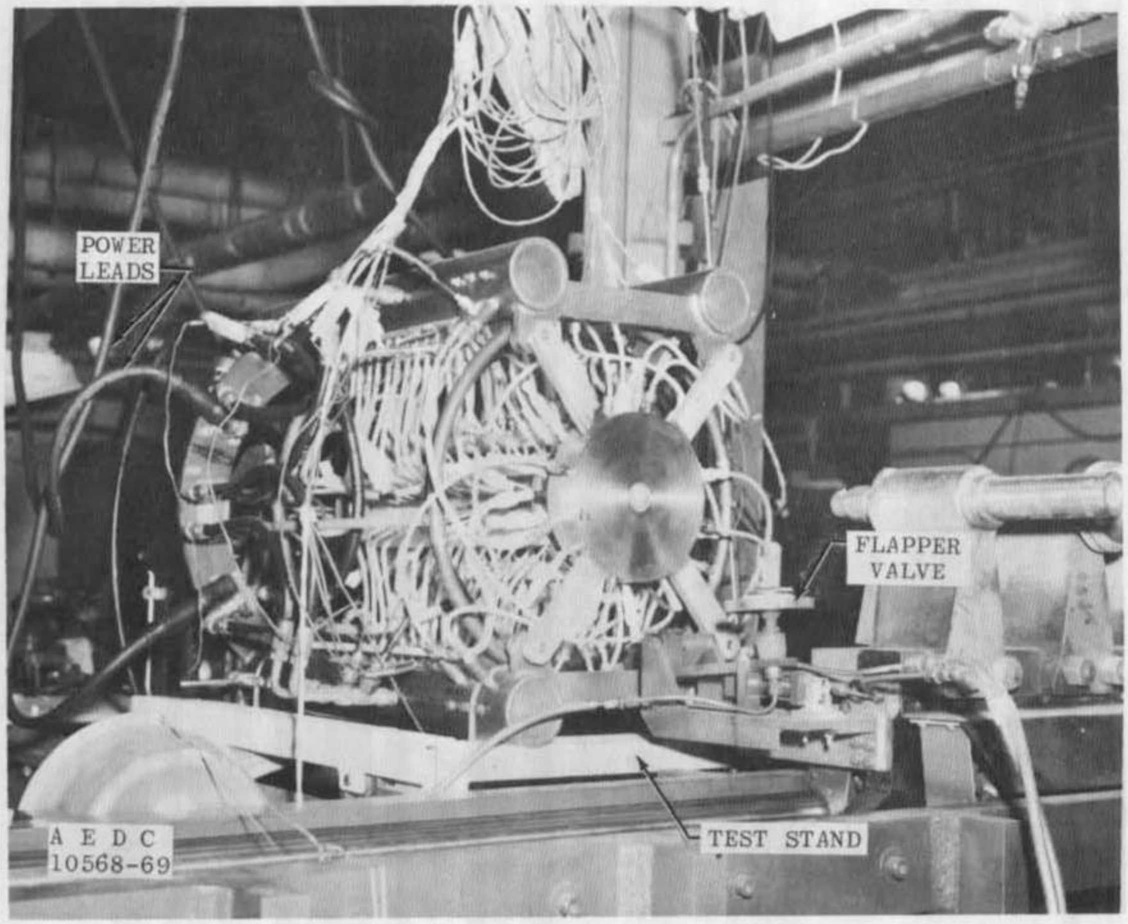
c. Front View
Fig. 6 Continued



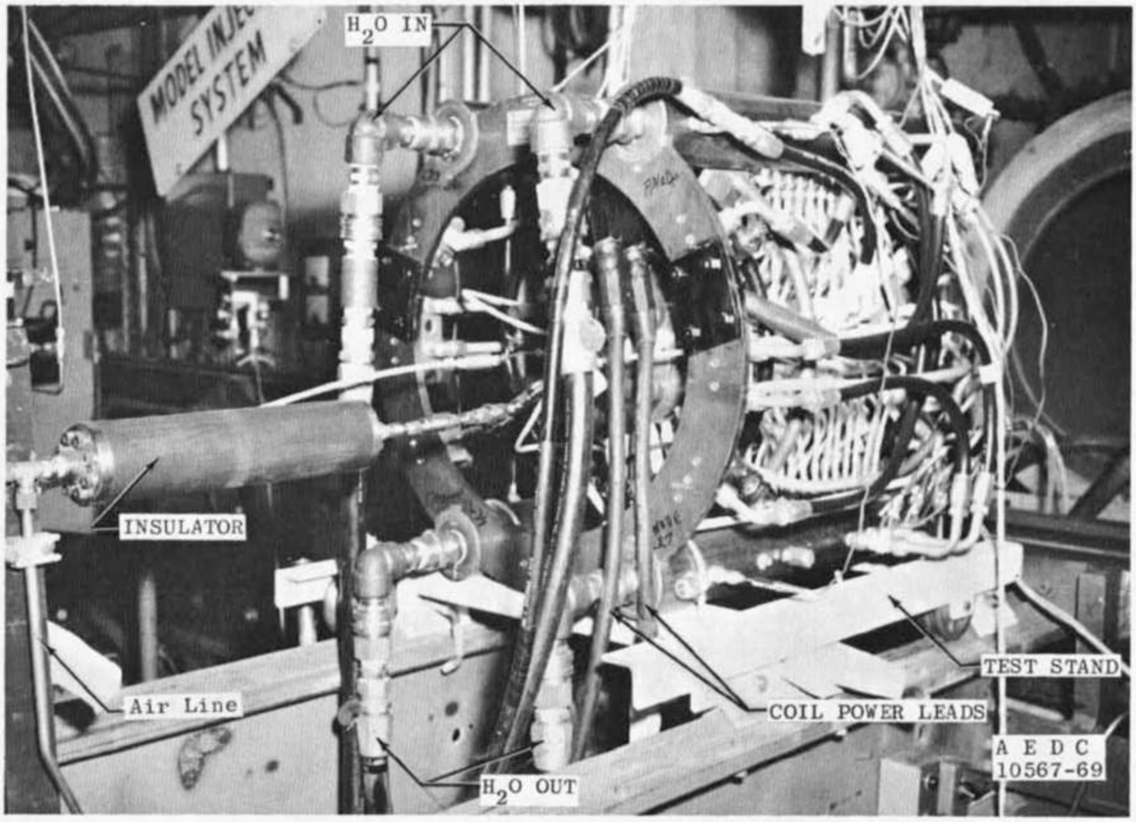
d. Side View
Fig. 6 Continued



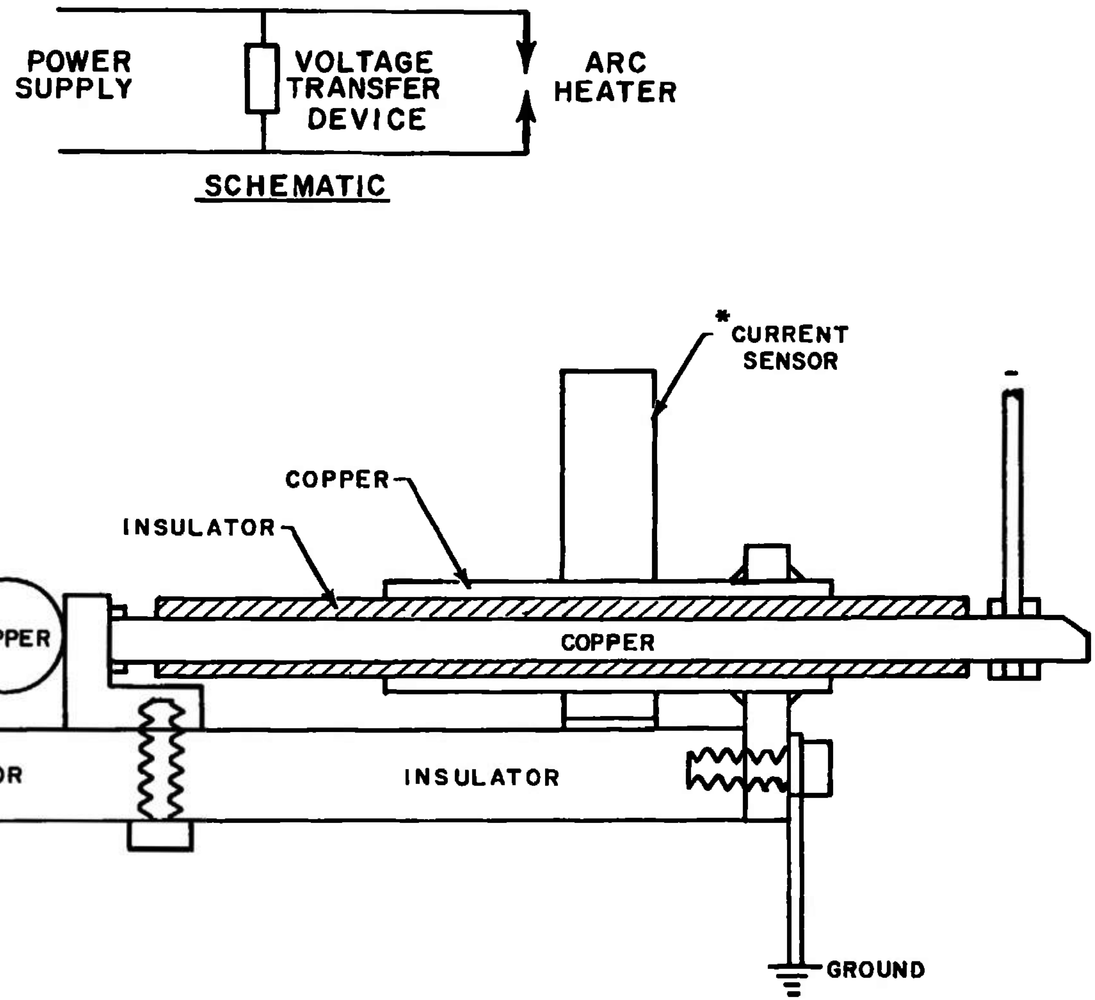
e. Rear View
Fig. 6 Continued



f. Front View, on Test Stand
Fig. 6 Continued



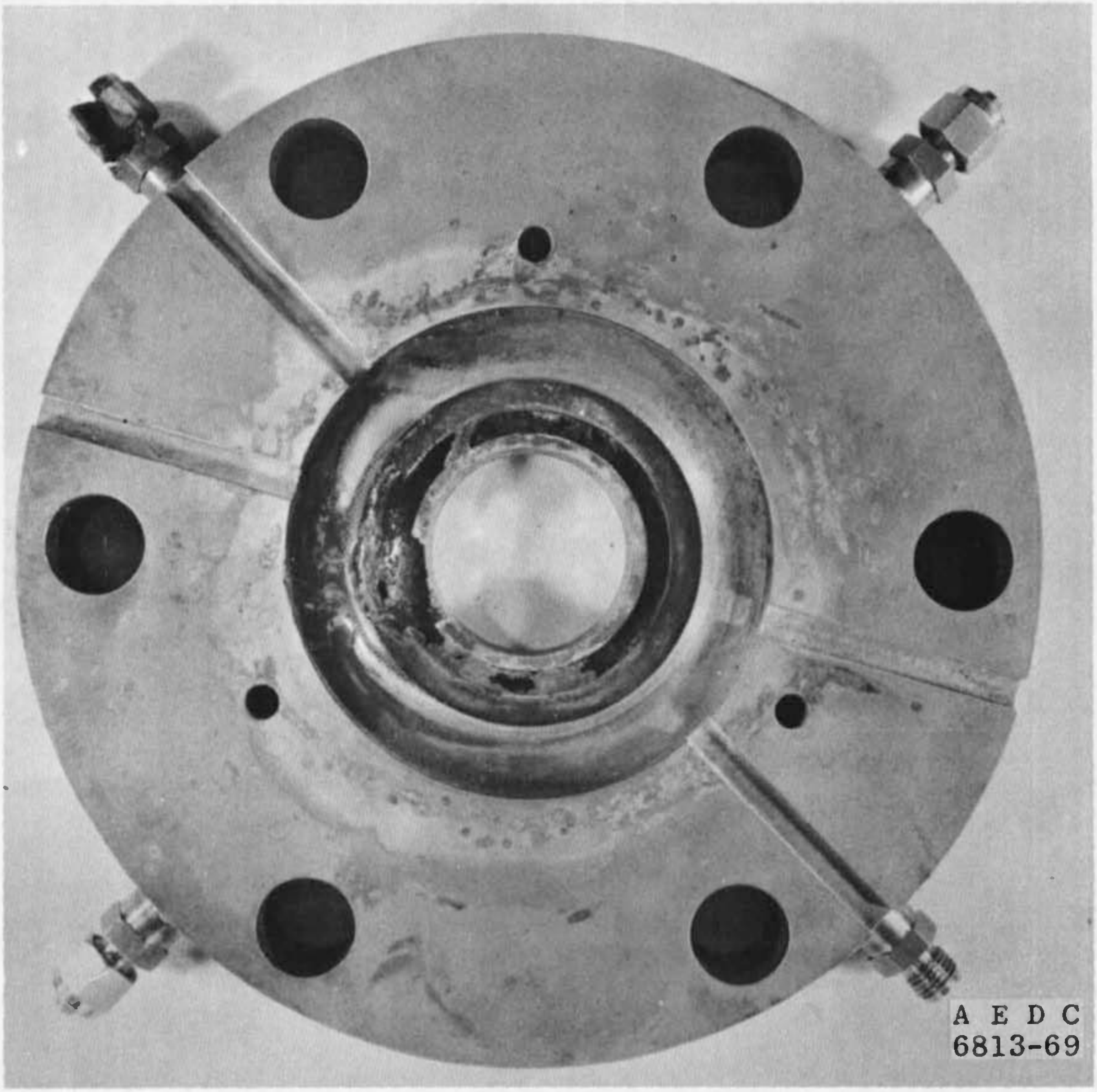
g. Rear View, on Test Stand
Fig. 6 Concluded



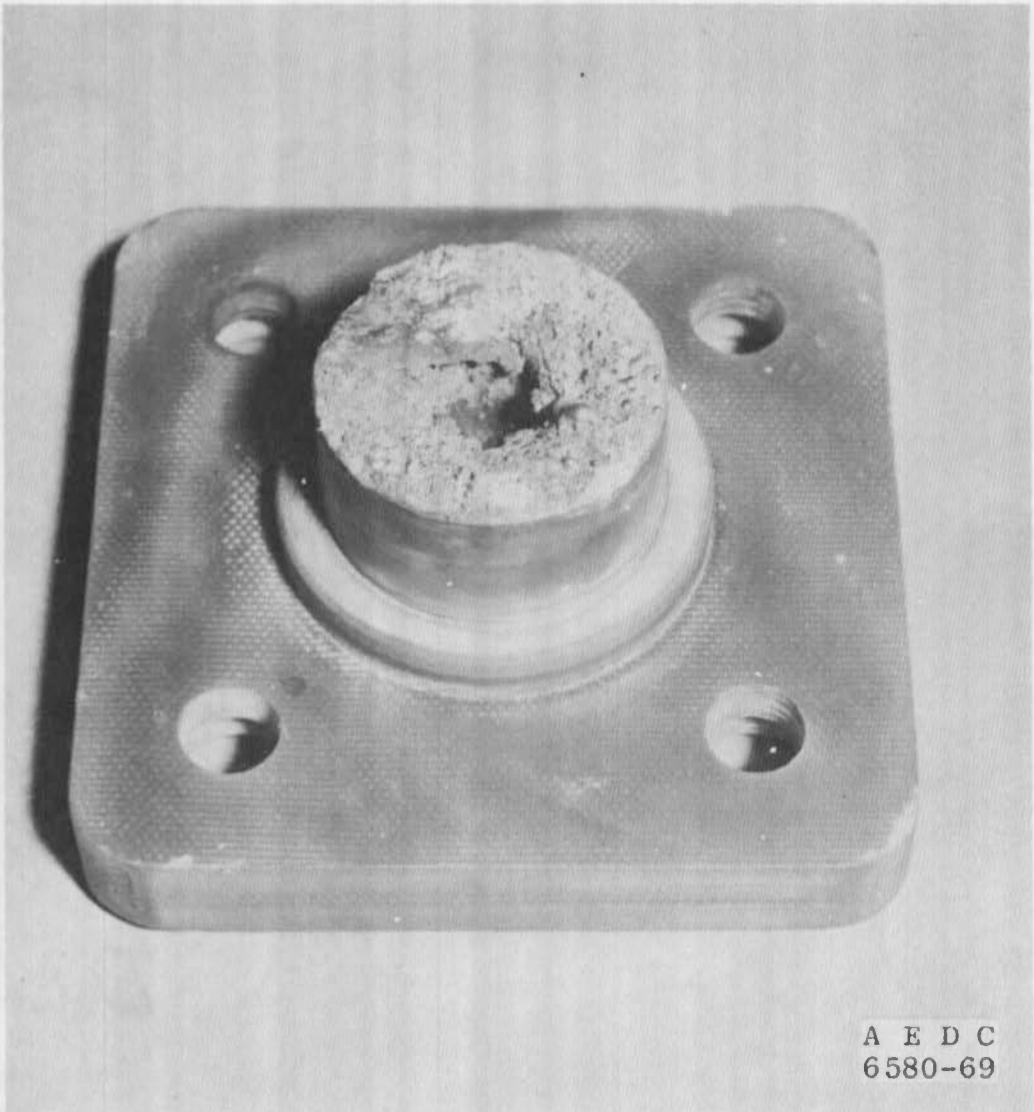
SYSTEM DESIGN CAPACITY = 750 amps FOR 0.5 sec DURATION

