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ABSTRACT

Development of thermal protection systems for new reusable launch vehicles and other reentry capsules demands further development of material test facilities. Several types of aerospace plasma heating devices are used for material tests including wall-stabilized multi-segment arc heaters, Huels or vortex-stabilized heaters, magnetically-stabilized heaters, induction-coupled devices, and magnetoplasmadynamic devices. A survey of facilities that utilize these devices is presented. Trends in the modernization and further development of these facilities is discussed. Industrial or commercial heaters and applications are also briefly discussed with emphasis given to environmental remediation techniques using plasma systems. An explanation of required enthalpy for aerospace heaters based on sample surface temperatures, emissivity and catalycity is presented. Pressure and mass flowrate requirements are developed based on the sonic flow relationship. With enthalpy and pressure requirements determined, governing equations, boundary conditions and relationships that are used in developing arc heaters are explained. Relevant plasma system thermo-physical properties are discussed in this section as well. A summary of arc heater numerical codes is presented. The primary focus of this work has been experimental and analytical investigations of low pressure wall-stabilized multi-segment arc heaters. Research topics include electrode erosion causes and effects, internal arc heater heat flux distribution and effects of gas vorticity and distribution on heater performance. Experimental work was performed primarily at the Deutsche Forschungsanstalt fur Luft-und Raumfahrt (DLR) L3K arc facility near Cologne, Germany. Experimental results demonstrate that a plasma arc can be divided between cathodes at arc chamber pressures up to 17 bar. Previously, arc division between

electrodes had been limited to 10 bar. Sensitivities of stable current division between electrodes to changes in arc current, ballast resistor settings, and gas distribution are observed and reported. In addition the results show that electrode erosion is strongly affected by backside cooling water velocities and distribution. Electrode copper loss is shown to be a linear function of the incident current squared and time. Experimental results are presented for off-nominal water flows to individual segments. These results show that under some off-nominal water flow conditions, cusped segments can overheat at heat flux levels less than 20 MW/m^2. Other experimental data have shown that cusped segments can withstand much higher heat flux when water flowrates are nominal. A possible failure process is postulated. Experimental results show the value of voltmeters between segments and photocells as diagnostic aids during heater system development. Diagnostic techniques and operating guidelines were developed to limit arc heater damage during anomalous operations.

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NOMENCLATURE

A	cross-sectional area (m^2)
A^*	sonic throat area (mm^2)
B	magnetic flux density (Gauss)
D	dissociation energy (Joules)
D	dielectric displacement
E	voltage gradient (V/m)
e	species energy level (erg)
E	electric field strength vector
F	Lorentz force
H	bulk total enthalpy (MJ/kg)
H	magnetic field strength
h_D	average atomic dissociation energy times atom mass fraction in external flow (MJ/kg)
h_s	stagnation point dissociation energy times atom mass fraction (MJ/Kg)
I	arc current (amp)
J	arc current density vector
k	Boltzman constant (Joule K^{-1})
L	Lewis number
L/D	length to diameter ratio
M	Mach number

NOMENCLATURE (cont.)

$\dot{m}$	mass flowrate (kg/s)
P_{to}	total pressure at nozzle end of heater (atm)
P_{t2}	model stagnation point pressure (Pa)
q_o	stagnation point heat flux (kW/m^2)
R_{eff}	effective nose radius of a flat-faced cylinder (m)
r	radial distance from constrictor centerline axis (m)
T	temperature (C or K)
t	time (sec)
u	velocity (ft/sec or m/sec)
V	voltage (volts)
z	axial distance (m)
ϵ	emittance
λ_w	surface catalytic factor
σ	Stefan-Boltzman constant
η	electrical conductivity (S/m)
ρ	density (kg/m^3)
ρ_e	free charge density
θ	azimuth coordinate (rad)
Θ	characteristic vibrational temperature (K)
μ	viscosity
μ_0	magnetic permeability

NOMENCLATURE (cont.)

Subscripts

chf	critical heat flux
r	radial component
s	stagnation point in external flow
sat	saturated
w	wall or surface conditions
z	axial component
θ	azimuthal component

LIST OF ABBREVIATIONS

CHF	critical heat flux
DLR	Deutsche Forschunfsanstalt fur Luft-und Raumfahrt E. V.
HIP	High Impact Plasma
ICP	induction-coupled plasma
IHF	Interaction Heating Facility
IR	infrared
ISAS	Institute for Space and Aeronautical Science
LIF	laser induced fluorescence
MDC	McDonnell Douglas Corporation
NASP	National Aerospace Plane
SVT-TG	Sverdrup Technology Group
TPS	thermal protection system

CHAPTER I

INTRODUCTION

Plasma arc heated test facilities have been used for development of materials for reentry vehicle thermal protection systems (TPS) in the US since the 1960's. Arc heater tests at NASA facilities have been instrumental in TPS development for every major US aerospace reentry vehicle including Gemini, Apollo, Space Shuttle, Galileo and others. In addition plasma arc facilities have been successfully used for the test and development of missile nosetip materials at the Arnold Engineering Development Center and McDonnell Douglas arc facilities. Plasma arc systems have also also been used for propulsion system tests at NASA's Langley Research Center in the Arc Heated Scramjet Test Facility (AHSTF). Much of the early work in arc heater development including the 50 MW heater was performed at Wright Patterson Air Force Base.

Plasma arc heated test facilities are best suited for material and propulsion system tests because they are the only proven test device that provide high enthalpy flowstreams for substantial time periods. As a result high enthalpy systems level or component acceptance or certification tests can only be performed in a plasma arc heated facility. Other types of hypersonic facilities including shock tubes or tunnels, Ludwieg tubes or blowdown tunnels cannot sustain flow enthalpies of more than 2000 BTU/lbm for minutes or hours as shown

by Figure 1.[1]

Against the background of more than 35 years of material systems tests for US spacecraft, the 20th century draws to a close with a number of new reusable launch vehicle concepts under development by commercial enterprises and military and civilian government organizations. Government prototype vehicles include NASA's X-33, X-34, X-38 vehicles, a US military space plane, and Japanese vehicles. Commercial ventures include Lockheed's VentureStar and others. In addition new planetary return missions from Mars or other celestial bodies such as comets or asteroids are receiving renewed funding and interest as well. Development of new materials for the propulsion and thermal protection systems of these vehicles and capsules is a focus of effort for the US, Japan and Europe.

The development of these new materials and propulsion systems are dependant on robust test facilities with improved test capabilities. Many areas of the Shuttle Orbiter TPS and the Apollo spacecraft were conservatively designed with a large factor of safety because the arc flowfield environment was not well understood. However, new generation vehicle TPS for future vehicles and spacecraft must be designed to minimum cost, weight and risk. This in turn forces the arc facility experimentalist to understand more completely the flowfield and the material sample response to flowfield chemistry. By realization of a better understanding of the arc heated test environment including incident heat flux, gas chemistry, flow enthalpies, surface pressure distribution and other parameters, the TPS designer can reduce the uncertainties in the data base. In so doing weight savings may be

[1]All figures are contained in Appendix A

realized that will allow the RLV or other vehicles to achieve mission requirements.

Plasma test facility flowfields are being characterized through a combination of nonintrusive and intrusive diagnostic test techniques and CFD flowfield calculation methods. Whereas in former programs designers were forced to ignore important phenomena like material catalytic efficiencies. the present day material test facility experimentalist is challenged to understand the impact of chemical reaction rates, species concentrations, flow velocities, temperature measurements and other flow parameters on sample mass loss, ablation rates, etc. New diagnostics techniques such as Laser Induced Fluoresce (LIF) are being utilized to characterize the flowfield.

With increased understanding of the aeroheating factors such as flow chemistry and material response to specific flowfields, there is a need to understand and characterize arc heater performance more completely. As an example many new materials are sensitive to flow species such as atomic oxygen. The amount of atomic oxygen or other chemical species in the arcjet flowfield may be a function of several parameters including arc heater design, gas injection distribution, argon flowrates, etc. Furthermore, the arc flowfield environment may be significantly different from the flight environment. Thus as flowfield and material response is understood more fully, a need to modify, improve or tailor arc heater designs to achieve specific test conditions arises. Historically, development of test facilities has proceeded in parallel with the development of new spacecraft.

With this explanation as a background, the primary objective and contribution of this research work is analysis and detailed examination of the design and experimental

improvements to low pressure wall-stabilized thermal plasma arc heaters. Although much experimental and analytical research has been performed on vortex-stabilized heaters in the US, the area of low pressure arc heater development has received considerably less attention since the 1970's. Nevertheless foreign interest in this area has driven the development of three new facilities with power levels of one to five MW and one facility with planned operational power of seventy (70) MW in the future.

Improvements and further developments are needed for both the vortex-stabilized and wall-stabilized heaters. As indicated by Figure 2 the NASA arc or wall-stabilized facilities offer more benefit to new material or TPS development for future spacecraft with Shuttle-like trajectories. Nevertheless the AEDC-like vortex-stabilized heaters may find future application in the propulsion testing arena by simulation of scramjet ascent trajectories.