* COUPLED TO ELEMENT WHICH SHORTS RECTIFIER

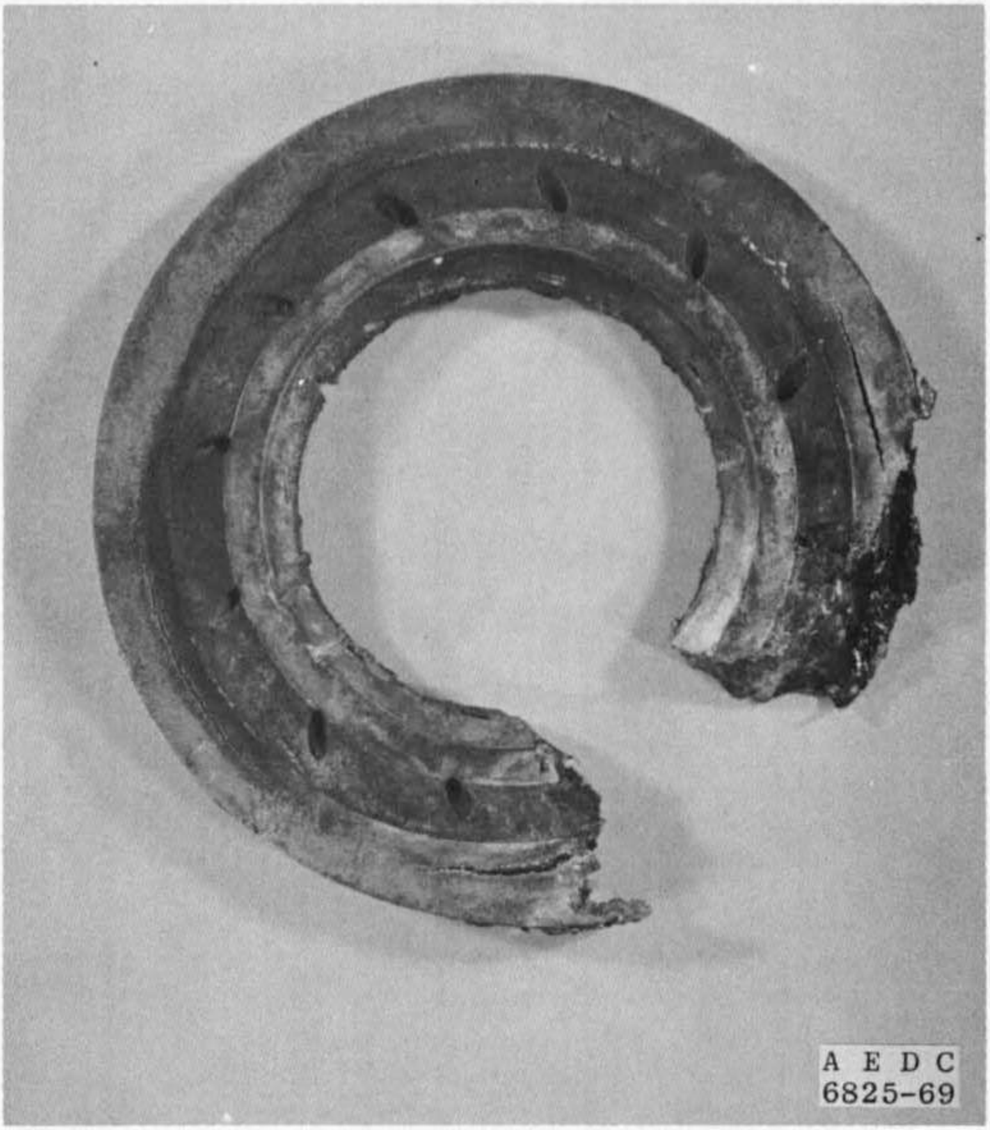
Fig. 7 Voltage Transfer Device



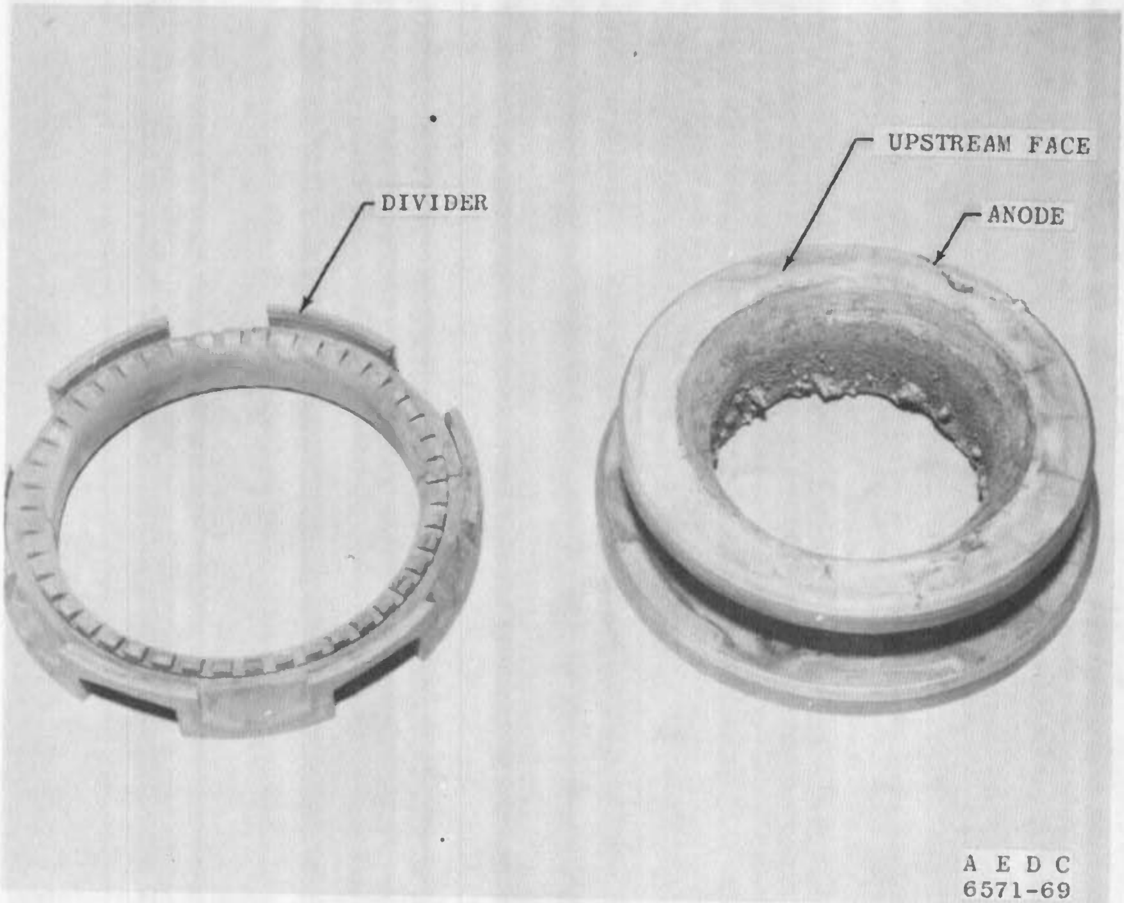
a. Cathode Plate
Fig. 8 Photographs of Damage to 1-MW Nitrogen Heater during Run E3