This work begins with a survey of operational plasma facilities. Aerospace plasma devices include multi-segment, Huels, magnetically-stabilized, induction-coupled and magnetoplasmadynamic heaters. Performance comparisons and characterization issues for these heaters are discussed. Changes and trends in the further development of plasma facilities are discussed. Arc facility modernizations and upgrades are summarized. Additional survey information is presented for commercial plasma systems including the DC and ICP torches. Commercial plasma applications are discussed with emphasis given to environmental remediation projects. Plasma environmental processes include in-situ remediation and pyrolysis vitrification.

This background precedes a presentation of the governing equations and boundary

conditions for the low pressure multi-segment arc heater. Analytical solutions with simplifying assumptions are discussed. The status and history of numerical codes is presented. Future code work may include development of genetic algorithms for arc heater design. A general and brief review of plasma thermodynamic and physical properties is also presented. Emphasis is given to plasma characteristics which affect the heater design criteria. A discussion of the sonic flow relationship is presented.

Chapter four presents the research results from experimentation with low pressure arc heater facilities. Research topics include electrode erosion, internal arc heater heat flux distribution, effects of gas vorticity and gas distribution on heater performance, failure analysis results from an individual segment in the constrictor and a presentation of diagnostic techniques for monitoring the health of the heater during development tests. These include photocells, flowstream observations and voltmeters between segments and electrodes.

Chapter five presents an overview of the design and experimental process for plasma system development.

Recommendations for future work and study are provided by chapter six.

Appendices provide figures, calculations, a test log detailing the experimental work at DLR and sample data from tests at DLR.

CHAPTER II

REVIEW OF PLASMA ARC DEVICES AND FACILITIES

In 1994 an AIAA short course entitled "Aerothermodynamic Facilities and Measurement: Review of Existing Facilities " was presented in conjunction with the 18th Aerospace Ground Testing Conference [1]. In 1996 a summary of arc heated test facilities was presented as part of the lead article in a special issue of the Journal of Propulsion and Power [2]. Although the AIAA course and the referenced journal article provided summaries of the aerospace arc heated facilities, changes to some facilities have occurred and some clarifications are needed. In addition new facilities have been developed and plans for other facilities are underway.

This chapter provides an update to the status of large scale current and future plasma arc facilities around the world. A summary of government, industry and university aerospace plasma arc test facilities is presented. In general, small scale university or laboratory facilities that are used for basic research, development or metallurgical purposes are not addressed. However, there are numerous facilities of this type with published research [3].

Several types of plasma arc devices have been used for aerospace material testing applications. These include multi-segment, Huels or vortex-stabilized, magnetically-stabilized, induction-coupled (ICP) and magnetoplasmadynamic (MPD) heaters. Facility location, performance and initial operational year for these heater types are presented in

tabular form. A brief development history for these heaters is presented as well.

Changes and trends in facility development will also be addressed. A number of existing U.S. arc facilities were originally developed in the 1960's. Many systems such as power supplies, flow control, cooling water and other components of these facilities need modernization or replacement. Non-intrusive diagnostic test equipment systems such as laser induced fluorescence (LIF) systems are being used as never before to provide insight into flowstream chemistry. This diagnostic information along with CFD results may suggest improvements to future plasma systems.

In parallel with aerospace test facility development, commercial arc facilities have been expanding at a prolific rate in the 1990's. This chapter will summarize some of the current applications for plasma arc technology in the commercial arena with emphasis given to environmental remediation processes. Existing facilities will be discussed.

General Performance Comparisons for Aerospace Plasma Facilities

Fig. 3 is a plot of arc device operating pressure vs enthalpy for five types of heaters. Operating envelopes are shown along with simple pictorial diagrams for each type of heater. The operational limits for these devices are not exactly determined and are a function of many parameters.

By inspection the induction-coupled heaters and magnetoplasmadynamic generators operate at much lower pressures than the other three devices. As a result simulation tests

using these devices are confined to high altitude portions of a spacecraft trajectory where material sample surface pressures are consistent with the lower pressure limits. Additionally these devices can operate at very high enthalpies. However, RF heaters provide the cleanest flowstreams for material tests because they do not utilize electrodes. As a result, the amount of copper in the gas is significantly diminished compared with other types of heaters. Similarly, the magnetoplasmadynamic heaters tend to be low power level devices with clean flowstreams. Both of these devices are well suited for material sample tests with model sizes 25 to 50 mm in diameter.

Modern Huels or vortex-stabilized heaters are rugged, reliable and relatively easy to operate and maintain. Their primary problems include flow fluctuations, high contamination, and inconsistent performance. They can be used at low pressures (10 bar) to obtain higher enthalpies (15 MJ/kg) but contamination levels are severe at these conditions. Attempts to increase enthalpies at all pressure levels have met with severe electrode erosion and higher contamination.

Magnetically stabilized heaters operate over a similar pressure range and have approximately the same complexity as that of the vortex-stabilized heaters. However, these devices operate with shorter arcs and have lower efficiencies than vortex-stabilized heaters. As a result, contamination levels are higher and enthalpies are generally lower than vortex-stabilized heaters for a given power setting.

In contrast to the performance limitations of other heaters, segmented heaters can be operated over a broad range of conditions. The AEDC H3 heater has operated at

pressures greater than 100 bar and power levels up to 70 MW. The NASA Ames segmented heaters have demonstrated inferred enthalpies up to 46 MJ/kg at pressures of one to five bar. Test streams are very stable with excellent test condition repeatability. Although the flowstreams are not as clean as RF or MPD devices, contamination levels are significantly lower than vortex-stabilized or magnetically-stabilized heaters. Several test techniques are possible with segmented heaters that utilize conical, semi-elliptic or channel nozzles. These include wedge, panel and stagnation tests. Model sizes are large enough to allow system verification and validation tests. As a result multi-segment heaters are the best choice for thermal protection system acceptance and certification tests.

Characterization Issues for Aerospace Plasma Facilities

Although a common set of performance parameters such as operating pressure, enthalpy, mass flowrate, efficiency and contamination levels describe plasma devices, direct comparison of performance levels is difficult because there are no accepted standards for enthalpy or contamination measurements.

As discussed and presented by others [4], there are at least three commonly used methods of flow enthalpy calculation i.e. energy balance as calculated from a thermal balance of the heater, inferred from measured test stream heating rates and pressures and the sonic flow method [5]. Variation of results arise from several factors including flow non-uniformities, measurement techniques, flowstream fluctuations and instrumentation. In most instances, sonic flow and energy balance enthalpies agree more closely than inferred enthalpy.

Although contamination level data for several facilities have been published through the years, there is no commonly established and accepted standard for determination of contamination in the flowstream. Various methods have been used including weighing of electrode assemblies or electrode liners, spectroscopy and intrusive measurement devices. Each of these methods produces different results for the same devices and conditions.

Survey of Operational Aerospace Plasma Arc-Heated Test Facilities

A typical plasma arc test facility arrangement for material tests is shown in block diagram form by Fig. 4. The plasma arc device may be one of several types as discussed in this section. For each of these a brief history of development, testing contributions and summary of performance parameters are listed.

Although many arc heated test facilities have been developed through the years, only a fraction remain functional today. Fig. 5 provides a timeline of plasma facility development since the 1970's. All of the facilities shown on this chart are operational or planned. Seventeen facilities have been developed or are under development over the course of the past ten years. This is roughly one half of all active facilities in the world today.

In this survey an effort has been made to list only demonstrated capabilities rather than design values for power, enthalpy and pressure. In some instances, listed enthalpies are energy balance values based on cooling water temperature and flowrate data whereas in other cases enthalpies are based on the sonic flow method or inferred from flowstream data. Where possible the method of enthalpy calculation for each facility has been indicated. Even in

instances where facility owners have used the same method of enthalpy calculation, results can vary to a significant degree because of differences in facility instrumentation.

Multi-Segment Arc Facilities

The multi-segment arc heater was initially developed at the NASA Ames Research Center [6]. Significant additional development has been accomplished at low pressures by NASA Johnson Space Center [7] and at higher pressures by Sverdrup Technology at the Arnold Engineering Development Center (AEDC) [8] and McDonnell Douglas Corporation [9]. Low pressure heaters operate up to 10 bar with multiple electrodes whereas high pressure heaters operate at pressures greater than 25 bar with a single electrode. Recent tests with the Sverdrup-designed DLR dual-electrode segmented heater at 16 to 17 bar have served to bridge this gap [10]. Although low pressure multi-segment heaters have demonstrated good reliability, high pressure segmented heaters have experienced problems with arcing to the constrictor bore. Experiments performed at UTSI have shown that vortex bursting is a possible cause of this problem.

Table 1 provides a summary of operational and planned multi-segment facilities around the world. Initial operation year refers to the first year of operation with the current heater configuration. Some facilities operated with other heaters prior to the listed year. It is important to note that listed maximum enthalpy, power and pressure do not occur at the same operating conditions. As shown by Fig. 3, higher pressure conditions are normally consistent with lower enthalpies.

Table 1 Summary of Operational and Planned Multi-Segment Plasma Facilities

Country	Owner/ Designator	Initial Operation Year	Maximum Power, MW	Maximum Pressure, bar	Maximum Enthalpy, MJ/kg	Comments
USA	NASA Ames/20-MW Panel	1972	20	10	32.5	Inferred enthalpy
USA	NASA Ames/ 60-MW Interaction	1974	60	10	46.4	Inferred enthalpy
USA	NASA Ames/ DAF	planned operation in 1998	1 to 2	goal is 5	goal is 300 for H2	Inferred enthalpy
USA	NASA JSC / TP-1	1973	10	10	37.1	Inferred enthalpy
USA	NASA JSC / TP-2	1991	10	10	37.1	Inferred enthalpy
USA	AEDC/ H-1	1976	30	120	12	Energy balance enthalpy
USA	AEDC/ H-3	1995	68	120	11	Energy balance enthalpy
Japan	NASDA /NAL	1993	0.75	1.1	27	Energy balance enthalpy
Japan	ISAS	1996	1	10	25	Energy balance enthalpy
Germany	DLR/L3K	1995	5	17	21	Sonic flow and energy balance enthalpy
Israel	Technion	1985	5	30	39	
Italy	CIRA/ Scirocco	planned operation in 1999	70	tbd	tbd	

Segmented heaters have been utilized for acceptance and certification tests for all US manned space vehicles including the Space Shuttle Orbiter, Apollo, and Gemini. In addition thermal protection systems for spacecraft capsules from several planetary entry and return missions including Galileo, Viking and others have been proven in multi-segment heater facilities.

Huels Arc Facilities

The Huels arc was developed in Germany by Chemische Huels in the late 1930's for making acetylene [11]. The design was based on a 1920's concept advanced by Asdische Anlin and Sod-Fabrik that was originally credited to German Professor Schoenherr in the early 1900's. In the 1950's, this concept was applied to high-temperature hypersonic flight simulation by the Linde Corporation under U. S. Air Force contracts [12]. Higher pressure arc heaters using the Huels concept were further advanced at the Air Force Flight Dynamics Laboratory [13] and the McDonnell Douglas Research Laboratory [14]. During this development period these heaters reached stagnation pressures of 250 bar with stagnation enthalpies of 5.6 MJ/kg.

Operational Huels heater facilities are summarized in Table 2. Although the most widely used application for these facilities is ablative materials development and testing, the arc facility at the NASA Langley Research Center is an example of an arc heated propulsion test facility [15]. The Direct Connect Arc facility at the NASA Ames Research Center is another facility that was used for propulsion testing during the NASP program.

Table 2 Summary of Operational Huels Plasma Facilities

Country	Owner/ Designator	Initial Operation Year	Maximum Power, MW	Maximum Pressure, bar	Maximum Enthalpy, MJ/kg	Comments
USA	NASA Ames/2*9 in Turbulent Flow	1971	20	40	9.3	Inferred enthalpy
USA	NASA Ames/ Direct Connect	1992	50	25	9.3	utilized for scramjet propulsion testing
USA	NASA Langley/ AHSTF	1976	10	45	3.7	utilized for scramjet propulsion testing
USA	AEDC/ H-R	1983	40	100	9.3	Energy balance enthalpy
USA	AEDC/ H-2	1989	40	100	9.3	Energy balance enthalpy
USA	Boeing (MDC)/ LCAT	1974	10	100	14	Energy balance enthalpy
France	Aerospatiale/ JP200	1979	20	60	13.2	Sonic flow enthalpy
France	Aerospatiale /9 MW HP	1987	9	130	5.1	Sonic flow enthalpy
France	AerospatialeSimoun	1987	5	15	14	Sonic flow enthalpy
Germany	DLR/ L2K	1989	1	14	25.5	Sonic flow enthalpy
Japan	ISAS	1990	0.5	10	16	Energy balance enthalpy

Magnetically-Stabilized Facilities

Magnetically-stabilized heaters were developed in the US at NASA Langley Research Center [16] and at the Redstone Arsenal [17] in the 1960's. Additional research was also performed at MDC's Laboratory [18].

Although research into these types of heaters was abandoned in favor of Huels or segmented heaters in the US, magnetically-stabilized plasma devices were extensively developed for large scale testing at TsNIIMASH in the former Soviet Union. This device as depicted in Fig. 2 has four electrodes that arc to the heater sidewall. There were several variations of this device including a coaxial heater with one electrode. These heaters were strongly utilized in the development of carbon-carbon thermal protection systems for Buran and other Soviet spacecraft. Several test techniques were utilized with these heaters including shroud, wedge and plate methods [19]. Table 3 lists the several facilities that use this device.

Table 3 Summary of Magnetically-Stabilized Plasma Facilities

Country	Owner/ Designator	Maximum Power, MW	Maximum Pressure, bar	Maximum Enthalpy, MJ/kg
Russia	TsNIIMASH /U15-T-1	40	12	7.0
Russia	TsNIIMASH /U15-T-2	50	50	8.1
Russia	TsNIIMASH /TT-1	10	80	9.3
Russia	TsNIIMASH /TT-2	6	25	46.5

RF Induction-Coupled Plasma (ICP) Facilities

Induction-coupled plasma heating devices were developed in the 1960's in the US and Europe [20]. Basic research work by Thomas Reed at Dartmouth University utilized a quartz tube for plasma containment [21]. This work was followed by Merle Thorpe and others in that time period who developed RF plasma devices first for NASA Lewis and later as commercial devices [22]. In the 1970's work by Dennis Keefer at the University of Florida and later at the AEDC contributed to the state of the art for these devices with the addition of bluff bodies to stabilize the plasma discharge [23]. Research and development for aerospace purposes ceased in the 1970's as emphasis focused on the higher power level multi-segment heaters. No aerospace ICP facilities exist in the US today.

In contrast, ICP devices were extensively developed and utilized in the former Soviet Union. As shown by Table 4 several facilities of this type are operational today including the highest power RF device in the world at the TsAGI aerospace facility. This device operates at 1 MW and low pressure utilizing a large quartz tube.

Following the open disclosure of these facilities to the Western world in the early 1990's, three different 100 to 150-kW class aerospace facilities of this type were developed in Europe. A 1.2-MW ICP facility is planned at the von Karman Institute in the near future.

Table 4 Summary of Operational Induction-Coupled Plasma Facilities

Country	Owner/ Designator	Initial Operation Year	Maximum Power, MW	Maximum Pressure, bar	Maximum Enthalpy, MJ/kg	Comments
Russia	Institute for Problems of Mechanics/ IPG-3	1980's	0.7	< 1		jet dia=200 mm
Russia	Institute for Problems of Mechanics/ IPG-4	1980's	0.1	< 1		jet dia=80 mm
Russia	TsAGI VTS or BTC	1980's	1.0	0.8	37.2	jet dia=300 mm
Russia	TsAGI BAT-104	1980's	0.16 to 0.24	0.4	37.2	jet dia=50 mm
Russia	TsNIIMASH Y-13-PHF	1982	1.0	<0.4	46.5	jet dia=200 mm
Germany	Univ of Stuttgart PWK 3	1994	0.15	< 0.02	27.5	
France	Aerospatiale/ Comete	1995	0.015	< 1	32.6	
Belgium	von Karman Institute	1997	<0.15	< 1		
Belgium	von Karman Institute	planned operation for late 1997 or early 1998	1.2	Goal is 1	tbd	jet diameter expected to be 160 mm

Magnetoplasmadynamic (MPD) Facilities

Based on the experience gained from magnetoplasmadynamic thrusters, the University of Stuttgart developed two plasma facilities, PWK1 and PWK2, for material tests [24,25] as indicated by Table 5. These facilities are ideal for material sample tests and catalycity studies at low pressure because as previously stated, copper contamination in the flowstream is significantly reduced compared to Huels and multi-segment heaters. In addition these facilities have been used to develop several intrusive and non-intrusive diagnostic instrumentation techniques including enthalpy, catalytic, electrostatic, and heat flux probes.

Table 5 Summary of Operational MPD Plasma Facilities

Country	Owner/ Designator	Initial Operation Year	Maximum Power, MW	Maximum Pressure, bar	Maximum Enthalpy, MJ/kg
Germany	Univ of Stuttgart PWK1	1987	0.25	1.0	116
Germany	Univ of Stuttgart PWK2	1990	1.0	0.5	150
Russia	MPDA-T16		4	<0.01	46.5

Arc Facility Modernization and Upgrades

With aerospace budgets declining around the world, funding for test facility improvements and modernization is diminished. In almost all cases facility owners must show a strong relationship between increased facility productivity and proposed improvements to justify the cost of changes.

This section provides an overview of modernization and upgrades planned for US, Japanese and European arc facilities in the immediate future.

USA: NASA Langley Research Center (LARC)

A new power supply is planned for the Arc Heated Scramjet Test Facility (AHSTF) at NASA Langley Research Center. Installation and operation with the new power supply are expected for the end of 1999. The supply will use thyristor rectifying elements with phase control and will put up to 2750 amperes at 5450 volts (15 megawatts) into the arc heater. The supply will operate for either 1.5 minutes on every 20 minutes or 5 minutes on every 30 minutes. Previously, the cathode was at a high negative potential. With the new power supply, the heater cathode will be operated at ground potential. Expected benefits of the new power supply are greatly reduced maintenance, increased arc power, improved versatility and controllability, elimination of arcing to the test section, and reduced power line harmonic content.

USA: NASA Ames Research Center (ARC)

A number of facility modernization and improvement changes are planned for the near-term at NASA Ames facilities. Since many of the arc facility components and systems are approaching 40 years in age, replacement of these components is needed to reduce maintenance costs and facility downtime.