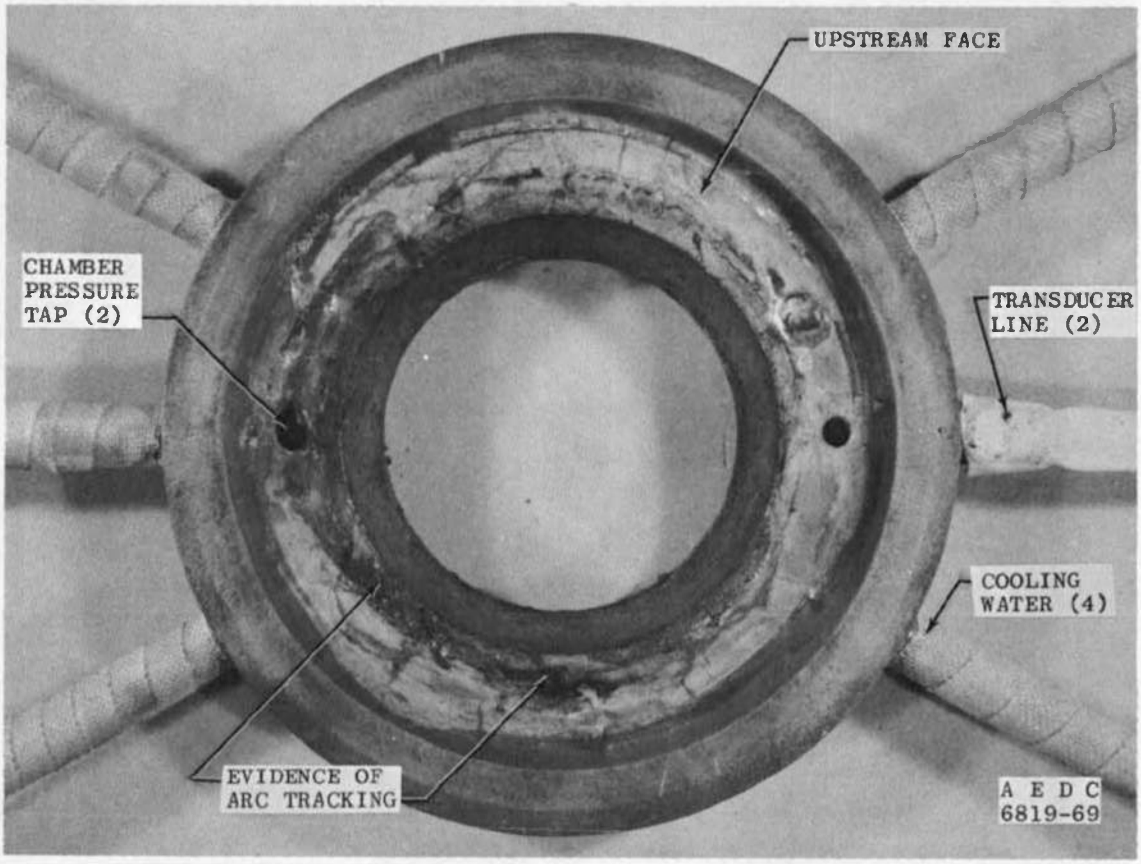
b. Cathode
Fig. 8 Continued



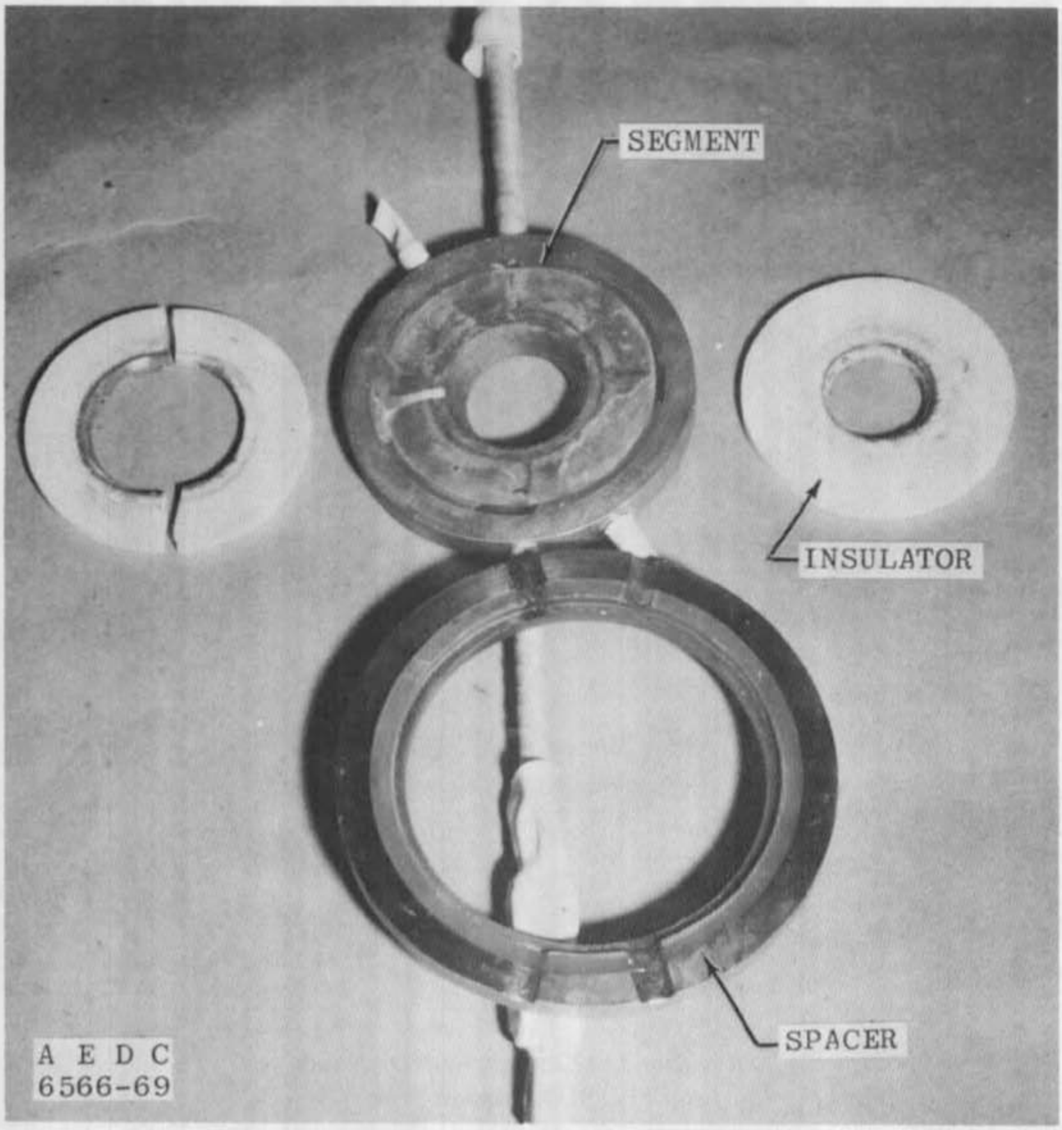
c. Gas Injection Ring
Fig. 8 Continued



d. Anode and Its Cooling Flow Divider
Fig. 8 Continued



e. First Segment Downstream of Anode
Fig. 8 Continued



f. Second Segment Downstream of Anode
Fig. 8 Concluded

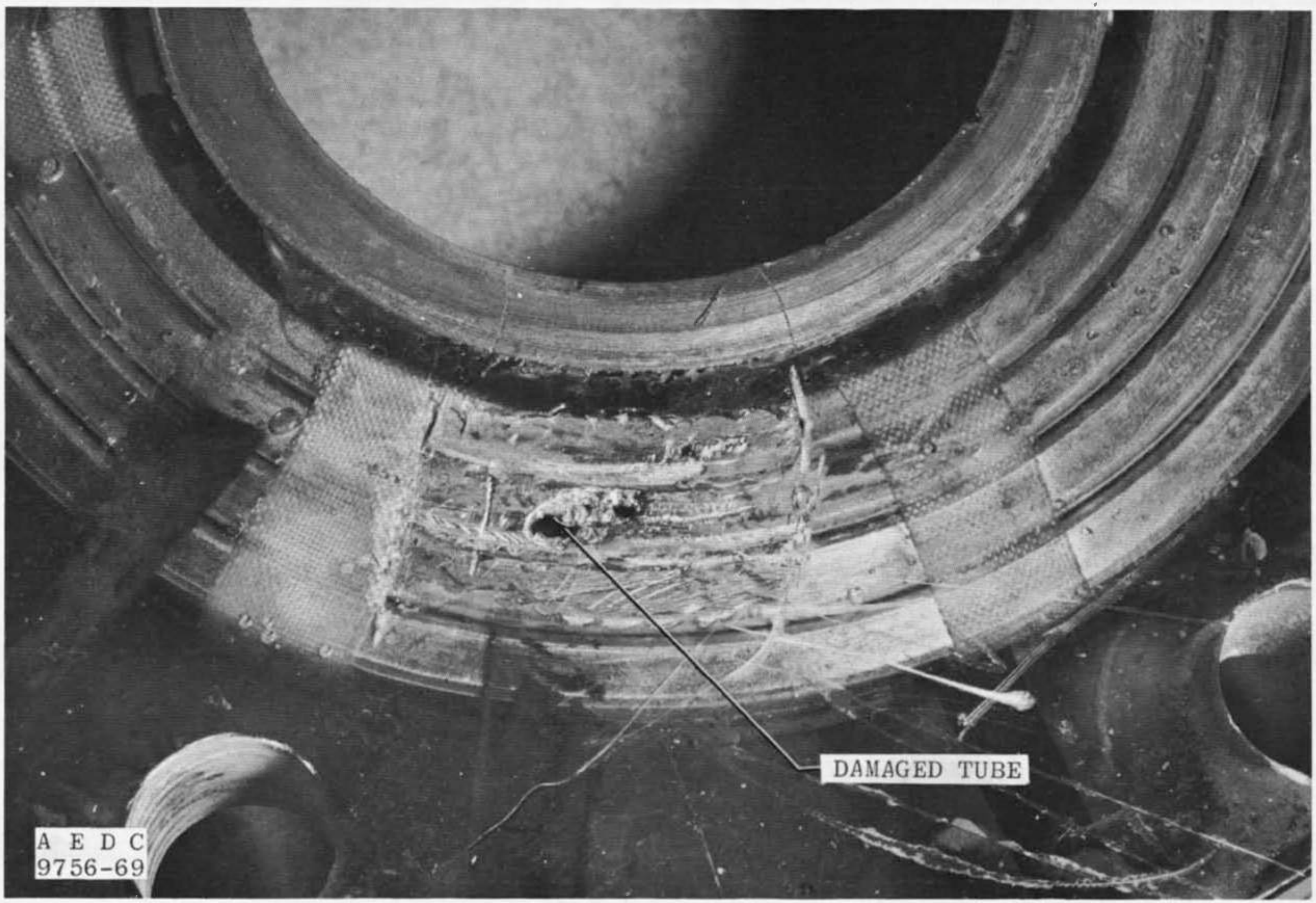
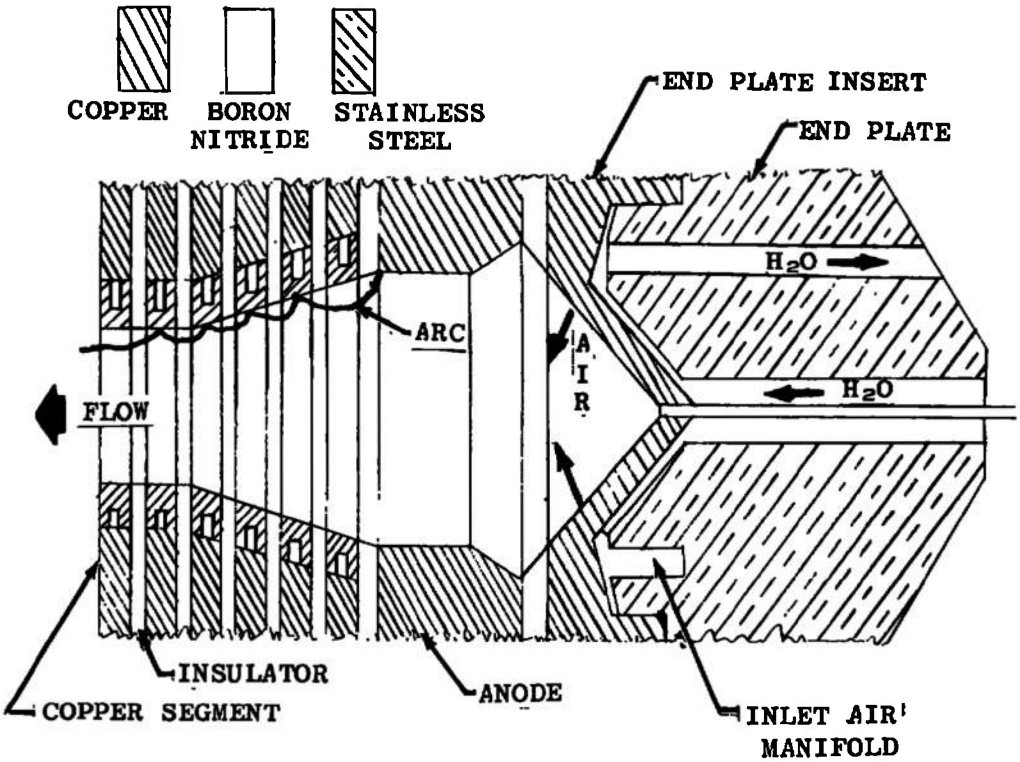
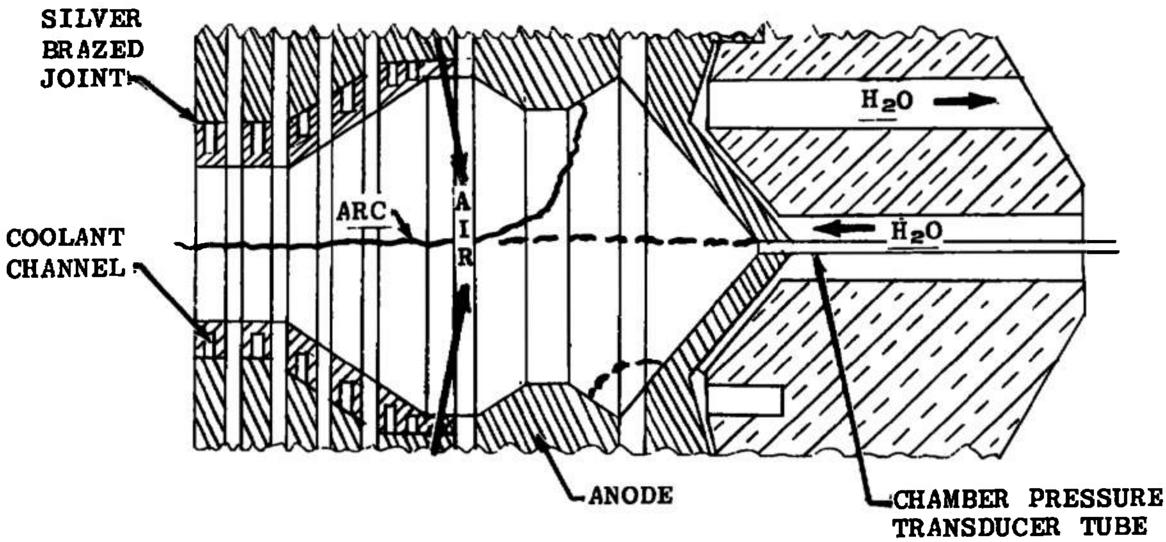