NASA Ames also has plans to develop a new 1-MW class diagnostic arc facility (DAF) that would be used for multiple purposes. Potential uses for this facility are: (1) chemical vapor deposition (CFD) experiments; (2) quick-turnaround thermal protection materials tests in a variety of atmospheric gases including air, carbon monoxide, hydrogen-helium, nitrogen, and argon; (3) component prototype testing; and (4) instrumentation development. This will be an independent test facility and as such will not require coordination of the DAF schedule with the larger "production-testing" arc heated facilities at Ames. Tests in the DAF will primarily support internal research projects. The facility will produce high enthalpy plasma flow suitable for chemical vapor deposition experiments and simulation of reentry flow environments.

USA: NASA Johnson Space Center (JSC)

Arc facilities at JSC remain busy with tests of Shuttle Orbiter and Orbiter-upgrade TPS. Tests of X-33 and X-38 thermal protection systems are also on-going. A major test facility upgrade was performed in the late 1980's and no new upgrades are planned for these facilities in the immediate future.

USA: Arnold Engineering Development Center (AEDC)

The technology development phase for the AEDC H3 segmented arc heater has been completed and plans are in progress to convert the H3 facility to customer testing for thermal protection materials [26]. A new model injection system, a family of nozzles, and other instrumentation systems are planned for operational status by the year 1999. This facility will continue to have an atmospheric exhaust capability.

Long range plans include upgrades to the H2 facility. Replacement of the Huels heater with a segmented heater based on the H3 heater design is planned. This new facility would have the capability of performing sub-atmospheric tests with a heater power capability of 60 MW.

USA: Boeing (MDC) Arc Heater Laboratory

The capability of the Boeing (MDC) arc heater laboratory has been enhanced in recent years by the addition of a semielliptical nozzle. This nozzle throat has been calibrated for operation with the active LCAT or the dormant HIP facilities. This nozzle throat provides a fairly uniform flowstream over a 75 mm by 100 mm flat plate sample. Nozzle extensions for larger samples have been fabricated, but not calibrated.

Japan: Institute of Space and Aeronautical Sciences (ISAS)

The initial Institute of Space and Aeronautical Sciences (ISAS) high enthalpy test facility capability consisted of a 500-kW Huels heater exhausting to atmosphere. Vacuum exhaust

capability was achieved in 1994 with the addition of a test chamber, water-cooled diffuser, air heat exchanger and vacuum system. Following these changes ISAS performed several material development and flow diagnostic tests using laser-induced fluorescence (LIF) techniques. LIF test results and a brief description of the facility test capability from 1994 to 1996 have been presented [27].

New facility test capability was added to the laboratory in 1996 to simulate the conditions of reentry into the Earth's atmosphere for the Asteroid Probe Project. This project known as MUSES-C proposes to land a probe on an asteroid, recover a sample and return the sample to Earth for analysis. The new test capability allows ISAS to develop thermal protection systems for the return capsule [28].

A new multi-segment arc heater, as shown by Fig. 6, and a power supply operating at power levels up to 1 MW were the primary facility additions to simulate convective heating conditions. Radiative heating conditions are also simulated with a new YAG laser. Some existing components such as the air heat exchanger and the cooling system were modified to achieve a higher power condition of 1 MW. Other components such as part of the test chamber were redesigned to incorporate the radiative heating test capability.

Japan: NASDA/NAL Arc Facility

The NASDA/NAL arc facility as modified in 1993 continues to operate at power levels up to 0.75 MW [29]. Small design modifications to the existing plasma device in recent years have included viewing windows at the rear of the heater and non-intrusive diagnostic test

instrumentation for individual segments.

Europe: Institute fur Raumfahrtsysteme (IRS)

Capabilities of the plasma facilities at the University of Stuttgart's Institute fur Raumfahrtsysteme (IRS) have been well documented [30]. The latest facility developments at the IRS include small arc heated devices, PWK4 and PWK5. Each of these heaters is magnetically-stabilized with a 2% thoriated tungsten cathode and a water-cooled copper anode. Oxygen and nitrogen are injected separately. PWK4 operates with flowrates of 5 to 10 g/s producing specific enthalpies of 25 to 30 MJ/kg. PWK5 is a similar but larger device operating at a chamber pressure of 1 bar. Specific enthalpies are less than 10 MJ/kg. PWK5 operates at a maximum power of 60 KW and mass flowrates of 1 g/sec.

Europe: Von Karman Institute (VKI)

The Von Karman Institute (VKI) with funding from the European Space Agency (ESA) has developed an induction-coupled plasma facility. Facility inauguration took place in the fall of 1997. Details of the facility development have been presented [31,32,33].

The principle components of the new VKI facility are two induction-coupled torches. A 150-kw torch with a jet diameter of 80 mm will be used to reach low pressure, high heat flux operating requirements. This torch utilizes only a quartz tube as the plasma containment mechanism during operation. A larger 1.2 MW torch with a jet diameter of 160 mm will be operated in the near future to meet higher pressure requirements. This torch will operate at

pressures up to 1 bar with a water-cooled segmented copper cage inside the quartz tube.

This facility utilizes a high frequency solid-state thyristor power supply. Four different nozzles are planned for supersonic operation. The largest nozzle exit diameter will be 84 mm. This is a subatmospheric facility with a full complement of diagnostic test instrumentation.

Europe: DLR LBK

Following the successful completion of commissioning and calibration of the new 5-MW L3K segmented arc facility in 1995, DLR performed a number of internal research programs and stagnation sample tests. Stagnation model sizes up to 150 mm in diameter have been tested. Additional tests are planned for ESA in the near future. A two dimensional semi-elliptical nozzle capability is planned to supplement the existing conical nozzles.

Europe: CIRA Scirocco

A new 70-MW multi-segment arc heater has been fabricated and assembled for this Italian facility. The heater design is similar to that of NASA Ames 60-MW IHF heater. A thyristor power supply has been built and installed. All facility subsystems are under construction. Civil work is expected to be complete by the end of 1997. Installation of all facility equipment is scheduled to be complete by the middle of 1998 with a first hot test scheduled for October 1998. Operational validation of the facility is scheduled for 1999 with final acceptance scheduled for the end of that year.

Trends in the Development and Improvement of Aerospace Arc Heated Test Facilities

Although continued development of new facilities at a rate of 1.5 per year as indicated by Fig. 5 is not likely, further expansion of existing facility capability is expected. As an example, further development and understanding of diagnostic test techniques is key to future improvements. Diagnostic instrumentation and techniques in use by facility operators today have been previously summarized by Scott [34] with updates in other publications. Understanding of the arcjet flowstream through these techniques is vital to the continued development of new materials. As an example, many arc heated facilities have added laser induced fluorescence (LIF) capabilities as a means of understanding the flow chemistry and its interaction with material samples [35,36,37]. An important additional step will be utilization of this diagnostic information as a guide for changes or improvements to existing and future plasma system designs.

This section provides some examples of future improvements to plasma systems and facilities. Fig. 7 presents these improvements on a timeline with previous significant progress in aerospace plasma systems.

Optimization of Arc Heater Designs

Improvement or optimization of the multi-segment plasma device design to simulate desired flow conditions requires evaluation of many parameters. These include pressure, mass flowrate, arc current, voltage and geometric dimensions such as constrictor bore diameter and

length, cathode inner diameter, throat size, and others. In addition, there are many possible gas injection distributions that affect heater performance and flow conditions. The traditional design approach has been to run several cases using the ARCFLO or SWIRLARC computor codes with various inputs for these and other parameters. After completion of these computer runs, the outputs are evaluated by designers and judgements made for new runs to refine the solutions. This solution methodology is time consuming and may not converge to an optimum heater configuration.

A more sophisticated means of optimizing the arc heater design may be through the use of genetic algorithms. A genetic algorithm evolves in ways that resemble natural selection to solve complex problems. Genetic algorithms have already been used by jet turbine designers to incorporate the best features of previous designs [38]. These algorithms have also been used successfully by electro-magnetic system designers [39].

As plasma system configurations are optimized, the design of individual components within these heater and power supply systems will require optimization. With the advent of miniature diagnostic instrumentation the internal heater environment is being characterized more completely. Consequently, design for individual standard and tapered segments may be improved. Improvements to the electrode assembly would require optimization of magnetic field strength, cooling water velocities and pressures, geometric shapes and electrode liner material characteristics.

Propulsion System Test Enhancements

Plasma facilities offer significant advantages over combustion heated or shock tunnels for propulsion tests [40]. To this point scramjet testing work in arc heated test facilities has been performed with 1960's design Huels arc heaters. Segmented heaters offer significant advantages over Huels heaters for propulsion tests at the same test conditions in that the flow stream is significantly cleaner and more stable. Demonstrated high pressure, high enthalpy heater operation up to 70 MW offers the possibility of testing larger scale propulsion models than current practice has allowed. The utilization of today's high pressure arc heater such as AEDC's H3 offers the potential for significant enhancement of scramjet propulsion system testing.

Commercial Plasma System Development

Many of the modern commercial plasma systems in the US and other countries around the world today are derivatives of 1960's aerospace plasma systems. As in the aerospace arena, several different types of plasma torches are commercially available for users today. Common types of torches include the DC torch, induction-coupled torches or AC plasmatrons. All of these devices require electrical power supplies, cooling water, gas supplies and control systems. As a result most commercial vendors typically offer totally integrated systems that can be customized for various applications.

This section provides a brief summary of commercial plasma devices and applications. Applications include steel smelting, scrap melting, chemical vapor deposition, vacuum

spraying processes [41] and others. The focus of this examination of commercial or industrial arc facilities is environmental waste remediation applications. Typical facilities for this application will be discussed. Table 6 is a list of some of these commercial facilities.

DC Plasma Torches and Applications

The commercial DC torch as illustrated by Fig. 8 is similar to the Huels heaters. Although the Huels aerospace system evolved to operate at pressures greater than 100 atm and power levels of 40 to 50 MW for durations of seconds, a modern commercial plasma unit typically operates at pressures of 1 atm and power levels of 1 MW or less for several hours. Typical operating conditions for this type of device would be a current of 500 to 600 amperes and 2000 to 1600 volts with air as the working gas. Based on these operating currents and pressures, the electrode life of a commercial plasma unit is measured in tens of hours of operation. Reliability and maintainability are high design priorities for these commercial systems.

A non-transferred torch utilizes both a cathode and an anode internal to the torch body whereas a transferred torch makes use of material that is in the direct path of the plasma as one electrode. Detailed descriptions of these devices are available in the literature [42]. Typical application for non-transferred arcs are destruction of organic waste streams.

As the US becomes increasingly environmentally sensitive, Federal regulations for the permitting of incineration devices and siting of landfills are becoming more stringent. As a

Table 6 Summary of Commercial Plasma Facilities for Environmental Remediation

Location	Owner	Maximum Torch Power, MW / type	Waste Stream Characteristics	Comments
Port Clinton, Ohio	Plasma Processing Enterprises	0.5/ transferred DC	asbestos fibers	operational since 1995
Kent, Washington	Alliant Tech Systems	0.6 / ICP	munitions, organic materials, R & D	demonstration in 1995/ facility has been leased by Thermal Conversions
Atlanta, GA	Georgia Tech	0.2/non-transferred DC	incinerator ash, asbestos, others	operational since 1991
Bordeaux, France	Europlasma	1.75/ non transferred DC	incinerator ash asbestos	operational since 1995
Chiba City, Japan	Kawasaki	1.5/ transferred DC	incinerator ash	operational since 1994
Butte, Montana	Department of Energy (DOE)	0.15/transferred DC	munitions	
Washington DC	Naval Research Lab (NRL)	0.15/ transferred DC		operational since 1993

result waste treatment and handling costs are expected to rise. This in turn should spur the search for viable alternatives to traditional means of waste treatment by commercial groups, academia and many government agencies. Innovative thermal technologies such as plasma systems are emerging as potential solutions to some of these problems. The plasma process is fundamentally different from incineration in that typical reaction temperatures are more than 5000 C for plasma system processes whereas the incineration process may occur at temperatures as low as 850 C. As a result incinerators may emit harmful gases and exhaust products, but the solid and gaseous emissions from plasma processes have proven to be non-harmful basic elements or non-toxic compounds.

These waste streams may be divided into the following categories: municipal solid wastes (MSW), biomedical wastes and hazardous wastes. There are several different aspects to hazardous waste problems involving US government agencies such as the Department of Energy (DOE), Defense Department (DOD), Environmental Protection Agency (EPA) and others. One US government report [43] estimates that the cost to remediate DOE hazardous waste is 13.5 billion dollars in 1995 dollars. Other sources indicate that this cost may be significantly higher. Hazardous waste streams include asbestos-containing materials, low-level radioactive wastes, and more common items such as lead based paints, oil soaked materials, PCB's, incinerator ash and others.

Many of these materials are buried or in the form of contaminated soils. In-situ plasma remediation as illustrated in Fig. 9 offers a potentially cost effective solution to these problems. In a patented process developed at the Georgia Tech Construction Research Center, a plasma torch is lowered into a borehole in a contaminated soil region. After torch

ignition, the torch is slowly raised to form a cylindrical melt residue of vitrified materials. An external hood is used to capture process off-gas. The torch is relocated as required to complete the remediation process.

An in-situ field test to remediate a contaminated waste site was conducted recently at the Department of Energy's Savannah River site [44]. Fig. 10 shows the 1-MW torch in operation prior to lowering into one of three boreholes. The duration of each experiment was between 40 and 105 minutes at power levels ranging from 650-kW to 950-kW. Three highly vitrified monoliths were created up to 1.1 meters in diameter by 1.1 meters high. This vitrified material was removed after the test to confirm the elimination of contamination. Based on the results of this test, projected remediation energy costs are 2600 kW-hrs per ton of contaminated soil. Larger 5-MW torches would conceivably reduce this cost even further.

Fig. 11 shows a schematic diagram of a plasma pyrolysis vitrification process. This type of system may be used to treat a variety of waste streams. Drums or bags of wastes are fed into a reaction chamber via hydraulic or mechanical feed systems. The torch is activated via a central control system and melts the waste, creating gas and slag residues. The off gas is treated, sampled and either released to the atmosphere or captured for resale. The vitrified slag may also have commercial value.

A mobile system of this type has been built to treat asbestos at Port Clinton, Ohio [45]. This system minimizes the opportunity for personnel exposure to asbestos fibers through handling since it can be moved to existing storage locations.

Induction-Coupled Plasma Torches and Applications

The University of Sherbrooke in Canada has recently developed and marketed ICP devices for commercial applications. These devices have ceramic bodies and operate up to 420 kW with tube oscillator power supplies. Induction coupled plasma (ICP) devices are most useful in processes that require a clean gas flowstream.

A 600-kW ICP device is the primary plasma generator for a facility originally located at the Alliant Techsystems Proving Grounds in Elk River, Minnesota. This facility has been relocated to Kent, Washington. This commercial plasma facility has a modular refractory-lined thermal reactor with multiple penetrations for instrumentation ports and diagnostic equipment. The reactor, facility controls, instrumentation, data acquisition and auxiliary gaseous. vacuum and cooling water systems were designed by Sverdrup Technology [46].

Induction-heated melters have also been used in combination with DC torches for specialized applications. A hybrid system was developed in the former Soviet Union during the 1970's and has been transferred to the Georgia Tech Construction Research Center for additional testing. This device was originally used to produce chemically active high purity metal alloys. Future tests will evaluate the feasibility of treating sensitive radioactive wastes [47].

CHAPTER III

GOVERNING EQUATIONS AND BOUNDARY CONDITIONS FOR PLASMA ARC HEATER ANALYTICAL SOLUTIONS

Material tests subject sample materials to conditions that occur during descent through the atmosphere of earth or other celestial bodies. In most cases experimentalists strive to simulate flight surface temperatures, pressures and time durations. These conditions are achieved through the delivery of adequate enthalpy and pressure from the arc heater. Simulation of descent trajectories for most vehicles require pressure and enthalpy conditions that can best be achieved with multi-segment heaters. As a consequence the remainder of this dissertation concerns this device.

This chapter provides a general description of the multi-electrode segmented arc heater, conical nozzle and stagnation model test configuration. An explanation of required enthalpy based on sample surface temperatures, emissivity and catalycity is presented. A method for determination of required pressure and mass flowrate based on the sonic flow relationship is discussed. With enthalpy and pressure requirements determined, governing equations, boundary conditions and relationships that are used in developing arc heaters are explained. Relevant plasma system thermo-physical properties are discussed in this section as well. A summary of arc heater numerical codes is presented along with a brief explanation of the sonic flow relationship.

Multi-Electrode Segmented Heaters: General Description

Figure 12 shows a multi-electrode segmented arc heater divided into three sections: an anode assembly, the constrictor section and a cathode assembly. A throat section with a conical expansion nozzle is attached to the heater. A ballast resistor assembly is shown also.

As the positive electrode, the anode may be either single or multiple units for higher current operation. At DLR the anode assembly at the upstream end of the heater consists of two identical centripetally cooled electrode assemblies. an inter-electrode segment, three rear isolator segments and a rear closure shell. The anode assembly is a modular unit and can be removed without disturbing the constrictor or cathode assemblies. Each electrode has an independent housing, spin coil module and electrode liner. This feature allows disassembly and replacement of the consumable liner without changes to or replacement of the spin coil or housing. Facility maintenance costs are reduced as a result.

The constrictor section is a long hollow cylinder or tube. It is made up of several water-cooled copper segments. Gas is injected at discrete locations along the constrictor wall to augment the arc stabilizing flowfield, sheath the constrictor wall with cold gas and protect the gaps between segments.

The cathode assembly is also a modular unit. The cathode is the negative electrode and may be single or multiple electrodes. The cathodes are the same as those utilized in the anode assembly except the coil is wound in the opposite direction to produce the correct

field direction. The cathode assembly also contains an inter-electrode segment and three tapered nozzle isolator segments. Removal and replacement of the cathode assembly requires sliding or rolling the anode and constrictor assemblies rearwards.

If more than one cathode or anode is used, a ballast resistor assembly is needed to balance the current between each of the electrodes. This assembly is normally made from water-cooled stainless steel tubes that are connected together by copper crossover blocks. Electrical resistances are changed by adjustment of the crossover block position.

The DLR arc heater and ballast resistor are shown in cross-sectional view with the 14 mm throat by Figure 12. Supports shown underneath the cathodes were never fabricated or installed. The heater is shown in a six-package arrangement in this view. Figure 13 is a photograph of the heater in a one-pack arrangement without hoses connected for either water or air.