Fig. 9 Photograph of Damage to Cathode Spin Coil during Run E9

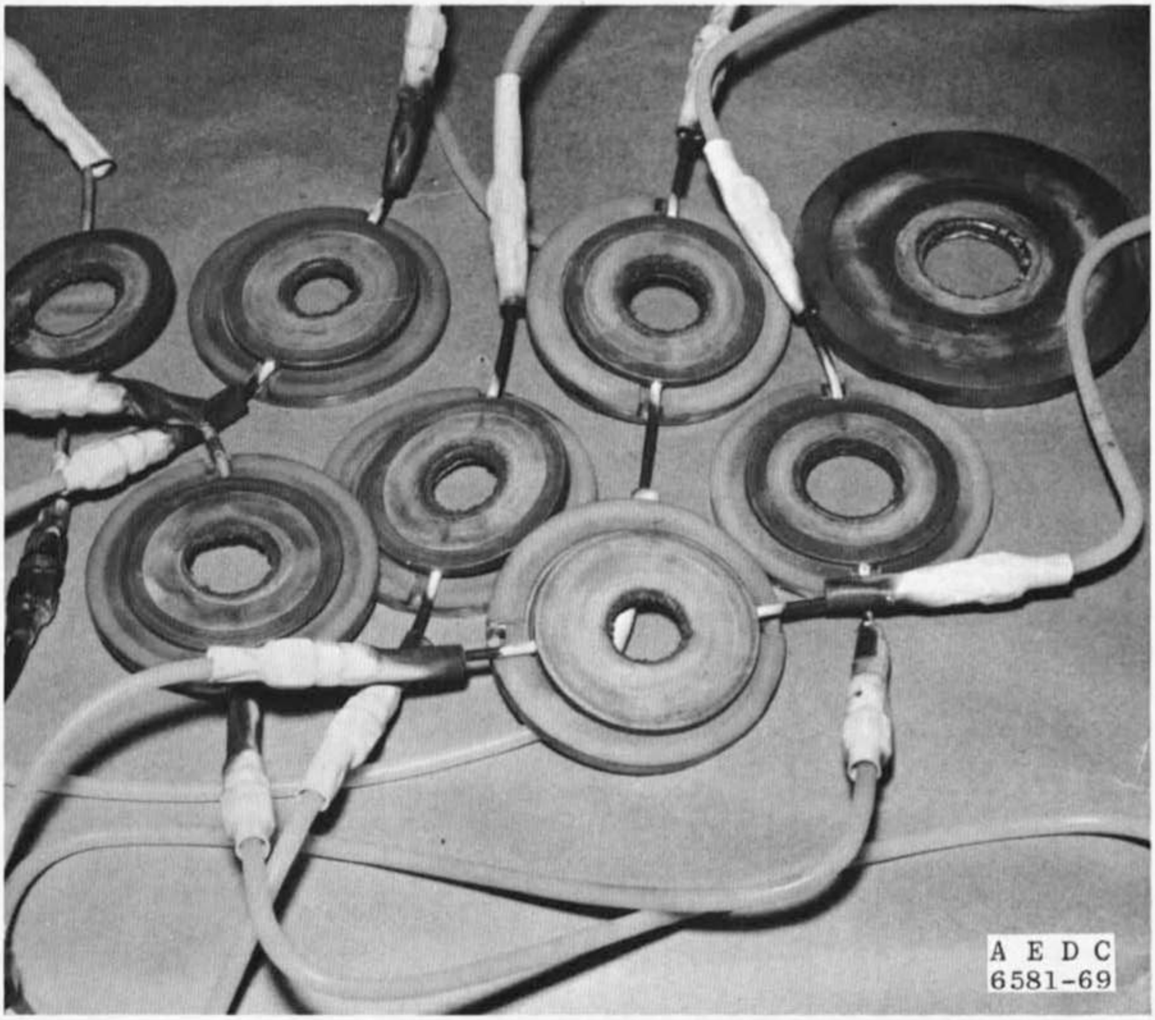


a. Runs E11 through E15

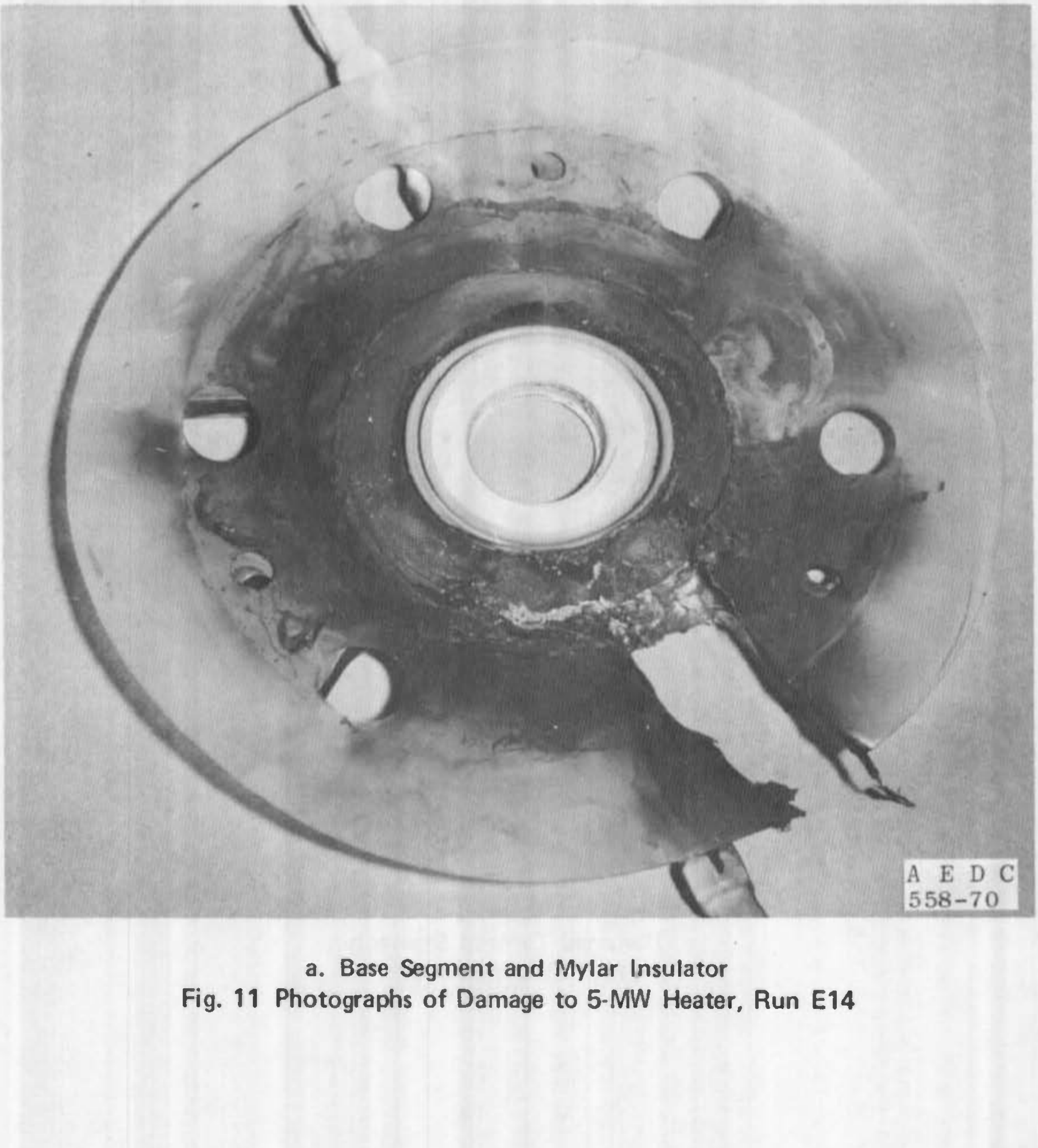


b. Runs E16 through E18

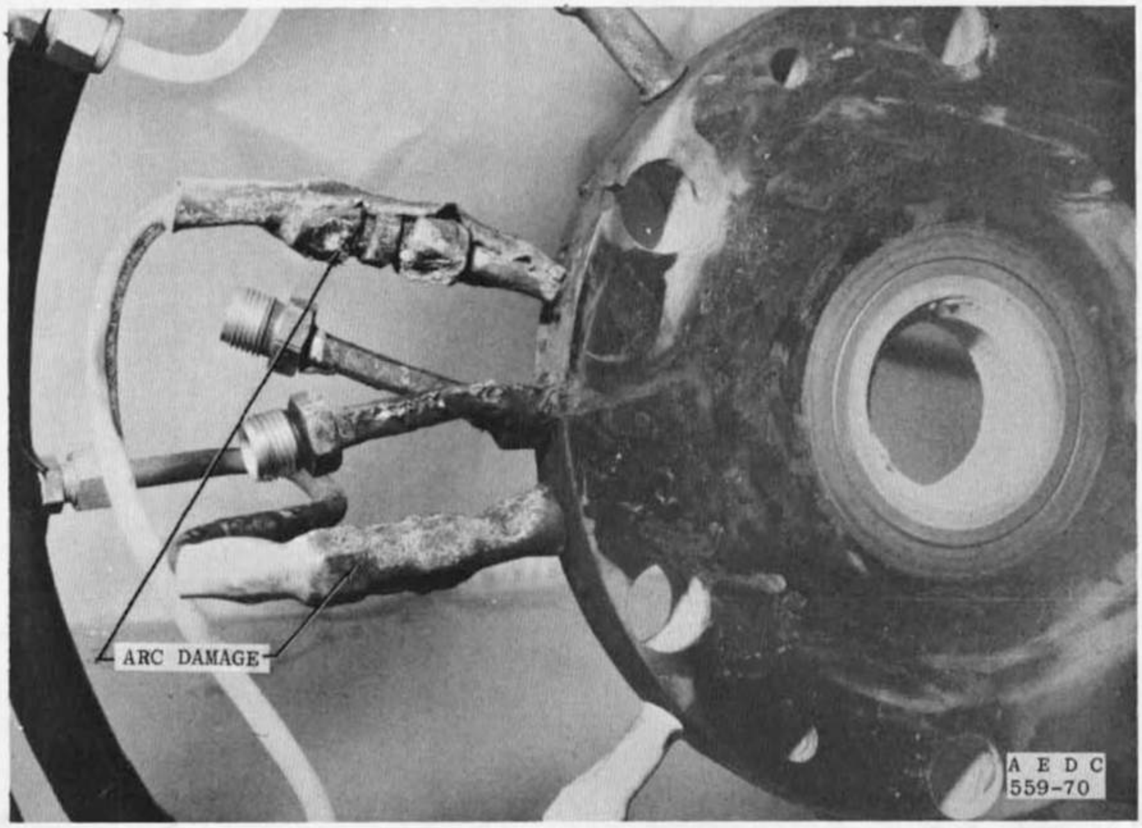
Fig. 10 Anode and Air Injection Configuration, 5-MW Heater



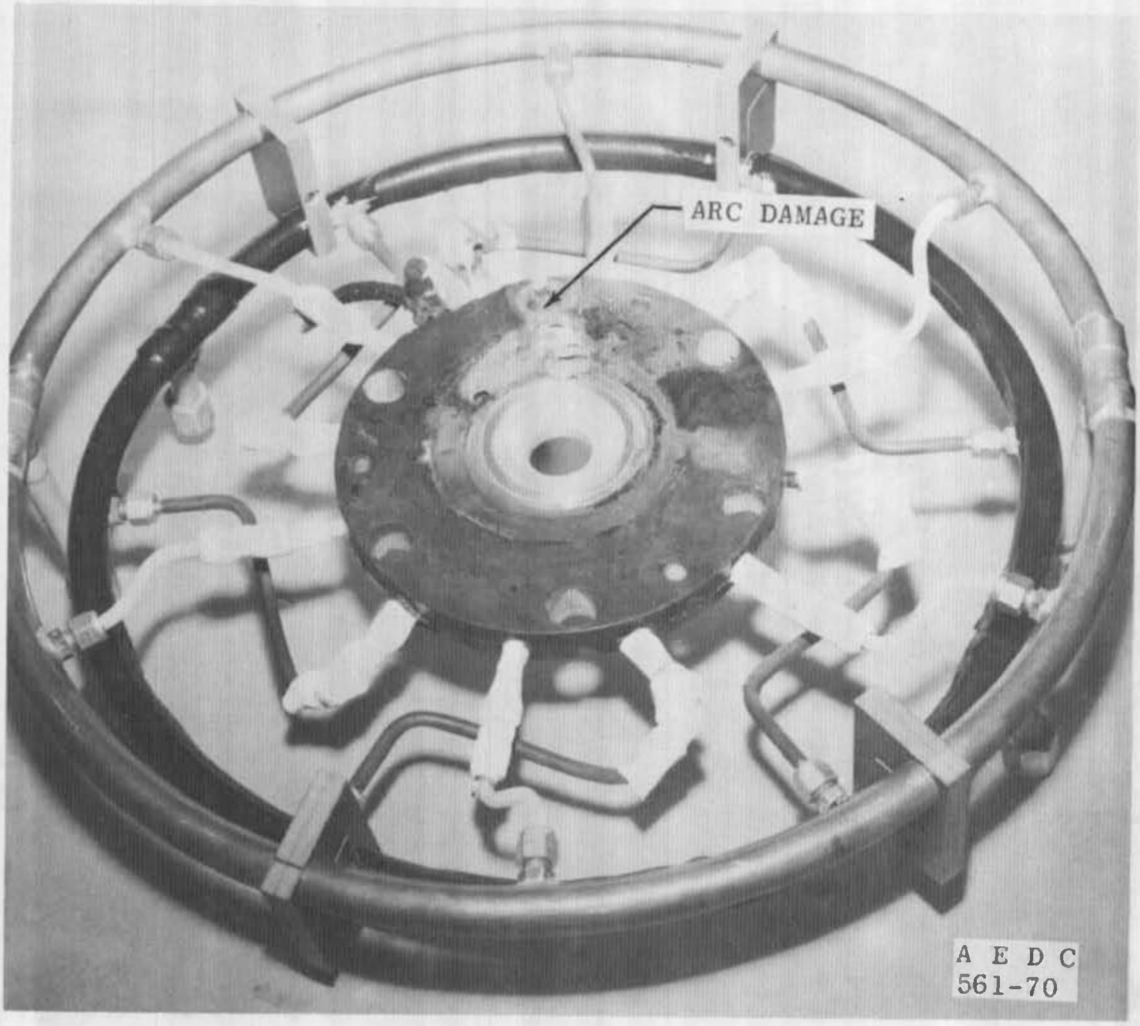
c. Damaged Tapered Segments
Fig. 10 Concluded



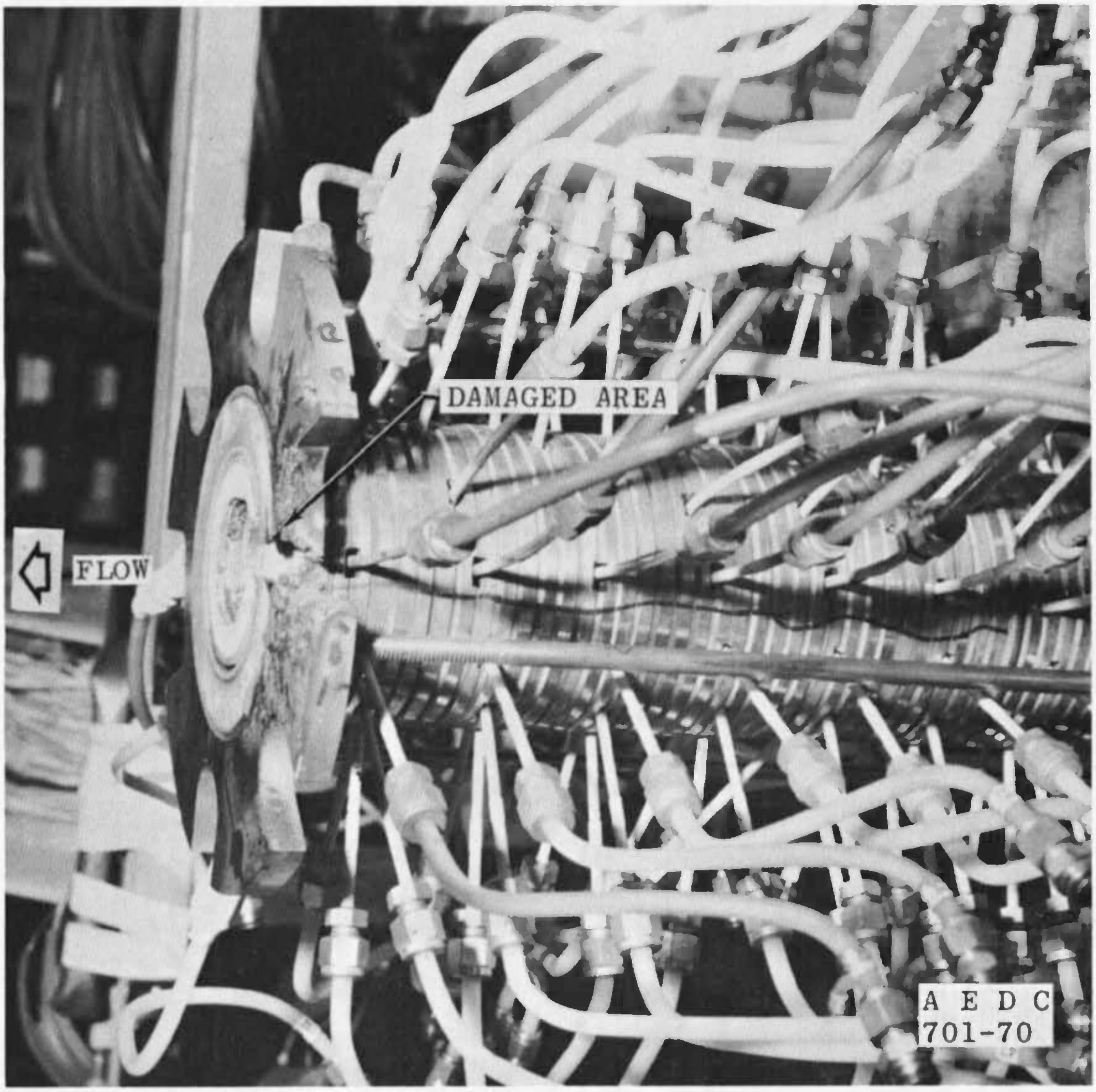
a. Base Segment and Mylar Insulator
Fig. 11 Photographs of Damage to 5-MW Heater, Run E14



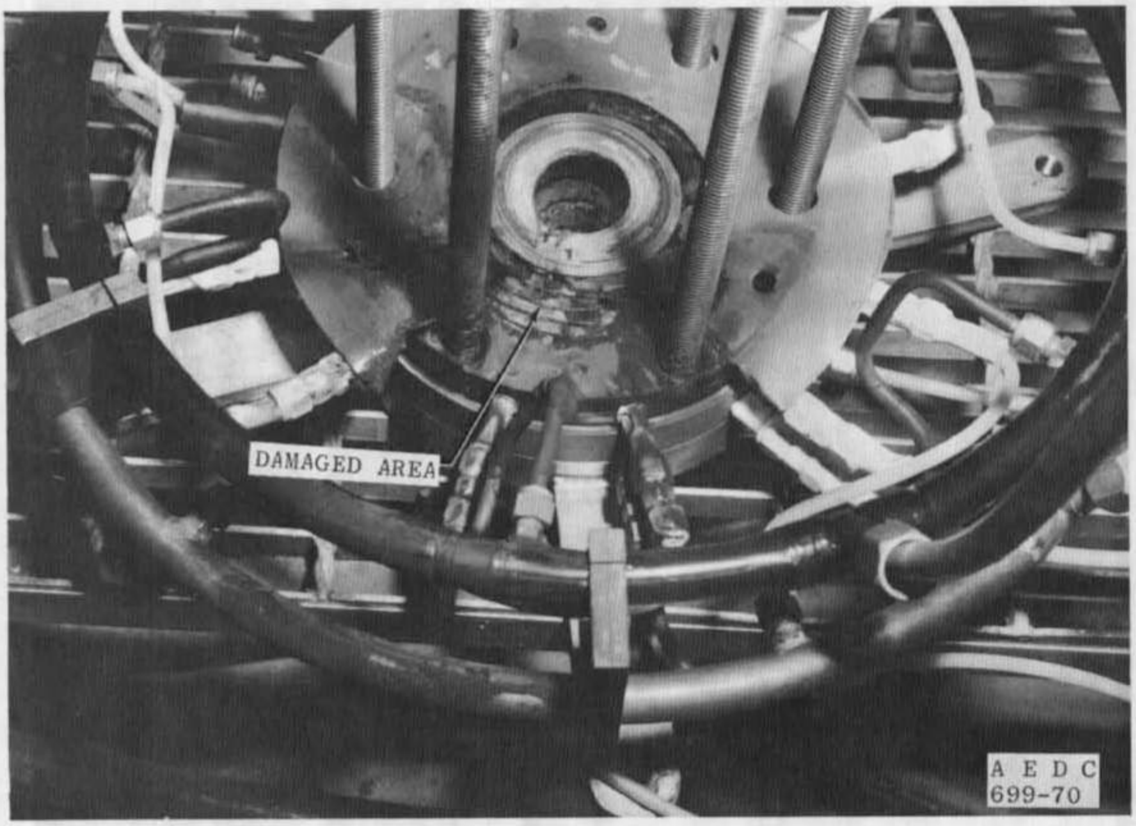
b. Upstream Face, Cathode Spin Coil
Fig. 11 Continued



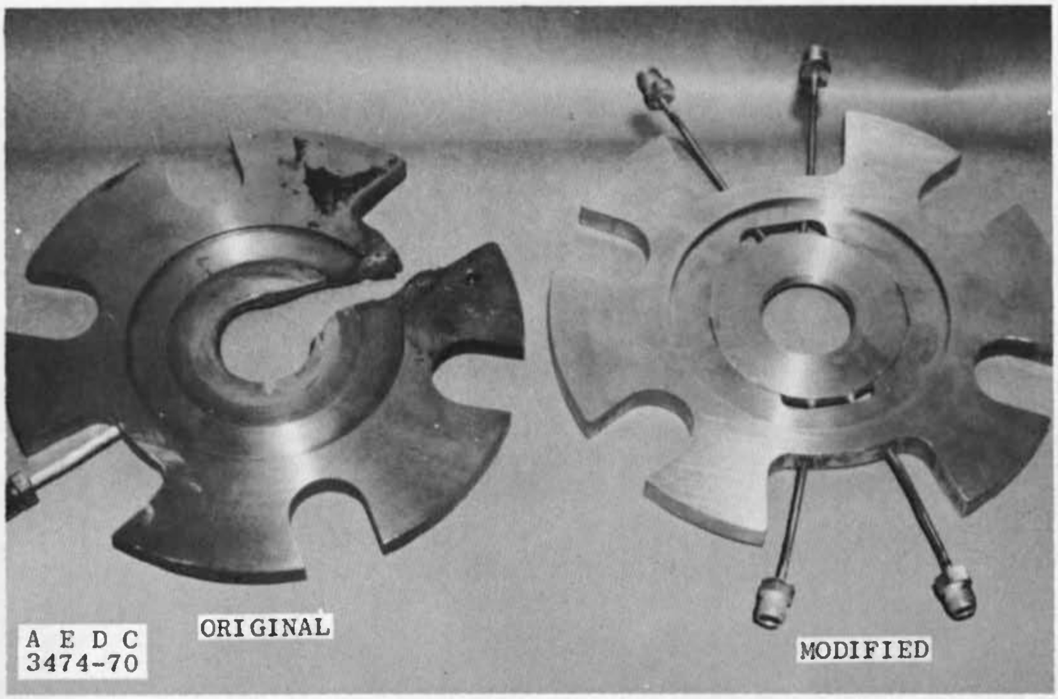
c. Downstream Face, Anode Spin Coil
Fig. 11 Concluded



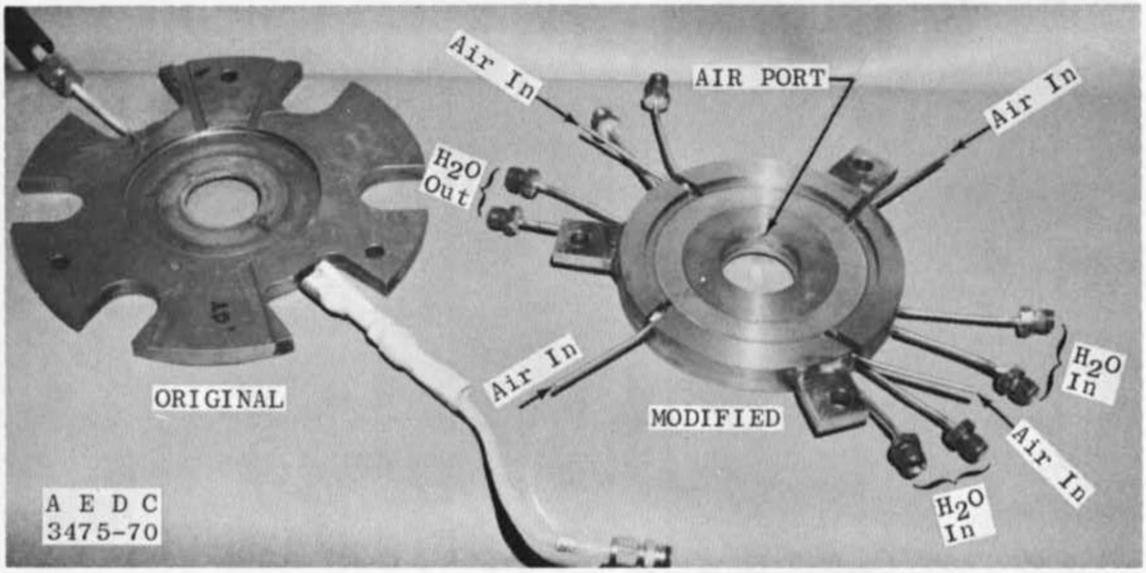
a. Downstream Base Segment
Fig. 12 Photographs of Damage to 5-MW Heater, Run E15



b. Cathode Spin Coil
Fig. 12 Concluded

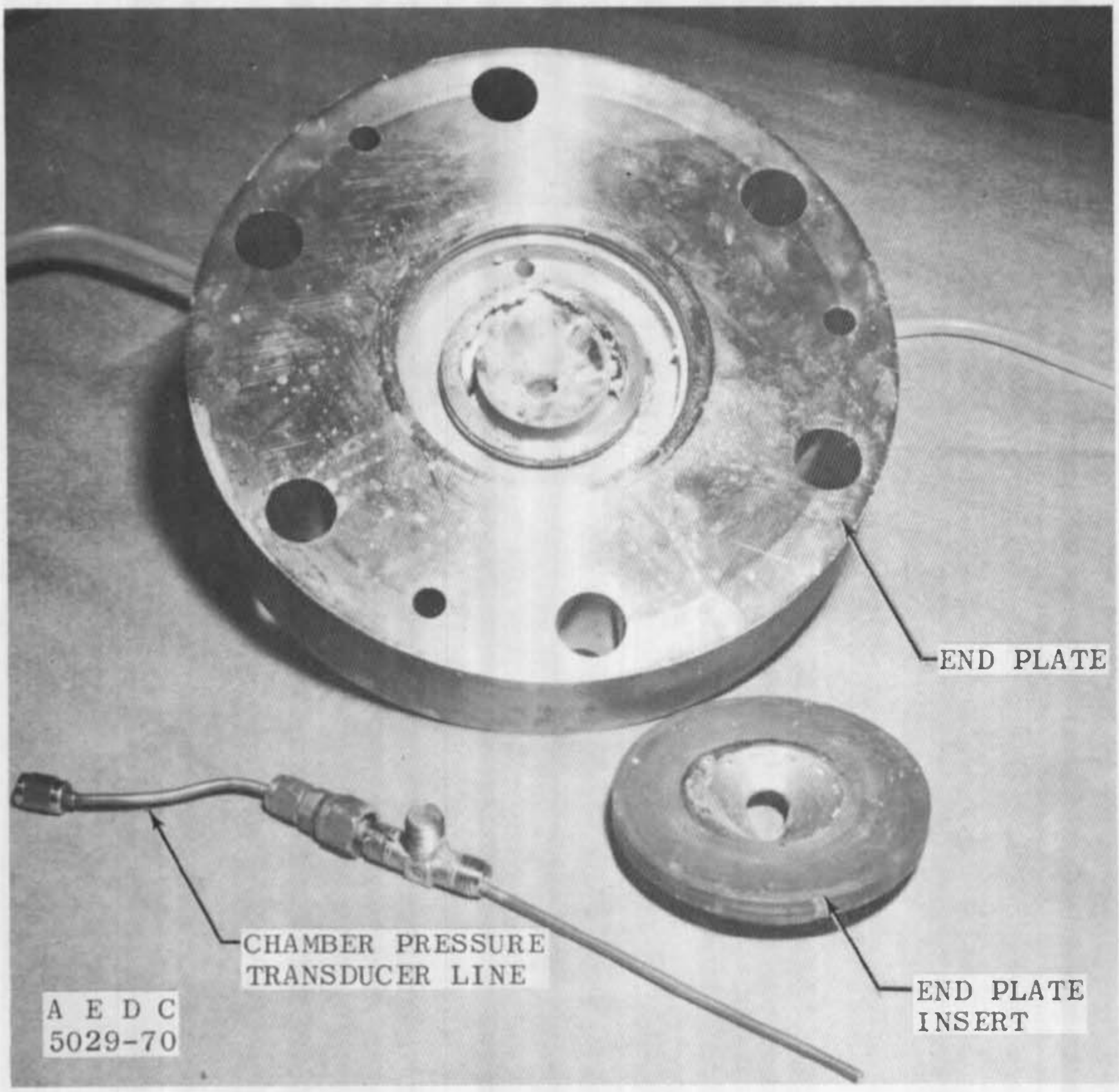


a. Downstream Segment

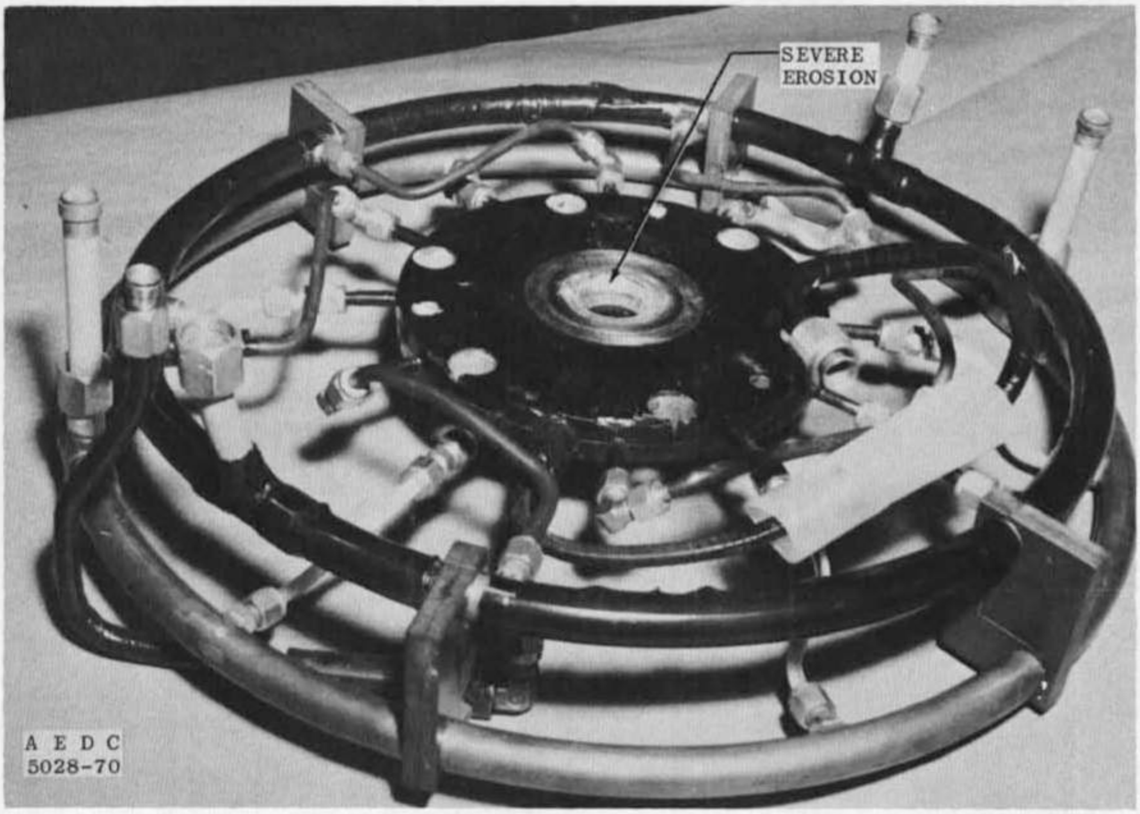


b. Upstream Segment

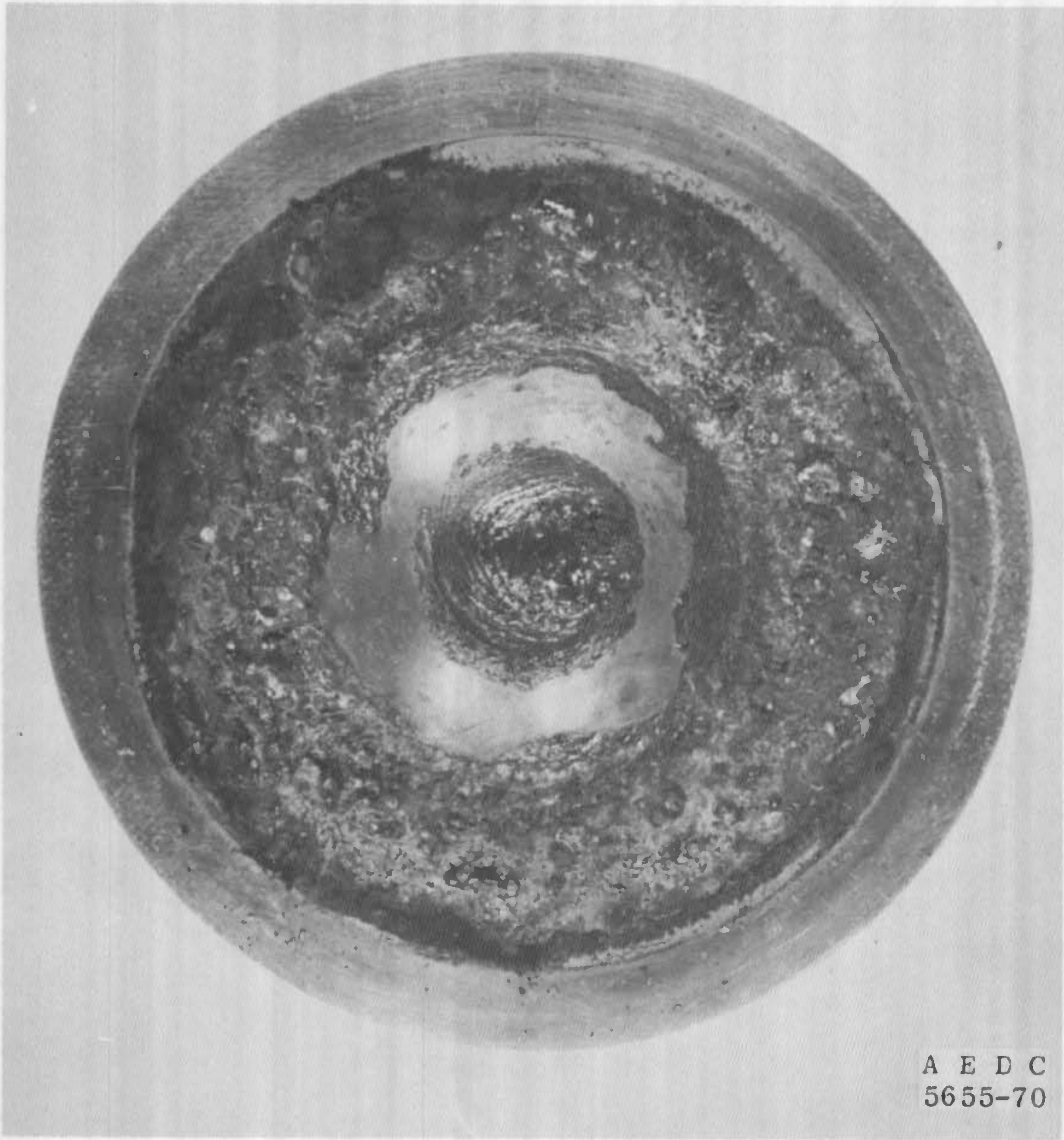
Fig. 13 Photographs of Original and Modified Base Segments