Plasma Thermodynamic and Physical Properties

With the application of power, a plasma arc column is initiated between the electrodes. A thermal plasma is an ionized gas comprised of molecules, atoms, ions, electrons and photons. The plasma ions may be found in either the ground or excited states. These plasma particles as mentioned above may be divided into two categories: heavy particles that are traveling at low velocities compared with the electrons and electrons with high velocities which are mainly responsible for inelastic collisions.

The arc column has well defined electrical and magnetic characteristics [48]. As an example, the arc column voltage gradient is a function of the type of gas and arc chamber pressure. Diatomic gases, such as air, have a higher voltage gradient (electric field) than monatomic gases, such as argon. As a result many arc facility operators will initially 'start' the heater with argon gas. After establishment of an arc column, air is injected to begin normal test operations. This technique is used to reduce electrode wear.

The arc column can be influenced by external magnetic fields as well. The equations governing the electric and magnetic fields are known as Maxwell's equations. From Pai [49] these may be stated as

$$\nabla \times H = \mathrm{J} + \partial D / \partial \mathrm{t} \quad (1)$$

$$\nabla \times E = - \partial \mathrm{B} / \partial \mathrm{t} \quad (2)$$

$$\nabla \cdot H = 0 \quad (3)$$

$$\nabla \cdot D = \rho_e \quad (4)$$

where ∇ is the gradient operator.

The plasma column responds to magnetic fields according to the Lorentz Force relationship:

$$\mathrm{F} = \mathrm{J} \times \mathrm{B} \quad (5)$$

where J, the electric current density, is due to the motion of charged plasma particles. The electric current density is given by

$$\mathrm{J} = \sum \rho_e \mathrm{u} \quad (6)$$

The plasma column of an arc heated device has inherent electro-magnetic instabilities. If an arc column is displaced away from its neutral axis by forces due to gas injection or other means, there is no natural restoring force to return the column to a neutral position. This behavior is contrasted with that of a helical spring attached at both ends by Figure 14 from reference 48. If the spring is stretched off-axis by a force, F_1, there is an opposing resultant force which returns the spring to a neutral axis. As the arc column deviates further from an equilibrium or neutral position, magnetic fields are more concentrated and tend to magnify the tendency for the column to continue off-axis. This characteristic is often referred to as "kink instability".

As a result of the arc column's tendency to kink, design of an arc heater requires column stabilization. Methods of stabilization include cold wall, external magnetic fields, and gas vortex. In most heaters a combination of stabilization techniques are utilized. Vortex-stabilization has been recognized as a means of arc stabilization for many years [50].

In a wall-stabilized arc device excursions of the arc column away from an equilibrium position are compensated by several interrelated factors. As the arc column approaches the water-cooled wall, arc temperature and electrical conductivity are reduced. Since the arc prefers the area of highest conductivity at the constrictor center, there is a tendency for the arc to return to the neutral axis. As the arc approaches the wall, magnetic pressure, $B^2/2\mu_0$, also increases and influences the position of the arc back toward the center.

Experience has shown that arc instabilities in the constrictor bore are predominantly associated with high pressure (>25 bar) heaters such as those at AEDC. At low pressures the

arc is more diffuse so that time transients are sufficiently long to allow the compensating factors as mentioned above to affect the arc location. At high pressure conditions vortex-stabilization techniques are required.

Model/Sample Requirements

Model size for material characterization and screening tests are typically 25 to 50 mm in diameter for 1-MW class heaters. In these type of tests the experimentalist quantifies thermo-physical material properties. However, model sizes for systems verification and certification tests are typically much larger. Larger models demand larger facility power requirements.

Fig. 12 shows a typical stagnation test configuration with a model mounted downstream of a conical nozzle. The model should be mounted as close as possible to the nozzle exit to minimize the required heat flux. However, this requirement is tempered in many cases by a requirement to view the model front face. It is desirable to view the front face with IR cameras or pyrometers that can measure the sample surface temperature. Typically, the model is mounted one nozzle exit diameter downstream of the nozzle exit. A typical sample is a thin 25 mm inch diameter ceramic disk held in place with spring-loaded pins.

Fig. 12 also shows a typical sample holder arrangement. When the sample reaches a state of radiative equilibrium, the stagnation point heat flux that must be supplied from the arc heater, q_o, is determined from the following simplified relationships:

$$q_o = q_{rad} + q_{cond} \quad (7)$$

$$q_{rad} = \epsilon \sigma T^4 \qquad (8)$$

Consideration of shape factors, chemical reactions and other second order effects are normally not considered since none of the first order terms are known with great accuracy. The emissivity of a new material may be a function of temperature and other factors. Similarly, the heat transfer lost through conduction, q_{cond}, will not be known prior to testing. It is important to limit q_{cond} to minimize the heat flux that must be supplied by the heater. As a result contact of the sample with thermally conductive materials must be limited. Based on experience the conductive heat loss for a well-designed sample holder may be estimated as 5% of the total heat transfer from the heater. With this assumption, q_o for a desired surface temperature and known sample emissivity can be determined.

Enthalpy Requirements

With the required heat transfer known, the Fay-Riddell equation [51] may be used to estimate the required heater enthalpy, H_{to}. In the original Fay-Riddell work this equation was stated as

$$q_o = 0.94(\rho_w \mu_w)^{0.1} (\rho_s \mu_s)^{0.4} * \{1+(L^{0.52}-1)(h_D/h_s\}(h_s-h_w) \sqrt{du/dx} \qquad (9)$$

This equation is for blunt, hemispherical bodies. Subsequent work by Sutton and Graves [52] produced a modified and simpler version of this equation as given by:

$$q_o = 0.35 \sqrt{p_{t2} / R_{eff}} (H_{to}-H_w) \qquad (10)$$

The model stagnation point pressure, p_{t2}, is normally specified based on the reentry vehicle's flight trajectory. Boison and Curtis performed work that can be used to determine the effective radius, R_{eff}, of flat-faced cylinders [53]. For $M >> 1$, H_w is a function of sample wall temperature and pressure.

Sonic Flow Relationship

The sonic-flow method of enthalpy measurement was derived in closed mathematical form by Winovich [54]. He assumed that the arc chamber could be considered a reservoir discharging through a sonic throat. The equations governing flow through a nozzle have been well established and are not repeated here. Winovich further assumed the flow was steady state, real gas and one-dimensional. With these assumptions trial and error calculations based on the continuity, energy, and state equations were performed. These calculations were made for a family of pressures and enthalpies. Curve-fitting the results of this process provides the exponents and coefficients of the approximate relationship as given below

$$\dot{m} = 0.293\ A^{*}\ p_{to} / H^{0.397} \qquad (11)$$

for enthalpy levels of $2.4 < H < 24$ MJ/Kg and $0.25 < P_{to} < 100$ atm. Parameters for this equation must be in metric units as listed in the nomenclature. Later efforts by NASA Ames have revised this equation for greater accuracy in areas of enthalpy interest as indicated by reference 5.

Despite efforts to make the sonic flow equations agree with exact real gas relationships in the thermodynamic regimes of interest, all sonic flow enthalpy equations assume uniform flow conditions through the nozzle throat. As a result, the relationship is rather inadequate as a means of describing heater performance because, in fact, flow conditions are nonuniform at the throat. A more important and useful parameter is the inferred heater enthalpy based on measured heat flux. The heat flux may be measured with Gardon gages or other instruments installed at the test sample location in the freestream. Surface pressure is also measured. With the incident heat flux and pressure known, the heater "inferred" enthalpy may be calculated.

The true sonic flow enthalpy based on stagnation pressure is indeterminate for a heater with a large throat diameter to constrictor diameter ratio. Arc chamber pressure measurements yield the static pressure whereas the sonic flow enthalpy calculation is based on stagnation pressure. The stagnation pressure is a function of the gas swirl strength and non-uniformities in total enthalpy and pressure profiles. Work performed in the UTSI water tunnel by Vakili [55] demonstrated significant radial velocity gradients in heater constrictor section. There are significant radial and axial pressure and enthalpy gradients in the heater as well. As an example, the DLR rear chamber static pressure measurement was typically 30 percent higher than the forward pressure measurement with the 29 mm throat as indicated by data from Appendix D. The forward pressure measurment was located in the nozzle isolator section immediately upstream of the nozzle throat whereas the rear measurement was upstream of the outer anode. In this dissertation all reference to arc chamber pressure is the forward measurement unless otherwise noted.

Pressure/Mass Flow Requirements

The arc heater mass flowrate is given by the continuity equation at the nozzle throat assuming one-dimensional flow

$$\dot{m} = \rho u A^* \quad (12)$$

$$\text{where } q = \tfrac{1}{2} \rho u^2 \quad (13)$$

$$\text{or } \dot{m} = 2 q A^*/u \quad (14)$$

For the model stagnation point, dynamic pressure, q, is approximately equivalent to $0.5p_{t2}$. As a result mass flowrate can be calculated for a given nozzle throat size. With mass flowrate determined, the sonic flow relationship as given by equation (11) may be utilized to determine the arc chamber pressure, p_{to}.