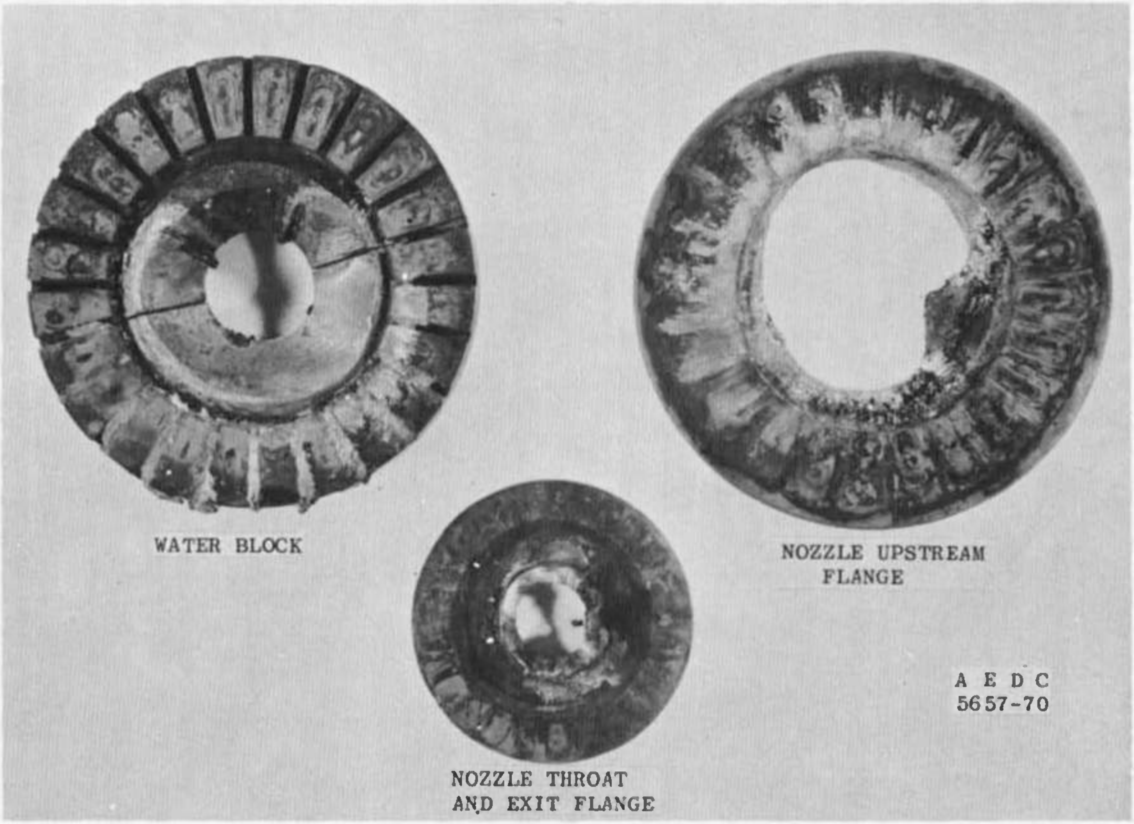
a. End Plate and End Plate Insert
Fig. 14 Heater Damage Sustained during Run E17



b. Upstream Side of Anode
Fig. 14 Concluded



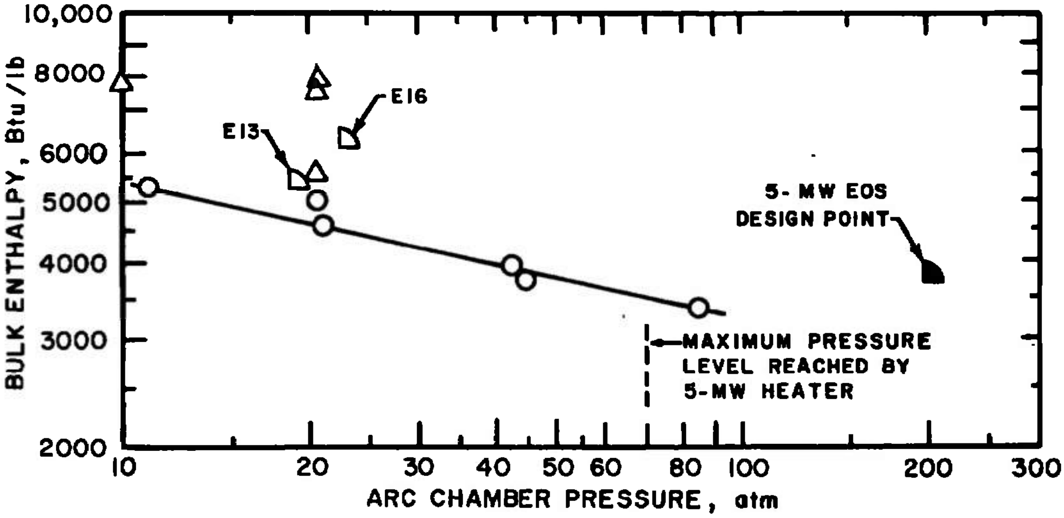
a. End Plate Insert
Fig. 15 Photographs of Heater Damage, Run E18



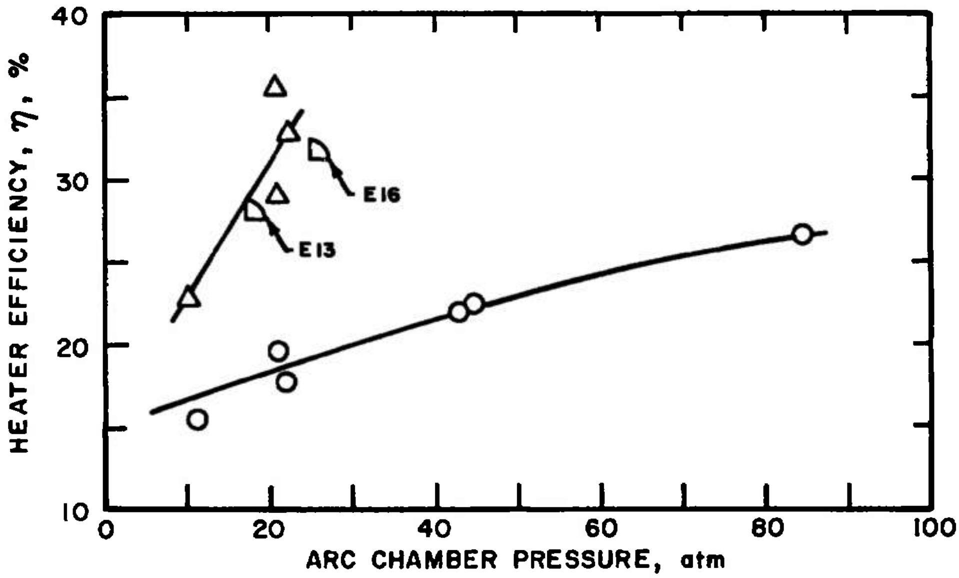
b. Exit Nozzle and Water Block
Fig. 15 Concluded

Sym	Test Gas	Power Rating, MW	Interelectrode Distance, In.	Exit Nozzle Throat Diam, In.
○	Air	1.0	5.501	0.111
△	N_2	1.0	5.501	0.111
◺	Air	5.0	17.561	0.215

Constrictor Column Diam. = 0.934 In.



a. Pressure and Enthalpy



b. Efficiency

Fig. 16 Thermodynamic Performance of EOS Arc Heaters

Sym	Heater	Test Gas	Arc Length, In.	d*, In.	d*/D	Nominal Power Rating, MW
□	Linde N4000	Air	Variable	0.375	0.250	4
◊	Linde N4000 (Improved)	Air	Variable	0.375	0.250	5
◺	EOS	Air	17.561*	0.215	0.230	5

*Assumed equal to interelectrode distance

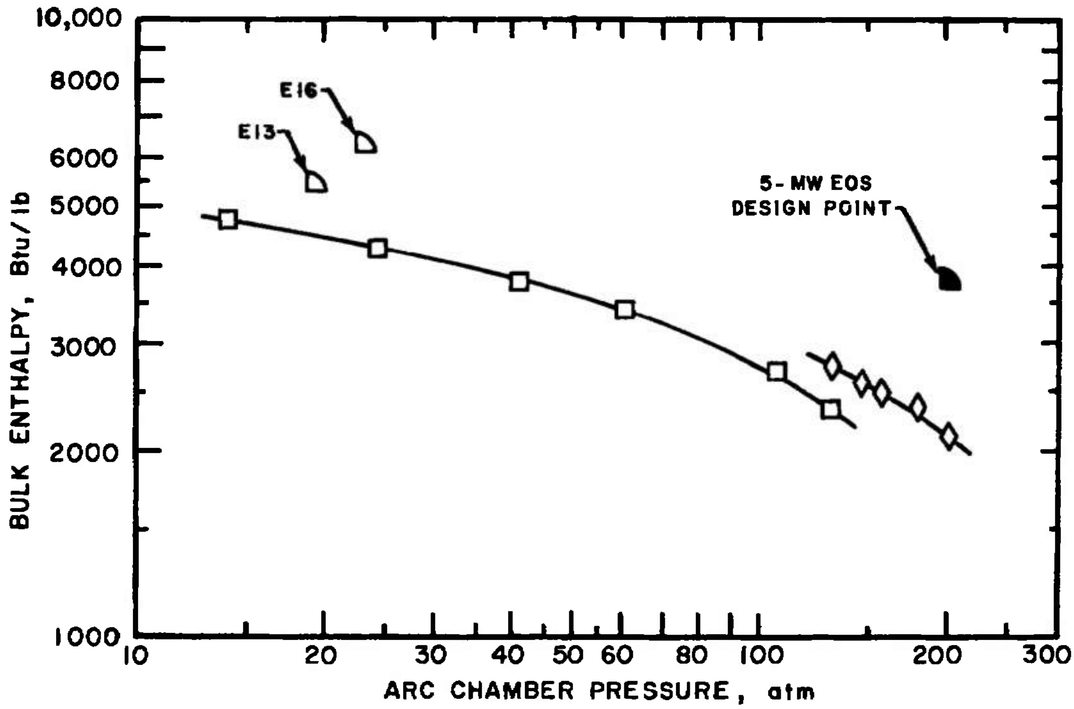
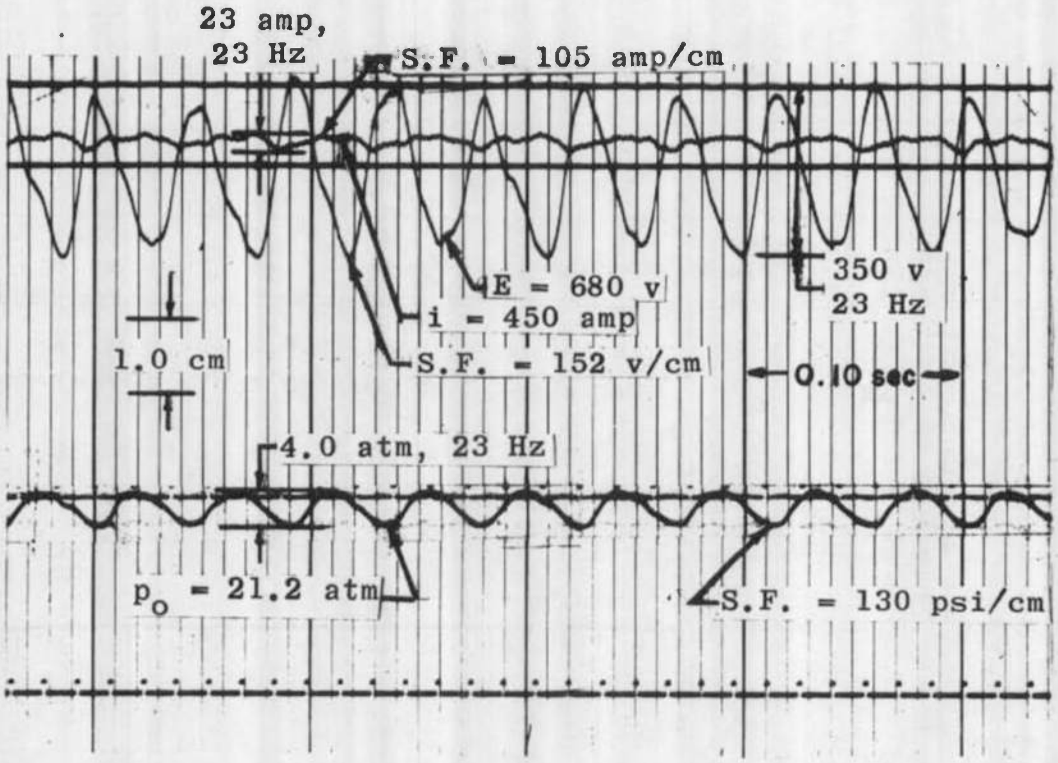
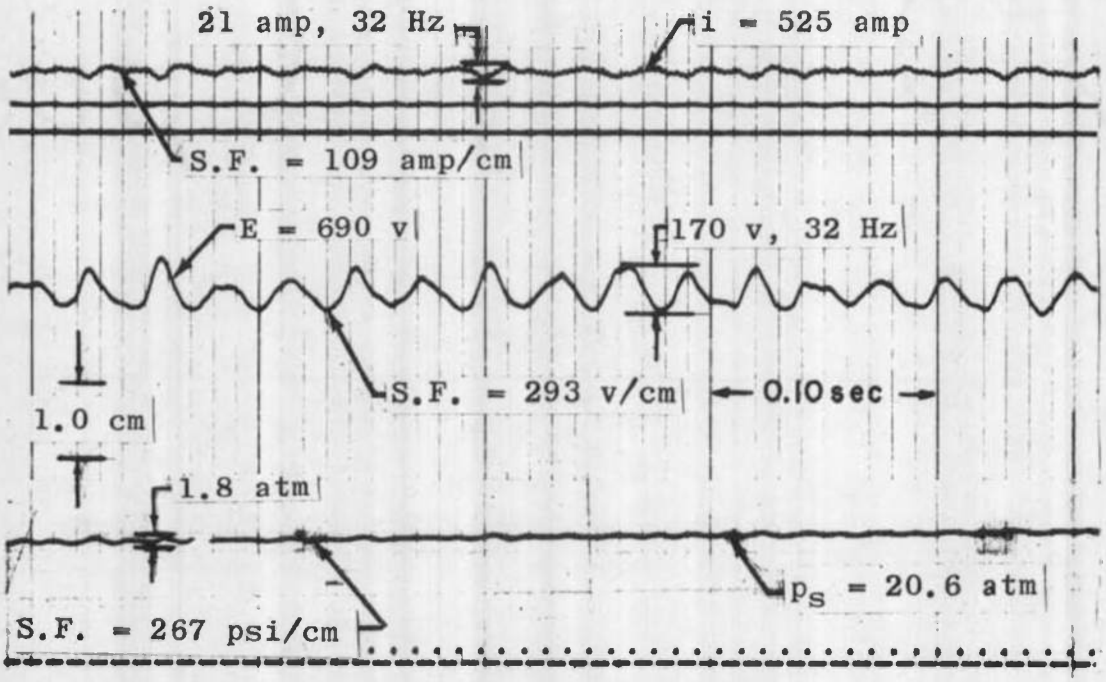


Fig. 17 Performance Comparison of 5-MW EOS and Linde N4000 Heaters

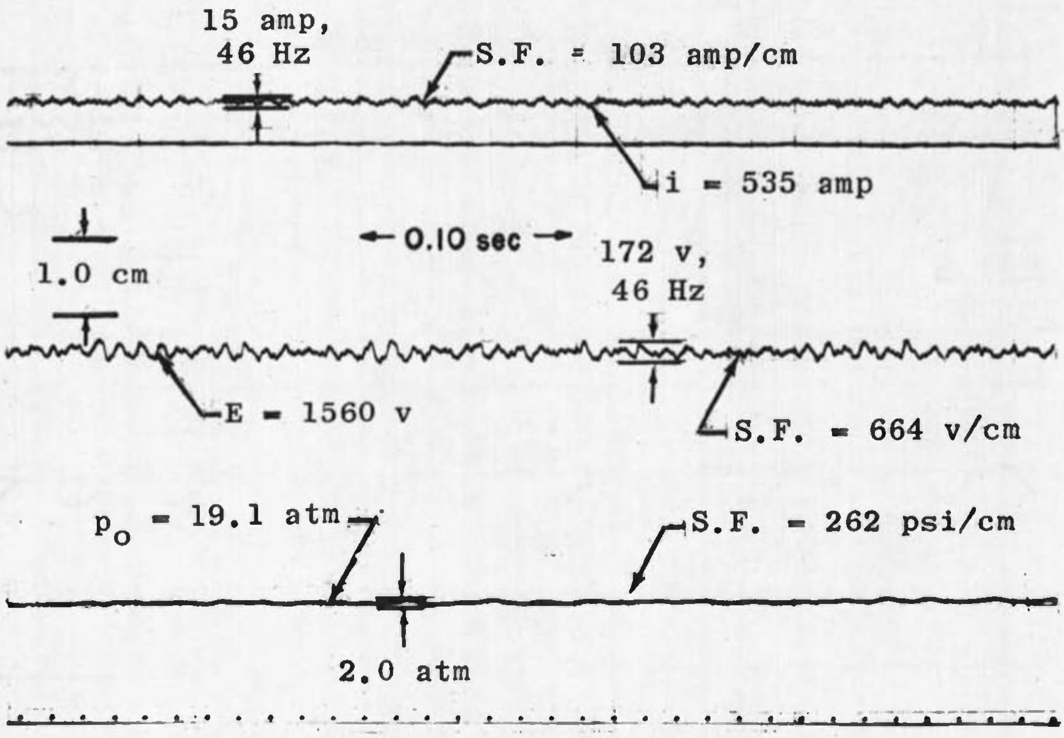


a. Run E2-5, Nitrogen, 1-MW EOS Heater

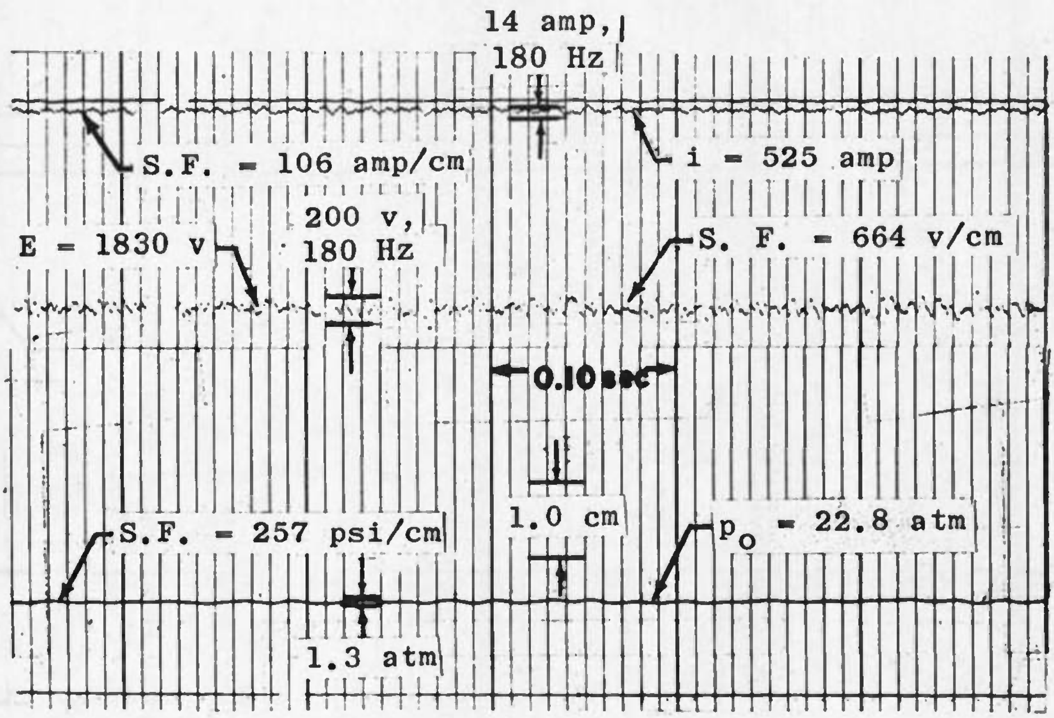


b. Run E9-1, Air, 1-MW EOS Heater

Fig. 18 Comparison of Variation in Arc Voltage, Arc Current, and Arc Chamber Pressure, EOS and Linde Heaters