The nozzle throat size should be equivalent to the constrictor bore diameter or smaller. As nozzle throat diameter is increased, the heater will operate at lower arc chamber pressures, p_{to}. Lower chamber pressures are desirable to limit heat transfer loss to internal heater segments and increase the heater efficiency. In addition, experimentation has shown that the heater is more tolerant to anomalies at lower pressures so that downtime due to repairs is minimized.

The model size is also a consideration in selecting nozzle throat and exit diameters. The nozzle exit diameter is normally twice as large as the maximum model diameter to avoid flow blockage problems.

Material Catalycity Considerations

Since incident heat flux, q_o, is required to raise the sample surface to a specified temperature level, material catalycity must be considered. A material's catalytic efficiency is the ratio of mass flux of molecules formed to the number of atoms impinging on a given surface. Catalytic efficiency, λ_w, is defined by Park [56] as

$$\lambda_w = 1/\{ 1+ 0.25 \sqrt{(\Theta_r/T)} \exp [(e - D_A)/kT] \} \qquad (15)$$

A material is said to be fully catalytic, $\lambda_w = 1$, if all incident atoms strike the surface and combine to form molecules. These molecules lose all latent heat of dissociation to the material surface. In contrast a material is said to be non-catalytic , $\lambda_w = 0$, if all incident atoms strike the surface and are reflected without any recombination or transfer of latent heat. A material surface is partially catalytic, $0 < \lambda_w < 1$, if only some of the atoms combine and lose latent heat to the surface [57]. During vehicle re-entry, catalytic atom recombination on the thermal protection system surface is a disadvantage because the net incident heat flux is increased. Material catalycity depends on several factors including surface properties, surface temperature and the degree of dissociation behind the model bow shock. Although material catalycities can be determined experimentally in the arc facility, these results will not be known a priori. As a result, a conservative assumption for the catalytic factor, λ_w, must be applied to the incident heat flux equation (10). The resulting equation is:

$$q_o = 0.35 \lambda_w \sqrt{p_{t2} / R_{eff}} (H_{to} - H_w) \qquad (16)$$

Experimental results have shown that the freestream centerline inferred enthalpy downstream of the nozzle exit plane is larger than the mass averaged bulk enthalpy as calculated from a thermal balance of the heater. This peaked or bell-shaped enthalpy profile results from incomplete mixing of gases inside the heater in the constrictor section as well as the cooler wall surrounding the arc. A central plasma core is surrounded by a cooler annulus area through much of the constrictor. The degree of mixing between these two flow areas is dependant on many factors including constrictor length, constrictor diameter and gas distribution.

Experience has shown that the ratio of centerline freestream enthalpy to mass averaged bulk enthalpy is normally between 1 and 2. Since the model will be mounted on the centerline, a ratio of centerline to bulk enthalpy, C_f, should be used as a basis for final determination of the heater design point enthalpy. However, this ratio is indeterminate a priori and must be assumed. The required bulk heater enthalpy, H_{to}, may finally be written as

$$H_{to} = (1/ C_f)\{H_w + (C_q \in \sigma T_w^4) /(0.35\sqrt{P_{t2}/R_{eff}}) \quad (17)$$

where $C_q = (1 + C_{ql})/\lambda_w$ and C_{ql} is a factor for heat loss due to conduction at the sample surface to model holder interfaces.

Numerical Solutions

With the establishment of enthalpy and pressure requirements, numerical codes may be used to determine an arc heater configuration and operational characteristics. This section provides a summary of governing equations and simplifying assumptions, a description and status of available codes and discusses code deficiencies. Comparison of numerical solutions and actual data are presented by reference 10.

As previously discussed the segmented heater is divided primarily into the anode assembly, the constrictor section and the cathode assembly. Analysis of the region close to the anodes or cathodes has been made by several authors [58,59]. Analysis of the near-electrode section for high pressure (100 atm) heaters is possible with a model developed by Felderman [60]. This model has been used to predict values of arc spot size and electrode mass loss. Spot size and anode mass loss prediction results compared well with observations from actual tests. However, the cathode mass loss from actual tests was three times larger than predictions.

A brief summary of past numerical code work for the segmented heater constrictor section is shown by Table 7.

Governing Equations and Boundary Conditions

Several assumptions are possible to simplify the analytical process. As presented in the literature [61], these are:

Table 7: Evolution of Arc Heater Analytical Codes

Date of Original Work	Sponsoring Organization	Analytical Code
1969 (obsolete)	NASA-Ames	ARCFLO I-low pressure
1975 (operational)	Aerotherm	ARCFLO II-high pressure (200 atm), added radiation model, turbulent flow, new properties [62]
1977-1978 (operational)	MDC	SWIRLARC-added swirl, spline fit of TP properties to ARCFLO II
1992 (operational)	SVT-TG	SHARC-same as SWIRLARC with mods to input and output formats to improve production
1994-1996 (Modules have been installed and validated individually for sample problems. Solutions for combined field conditions have not been obtained and no additional funding is available.) [63]	SVT-AEDC/UTSI	XLIM3D-CFD code based on Reddy/Jacocks algorithm-incorporates electromagnetic and multi-dimensional radiation model-based on high pressure heater

1) Since the constrictor is essentially a hollow cylinder with symmetric air injection, axially symmetric geometry may be assumed. A symmetric air injection technique is employed as well. Thus $\partial / \partial\theta = 0$. Asymmetric air injection is possible due to assembly problems, but these conditions invariably lead to anomalous heater operation. Test Run 6-18P from DLR commissioning experience is an example of this condition-see Appendix C.

2) Air and a small amount of argon are injected into the arc chamber from manifolds. The flowrate out of the arc chamber is controlled by a sonic throat. As a result steady, stable gas flow can be assumed for a given total pressure. Thus $\partial / \partial t = 0$.

3) Electric field is parallel to the constrictor axis and constant along a radius.

4) Electron, ion and heavy particle temperatures are considered equal. As a result local thermodynamic equilibrium is assumed.

5) Quasi-cylindrical flow (boundary-layer type) is assumed. Radial velocities in the constrictor are much smaller than axial or circumferential velocities, and the gradients in the radial direction are much stronger than those in the axial direction or $v_r << v_z \sim v_\theta$ and $\partial/\partial r >> \partial/\partial z$.

The boundary conditions are no-slip conditions at the wall, constant wall enthalpy and symmetry at the centerline. There are some localized points of air injection that violate the

assumption of no-slip conditions. At the wall $r = r_w$, $h = H_w$, $v_z = 0$. At the center $r = 0$, $v_r = v_\theta = 0$, and $dh/dr = dv_z/dr = 0$.

With these assumptions and boundary conditions, the governing equations for the arc heater constrictor section may be stated as follows in cylindrical coordinates:

The energy equation is

$$v_z \partial h/\partial z + v_r \partial h/\partial r = v_z \partial h/\partial z + v_r \partial p/\partial r + \eta E^2 - 1/r \partial(rq)/\partial r \qquad (18)$$

Continuity is given by

$$\partial (\rho v_z) /\partial z + 1/r \partial (r\rho v_r)/\partial r = 0 \qquad (19)$$

Axial momentum is

$$\rho v_z \partial v_z/\partial z + \rho v_r \partial (v_\theta/\partial r) = 1/r \partial(r \tau_{rz})/\partial r - \partial p/\partial z \qquad (20)$$

Radial momentum is

$$\rho v_\theta^2/r = \partial p/\partial r \qquad (21)$$

Swirl momentum is

$$\rho v_z \, \partial v_\theta/\partial z + \rho v_r \, \partial v_\theta/\partial r + \rho v_r v_\theta/r = 1/ r^2 \, \partial/ \partial r \, (r^2 \tau_{r\theta}) \qquad (22)$$

Mass flow is given by

$$\dot{m} = 2\pi \int v_z \, r \, dr \qquad (23)$$

Electric field gradient is

$$E = I / \int \eta \, dA \qquad (24)$$

SHARC Code and Algorithm

The SHARC code solves the time-averaged parabolic nonlinear partial differential conservation equations by finite-difference techniques. Fig. 15 depicts a calculation methodology to determine arc heater configurations, i.e. constrictor bore diameter, length and operating conditions. The SHARC code is identical to the SWIRLARC code except for changes to input and output format statements to improve production and data processing. Inputs to the SHARC program include arc chamber pressure, p_{to}, current, mass flowrate, heater length and bore diameter, gas injection distribution and other boundary conditions. These parameters are selected based on requirements previously discussed as well as recognized design limits for components based on previous experience. As an example, nominal design values for arc heater currents should not

exceed 600 to 700 amperes per electrode to avoid excessive erosion and wear. These limits may vary to some degree based on facility requirements and conditions.

The outputs of the code are constrictor wall heat flux, enthalpy, voltage between individual segments, and overall voltage. One of the SHARC outputs, enthalpy, is used as an input to the sonic flow equation. The sonic flow equation is solved for arc chamber pressure, P_{to}. This pressure is compared with assumed SHARC code input pressure. If this comparison is less than limits, the parameters are consistent and work proceeds to new conditions. If the pressure comparison is greater than limits, adjustments are made and the process is repeated.

Although this algorithm has provided reasonably good agreement with data as presented in reference 10, improvements are desirable. As an example, future designs can achieve higher performance levels if heat flux to the constrictor bore and electrodes can be predicted more accurately a priori. SHARC code deficiencies as previously presented by Felderman in reference 63, are listed below.