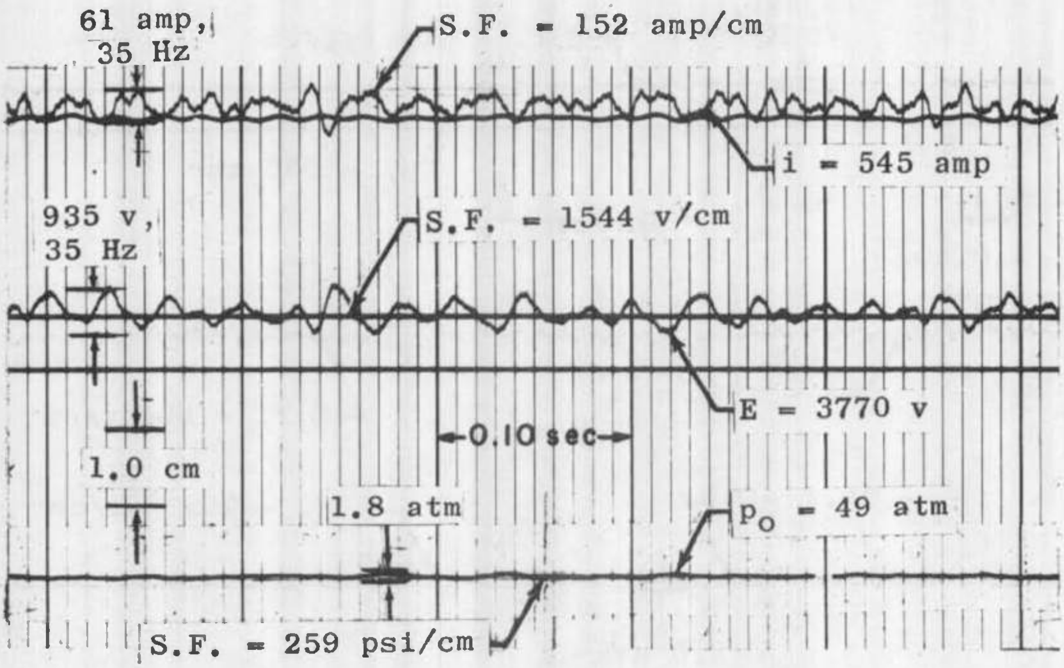


c. Run E13, Air, 5-MW EOS Heater

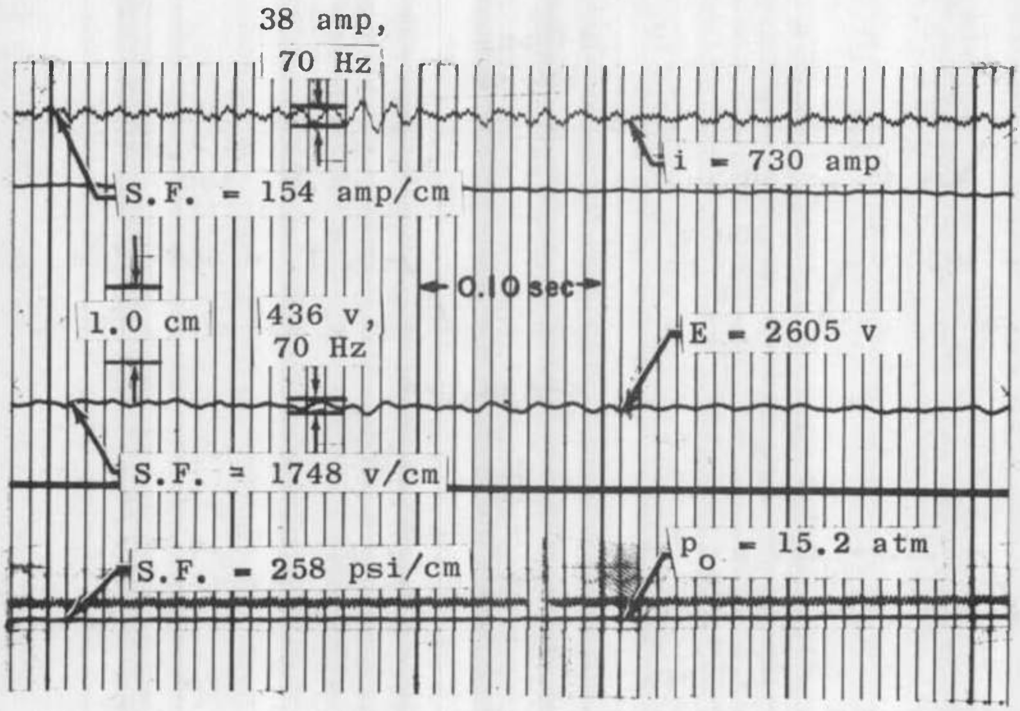


d. Run E16, Air, 5-MW EOS Heater

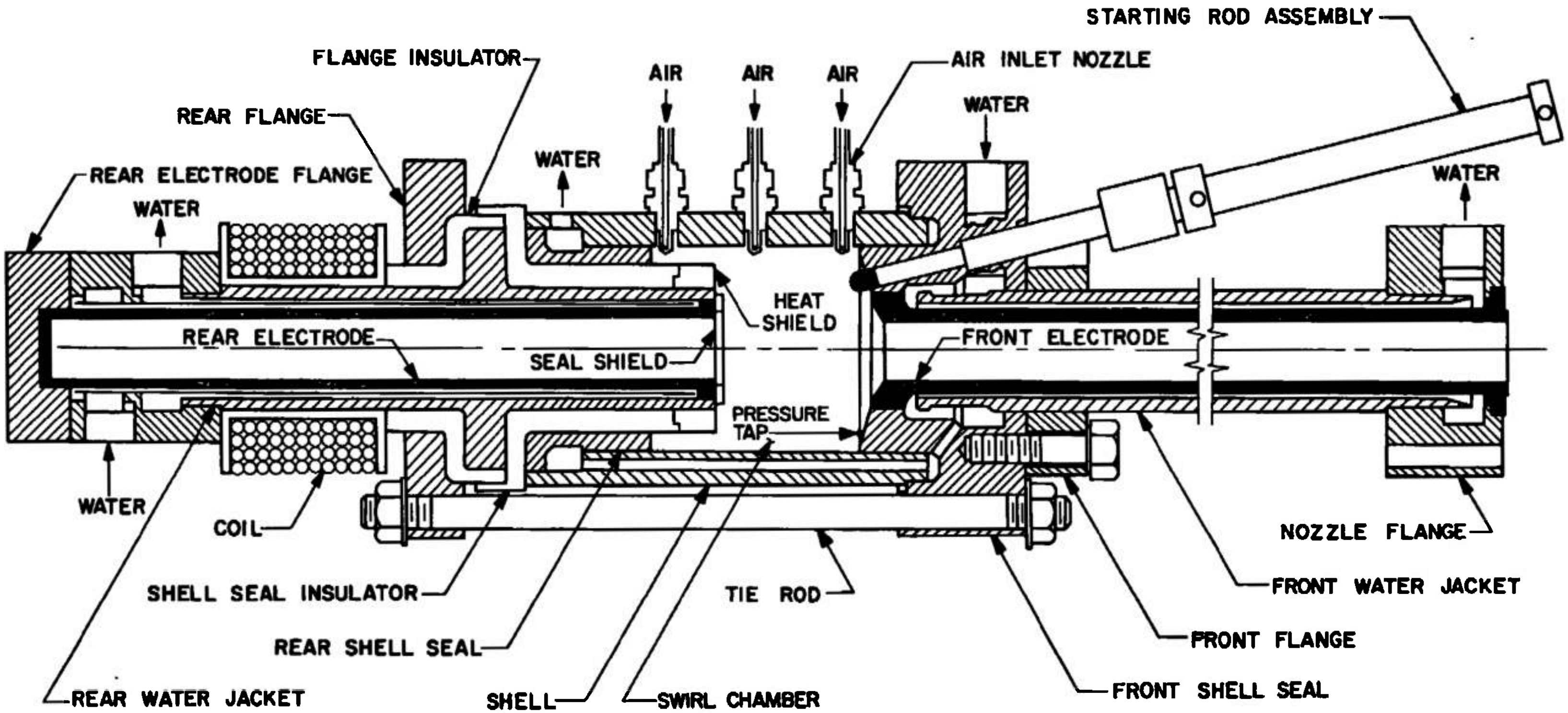
Fig. 18 Continued



e. Run HP4-2, Air, 5-MW Linde N4000 Heater, Improved Version

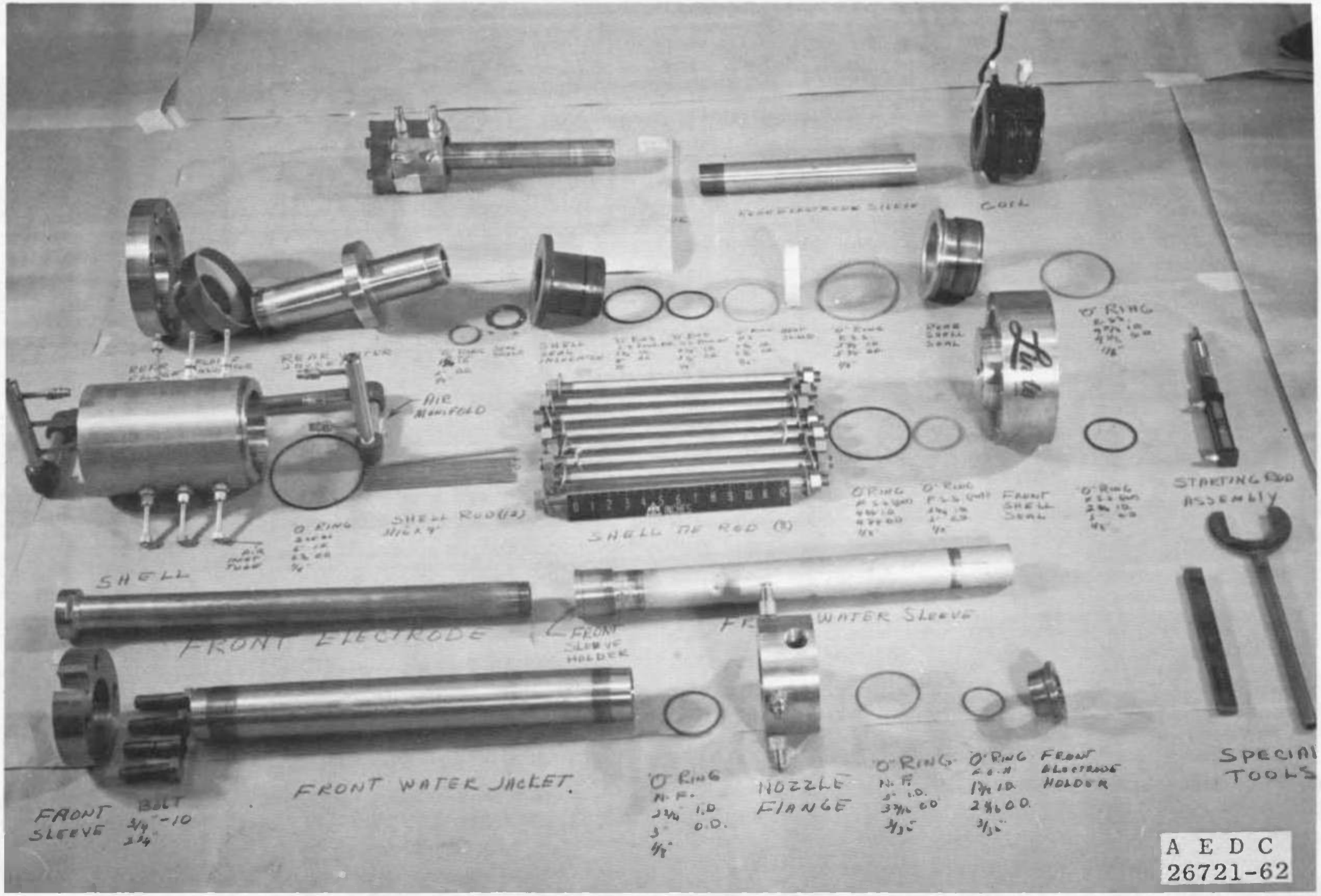


f. Run 70-B2, Air, 5-MW Linde N4000 Heater, Improved Version
Fig. 18 Concluded

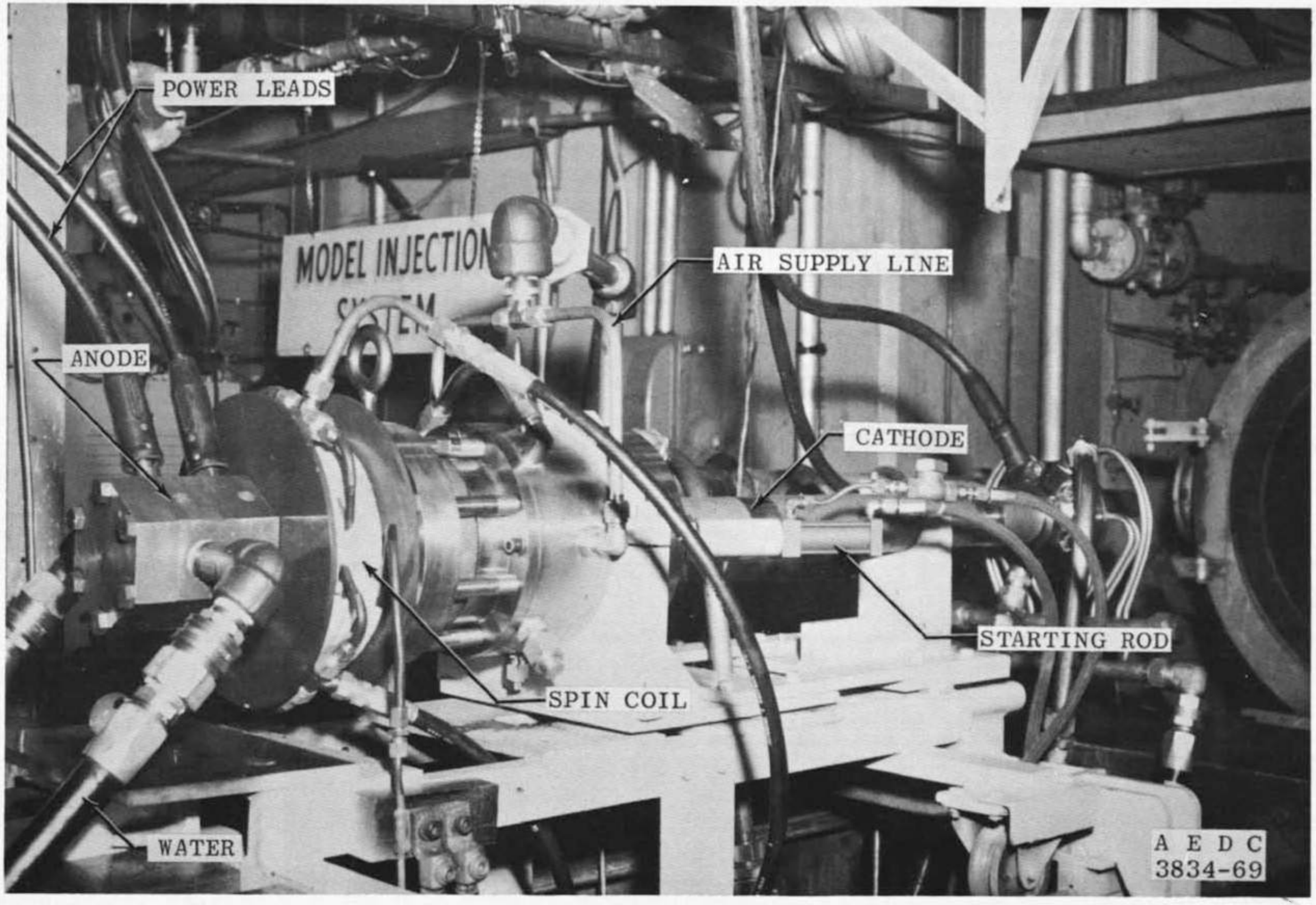


UNCLASSIFIED

a. Drawing
Fig. 19 Linde Model N4000 Arc Heater



b. Exploded View
Fig. 19 Continued



c. Installed on Test Stand
Fig. 19 Concluded

TABLE I
RUN LOG FOR 1-MW HEATERS

RUN AND DATA POINT NUMBER	DATA POINT Δt, sec	TOTAL TIME FOR THIS RUN, sec	TEST GAS	p_o atm	h_o Btu/lb	$\dot{m}$ lb/sec	E volts	i amp	P_{IN} kw	P_{LOSS} kw	P_{GAS} kw	η percent	REMARKS
E1-1	31.0	-	N_2	8.5	6280	0.0060	415	295	122	84	38	31.2	
E1-4	92.6	113	N_2	8.4	5525	0.0060	350	505	177	143	34	19.2	
E2-1	85.3	-	N_2	9.8	7895	0.0069	420	465	195	139	56	28.8	
E2-2	109.2	-	N_2	9.7	5570	0.0069	430	310	133	93	40	30.0	
E2-3	184.6	-	N_2	10.0	7225	0.0072	405	585	237	183	54	22.8	
E2-4	348.7	-	N_2	20.5	7920	0.0131	640	580	372	264	108	29.0	
E2-5	378.8	-	N_2	21.2	7415	0.0131	680	450	306	206	100	32.7	
E2-6	408.3	409	N_2	20.5	5575	0.0132	715	300	214	138	76	35.5	
E-3	-	43	N_2	-	-	-	-	-	-	-	-	-	Severe damage caused by arc-over.
	Total	565											
E-4	-	3.0	Air	-	-	-	-	-	-	-	-	-	Minor damage caused by arc-over.
E5-1	20.0	-	Air	8.8	7145	0.0072	515	525	271	216	55	20.3	
E5-2	60.0	64	Air	11.1	5415	0.0071	495	525	260	220	40	15.4	
E6-1	50.0	51	Air	21.3	4580	0.0137	690	535	369	304	65	17.6	
E7-1	40.0	41	Air	44.5	3690	0.0291	1075	500	546	425	121	22.2	
E-8	-	1.0	Air	-	-	-	-	-	-	-	-	-	Arc-over caused no damage.
E9-1	14	-	Air	20.6	5015	0.0135	690	525	362	291	71	19.6	
E9-2		50	Air	42.8	3945	0.0282	1040	510	530	414	116	21.9	
E10-1	119.3	120	Air	84.8	3335	0.0625	1745	470	820	608	218	26.6	
	Total	330											

TABLE II
RUN LOG FOR 5-MW HEATER

RUN NO.	TEST GAS	p_o atm	h_o Btu/lbm	$\dot{m}$ lb/sec	E volts	i amp	P_{IN} kw	P_{LOSS} kw	P_{GAS}	η percent	RUN TIME sec	REMARKS
E11	Air	-	-	-	-	-	-	-	-	-	0	Rectifier malfunction - Heater not operated.
E12	Air	-	-	-	-	-	-	-	-	-	0	Rectifier malfunction - Heater not operated.
E13	Air	19.1	5430	0.042	1560	530	825	595	230	28.0	20	
E14	Air	-	-	-	-	-	-	-	-	-	2.5	Severe damage caused by arc-over.
E15	Air	-	-	-	-	-	-	-	-	-	7.0	Severe damage caused by burnthrough.
E16	Air	22.8	6135	0.048	1830	530	970	665	305	31.6	25	
E17	Air	69.9	-	0.214	4525	370	1675	-	-	-	14	Cooling water ΔT's did not stabilize; heater damaged by arc-over.
E18	Air	-	-	-	-	-	-	-	-	-	27	Severe damage caused by arc-over.
										TOTAL	95.5	

TABLE III
DAMAGE LOG FOR 1-MW HEATERS

RUN NO.	TEST GAS	RUN TIME, sec	DESCRIPTION OF RUN	SYSTEM ELECTRICAL CONFIGURATION												
				Power Supply	Discharge Nozzle	Holding Circuit	Voltage Transfer Device	Air Lines	Spin Coil(s) Power	Tap Number*		Series Ballast, ohm	B-Field Vector Direction		Electrode Polarity	
										Start	Run		At Cathode	At Anode	Downstream	Upstream
E-1	N_2	113.0	No damage	Floating	Grounded	Not Installed	Not Installed	Insulated (3")	d-c welder	5	8	2.32	None	Down-stream	Positive	Negative
E-2	N_2	409.0	No damage	Floating	Grounded	Not Installed	Not Installed	Insulated	d-c welder	5	7,9	2.32	None	Down-stream	Positive	Negative
E-3	N_2	43.0	Heater damaged severely by arc-over from cathode plate to gas supply line - See Figs. 3c and 8	Floating	Grounded	Not Installed	Not Installed	Insulated	d-c welder	6	6	2.32	None	Down-stream	Positive	Negative
Total		565														
E-4	Air	3.0	Heater undamaged by arc-over from anode to backplate, around inlet air insulator to ground, from ground to nozzle, then to cathode.	Floating	Grounded	Not Installed	Not Installed	Insulated	d-c welder	8	8	2.32	Down-stream	Down-stream	Negative	Positive
E-5	Air	64.0	No damage	Floating	Floating	Not Installed	Not Installed	Insulated (12")	d-c welder	8	8	2.32	Down-stream	Down-stream	Negative	Positive
E-6	Air	51.0	No damage	Floating	Floating	Not Installed	Not Installed	Insulated	d-c welder	6	8	2.32	Down-stream	Down-stream	Negative	Positive
E-7	Air	41.0	Heater disassembled and revealed only slight damage from normal wear-and-tear during Runs E-5, E-6, and E-7	Floating	Floating	Not Installed	Not Installed	Insulated	d-c welder	8	8	2.32	Down-stream	Down-stream	Negative	Positive
E-8	Air	1.0	Arc-over; anode to end plate, to ground via spin coil, from ground to flapper valve to nozzle to cathode. No damage because of rapid shutdown	Floating	Floating	Not Installed	Not Installed	Insulated	d-c welder	8	8	2.32	Down-stream	Down-stream	Negative	Positive
E-9	Air	50.0	Arc-over from cathode to cathode spin coil while increasing voltage. Cathode spin coil damaged - See Fig. 9	Floating	Floating	Not Installed	Not Installed	Insulated	d-c welder	8	8	2.32	Down-stream	Down-stream	Negative	Positive
E-10	Air	120.0	No damage	Floating	Floating	Installed	Not Installed	Insulated	d-c welder	8	8	2.32	Down-stream	Down-stream	Negative	Positive
Total		330.0														

*Tap-changing-under-load transformer, see Fig. 2.

TABLE IV
DAMAGE LOG FOR 5-MW HEATER

RUN NO.	TEST GAS	RUN TIME, sec	DESCRIPTION OF RUN	SYSTEM ELECTRICAL CONFIGURATION												
				Power Supply	Discharge Nozzle	Holding Circuit	Voltage Transfer Device	Air Lines	Spin Coil(s) Power	Tap Number*		Series Ballast, ohm	B-Field Vector Direction		Electrode Polarity	
										Start	Run		At Cathode	At Anode	Downstream	Upstream
E-11	Air	0	Rectifier malfunction - voltage Transfer device actuated - no damage	Floating	Floating	Installed	Installed	Insulated (12")	d-c welder	8	-	2.32	Upstream	Down-stream	Negative	Positive
E-12	Air	0	Same as Run E-11.	Floating	Floating	Installed	Installed	Insulated (12")	d-c welder	9	-	2.32	Upstream	Down-stream	Negative	Positive
E-13	Air	20.0	No damage	Floating	Floating	Installed	Installed	Insulated (12")	d-c welder	9	9	2.32	Upstream	Down-stream	Negative	Positive
E-14	Air	2.5	Arc-over - Downstream base segment and cathode spin coil severely damaged. See Fig. 11.	Floating	Floating	Installed	Installed	Insulated (12")	d-c welder	10	10	2.32	Upstream	Down-stream	Negative	Positive
E-15	Air	7.0	Hot gas burned through down-stream base segment. See Fig. 12	Floating	Floating	Installed	Installed	Insulated (12")	**	10	10	2.32	Upstream	Down-stream	Negative	Positive
E-16	Air	25.0	No damage	Floating	Floating	Installed	Installed	Insulated (12")	**	9	9	2.32	Upstream	Down-stream	Negative	Positive
E-17	Air	14.0	Arc-over severely damaged end plate. See Fig. 14.	Floating	Floating	Installed	Installed	Insulated (12")	**	9	9	2.32	Upstream	Down-stream	Negative	Positive
E-18	Air	27.0	Arc-over destroyed discharge nozzle, see Fig. 15; severe damage to end plate insert, see Fig. 15.	Floating	Floating	Installed	Installed	Insulated (12")	**	11	11	2.32	Upstream	Down-stream	Negative	Positive

*Tap-changing-under-load transformer - See Fig. 2.

**Coils in series with arc.

TABLE V
SEQUENCE OF EVENTS FOR RUN E17

TIME, sec	DESCRIPTION OF EVENTS
0	Arc initiated using helium.
0.7	Air supply valve opened.
3.4	Chamber pressure and arc voltage increased.
8.0	Airflow to arc heater began programmed increase, continuing until heater shutdown.
9.4	Slug of near molten material in effluent observed, probably from anode or end plate insert.
9.8	Effluent brightness increased.
11.2	Arc jumped from anode to end plate.
12.4	Flame (arc) observed at rear of heater (external)
12.6	Arc now external.
13.7	Heater shut down.

TABLE VI
SEQUENCE OF EVENTS FOR RUN E18

TIME, sec	DESCRIPTION OF EVENTS
0 ↓ 0.65	Heater lit on helium, air supply valve opened. Presence of molten material in effluent indicated possible arc attachment to the end plate insert.
2.74	Chamber pressure rose suddenly, air metering venturi unchoked, nozzle ΔT decreased, and effluent brightness decreased. Probable cause was blockage of nozzle throat by a piece of insulating material from between the anode and end plate.
8.4	Chamber and venturi pressures indicate nozzle throat blockage removed; effluent intensity increased.
9.7	Nozzle burned through, water observed as a vapor cloud recirculating around free jet.
13.5 ↓ 25.3	Supply airflow increased, nozzle destroyed, arc voltage increased abruptly at 13.5, 17.4, and 25.3 sec.
26.8	Heater blew out and was shut down.

TABLE VII
COMPARISON OF DIMENSIONAL PARAMETERS AND VARIATION OF OPERATIONAL PARAMETERS FOR THE EOS AND LINDE HEATERS

RUN NO.	FIG. NO.	HEATER	NOMINAL RATING MW	TEST GAS	GAS MASS FLOW lb/sec	ℓ/D	d^*/D	p_o Mean Value, atm	p_o Variation from Mean, atm	p_o Frequency of Variation, Hertz	p_o Variation, percent of Mean	E Mean Value, v	E Variation from Mean, v	E Frequency of Variation, Hertz	E Variation, percent of Mean	I Mean Value, amps	I Variation from Mean, amps	I Frequency of Variation, Hertz	I Variation, percent of Mean
E2-5	18-a	EOS	1	N_2	0.0131	6.70	0.119	21.2	±2.00	23	9.4	680	±175	23	25.8	450	±11.5	23	2.6
E9-1	18-b	EOS	1	Air	0.0135	7.50	0.119	20.6	+0.90	-	4.4	690	±85	32	12.3	525	+10.5	32	2.0
E13	18-c	EOS	5	Air	0.0415	20.40	0.230	19.1	±1.00	-	5.2	1560	+86	46	5.5	535	±7.5	46	1.4
E16	18-d	EOS	5	Air	0.0484	20.40	0.230	22.8	±0.65	-	2.9	1830	±100	180	5.5	525	±7.0	180	1.3
HP4-2	18-e	Linde N4000	5	Air	0.451	34.6	0.250	49.0	±0.90	-	1.8	3770	±468	35	12.3	545	±30.5	35	4.2
70-82	18-f	Linde N4000	5	Air	0.276	28.0	0.415	13.2	±0.22	-	1.3	2605	±218	70	8.4	730	±38.0	70	5.2

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13. ABSTRACT

Results of testing three electric arc heaters designed by Electro-Optical Systems (EOS) are presented. Two of the heaters had power input ratings of 1 MW; one was designed for nitrogen and one for air operation. The third was rated at 5 MW for air operation. All three heaters were of segmented constrictor design for d-c operation. Operating experience and design information were gained from the 1-MW heaters. In their present form, neither is useful for ablation or aerodynamic tests because of unreliable operation and unsteady pressure and power outputs. The 5-MW heater was designed for 200 atm pressure and 3830 Btu/lb enthalpy. This goal was not achieved because of repeated failures and heater damage caused by electrical arc-overs. The best demonstrated performance by the 5-MW EOS heater was 6135 Btu/lb at 23 atm pressure. Some comparisons are made of the thermodynamic performance, component durability, and maintainability of the 5-MW EOS heater and a Linde heater of equal power rating. All testing was done at Arnold Engineering Development Center.

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