- Only the constrictor section geometry can be modeled at this time. As shown by Fig. 12, the actual arc heater geometry has several diameter changes. It is desirable to model the converger, diverger, electrode region and throat section of the heater as well.

- Methodology for modeling gas injection is not very realistic. As an example, the model requires continuous gas injection between designated endpoints along the

constrictor as indicated by Figure 15. However, in practice, gas is injected at discreet points between segments at various flowrates. The impact of this modeling discrepancy on convective wall heat flux is unknown.

- SHARC uses a 2-band radiation model. The 2-band model divides the wavelength region into two regions. Absorptive properties are considered to be constant in each region even though the radiative properties are a widely-varying function of species and wavelength. At higher enthalpies a more sophisticated model is needed. It may be possible to evaluate the actual species and to tailor the radiation model accordingly.

- SHARC does not allow for reverse flow in the constrictor. The amount of reverse flow varies with the gas injection distribution.

Other Code Options

General purpose two-dimensional codes are available that can also be used to satisfy the governing equations. A two-dimensional code is completely adequate for the low-pressure heater since motion of the arc inside the constrictor does not impact the constrictor walls. The geometry of all heater sections can be input so that some of the problems described above can be avoided in the future. These codes include a) Mach 2: A Two-Dimensional MHD Simulation Code for Complex Experimental Configurations [64] from Phillips Laboratory and b) two-dimensional Arbitrary Lagrangian Eulerian (ALE) codes from the Lawrence Livermore Laboratory [65].

DLR Heater Configuration Development

The general design process discussion as presented in this chapter is presented as background information only. For the DLR heater design, sample conditions were not specified. Instead, nozzle throat diameters, arc chamber pressure, enthalpy and mass flowrate requirements were specified for two acceptance point conditions as listed by Table 8. Actually, specification of only three parameters is necessary since the sonic flow relationship allows the algebraic calculation of the fourth. In addition to the listed parameters of Table 8, contamination levels were limited to minimal quantities.

Table 8 DLR Acceptance Point Conditions

Parameter	Acceptance Point 1	Acceptance Point 2
Pressure, bar	4	18
Enthalpy, MJ/Kg	20	20
mass flowrate, g/s	100	100
time duration, minutes	30	3 runs of 7 minutes each

DLR provided a nozzle for each of the acceptance conditions in Table 3. For the lower 4 bar pressure, a 29 mm throat diameter was specified. The higher pressure point was to be satisfied with a 14 mm diameter throat. Using the SHARC code as previously outlined, the DLR segmented heater constrictor bore diameter was selected as 32 mm with a constrictor length of 1280 mm to meet these requirements. Difference in heater length was easily accommodated because the constrictor assembly is divided into packages that contain sixteen segments each. There were a total of six packages. One of these packages was divided into subpacks of eight segments to provide even greater flexibility. Each segment thickness was 1 cm.

SHARC code predictions were based on a significant air injection immediately downstream of the inner anode. With this gas distribution SHARC predicted that acceptance points could be reached with a current of 1000 amperes. However, actual test data after the heater was built with the given dimensions showed that a current of 1200 amperes was needed to reach acceptance point 1. In practice significant air injection downstream of the inner anode did not allow the current to divide between the anodes. As a result, primary air injection was in the constrictor rather than the converger. Higher current operation was needed to compensate. This created higher than expected heat flux conditions on the electrodes and resulted in higher erosion losses. Chapter IV will illustrate the problems that arise when current is increased to the electrodes. This example illustrates the need for codes that can predict the performance more accurately. One of the contributions of the DLR heater development is that of a reliable source of empirical data that can be used whenever it is practical to verify future code results.

CHAPTER IV

PLASMA SYSTEM RESEARCH RESULTS

Experiments were performed at the Deutsche Forschungsanstalt fur Luft-und Raumfahrt E. V. (DLR) laboratory near Cologne for approximately 4 months under my direction to demonstrate performance of a new multi-electrode segmented heater for the L3K test position. The development of any new plasma arc device requires not only an intense analysis and design period, but also a significant experimental effort. This developmental period was characterized by trial and error techniques based on engineering judgement and tempered by applicable experiences of other experimentalists. Sometimes changes made in the interest of improving performance degraded system stability. As a result additional changes were needed to restore stability. In this way system performance was improved with acceptable stability levels.

The modified DLR facility commissioning tests took place in phases over a time period from January 1994 to October 1995 as presented by Table 9. Time intervals between each phase were necessary for a number of reasons including readiness of other facility systems and availability of hardware spares and operating personnel. Personal notes of day to day details from phases 5 through 7 are provided as Appendix C.

Stable operation of the plasma system with an air mass flowrate of 300 gm/sec was demonstrated with a four-pack (L/D=30) configuration and the 29 mm throat. Some early

Table 9 Summary of DLR L3K Segmented Heater Tests/Events

Test Phase	Date	Comments
1	January 1994	power supply checkout/ arc heater assembly
2	April 1994	one pack testing, four pack testing, demonstration of stable operation at $\dot{m}$ = 300 g/s
3	August 1994	Run 6-1A, damage to anode assembly, converger pack
4	December 1994	six pack testing successful division of arc between anodes
5	March/April 1995	first attempt at acceptance point 1 test, electrode cooling redesign
6	May/June 1995	Acceptance point 1 test Acceptance point 2 test
7	October 1995	Final acceptance point 1 test

tests were performed with the 14 mm throat and a four-pack (L/D=30) configuration.

After the results of these early tests were analyzed, all future tests were performed with a six-pack (L/D=40) configuration. Out of more than 180 test runs, most of these runs were performed with the 29 mm throat diameter and the L/D= 40 configuration. Twenty tests with the smaller 14 mm throat diameter configuration were conducted. Total accumulated commissioning test time was more than 12.800 seconds for all configurations.

The primary objective and contribution of this work is the analysis and detailed examination of the design and experimental improvements to multi-segment wall stabilized arc heaters. Primary research areas are electrode erosion, internal heat flux studies, division of current between electrodes and diagnostic techniques for safely monitoring heater performance. Each of these topics will be discussed in sections that follow. Design guidelines for future work are summarized in chapter V and VI.

Electrode Erosion

Electrode erosion has been discussed and studied on several occasions. Several references from previous work are available [66,67,68,69]. Arc heater electrodes are by design consumable parts. Nevertheless, a long electrode life is operationally desirable to reduce facility downtime and maintenance costs. Freestream contamination level is also to some extent influenced by the electrode wear. Lower levels of freestream contamination are very desirable for new material development to avoid influences on material catalytic and erosive behavior.

There have been a number of efforts to improve electrode life in the history of arc heater development. Some of the techniques that have been used include: change of the material from copper to silver alloys, bathing the electrode surface with argon, changes to the backside cooling water, adjustment of magnetic field strength, increased local gas swirl, etc. This research will present factors that affected electrode erosion and wear at DLR and other facilities. From this study, conclusions are made that in effect become design tools or guidelines for future design work. As an example, there is a need to optimize cathode inner diameter as a function of other critical heater parameters like nozzle throat diameter, constrictor bore diameter, power, magnetic field strength, facility power and others.

Measurement of Electrode Weight Loss at DLR

Figure 16 is a photograph of an electrode assembly and redesigned coolant flowguide. The electrode consists of a removable liner, a spin coil assembly and electrode housing. The electrode housing has four connections to both the cooling water supply and return system. Water connections are made with quick disconnects. The removable liner reduces facility maintenance costs and downtime since liners may be electroplated after use and returned to service. This is the first arc heated facility to utilize the concept of removable electrode liners.

Prior to heater assembly the electrodes and liners were weighed to obtain a baseline for future measurements. The heater assembly was disassembled periodically for maintenance and inspections. During these periods the electrode liners and electrode assemblies were again carefully weighed and inspected. The method of weighing the electrode assemblies

proved to be inaccurate because of the difficulty in removing residual water from the assembly and small differences in large electrode weights. On the other hand, the method of comparing electrode liner weights was a much more accurate and consistent means of electrode copper loss determination. A typical electrode liner weight is approximately 400 grams.

Phases 5 and 6 produced two long-duration runs that serve as a basis of comparison for electrode weight loss. Changes to the design and configuration of the arc heater between test phase 5 and 6 include: a) a new configuration coolant flowguide to improve the distribution of water to the backside of the liner, b) alignment of the heater centerline, c) reduction of the overall current, d) gas distribution and others. The forward arc chamber pressure for each of these runs was approximately 4 bar.

Results of these tests are shown by Table 10. The difference in liner weights, listed as del W, has been normalized by the total $I^2 Rt$ for each electrode. Table 10 shows that normalized electrode weight loss was reduced for each of the four electrodes. For the anodes the reduction was a factor of three to six whereas normalized cathode electrode weight loss was reduced by a factor of two.

The primary source of improvement was increased cooling water velocity on the backside of each of the four electrode liners. Cooling water velocity was increased from 10 to 12 m/sec to 25 m/sec by redesigning the coolant flowguide. The new coolant flowguide also enhanced the uniformity of cooling on the backside of the liners. Figure 17 shows areas of overheating on the backside of the liners after run 6-12A. The liner backside did not have

Table 10 Comparison of Electrode Weight Loss after Runs 6-12/6-12A and 6-17

Electrode	del W_1 612/612A	$(I^2R)t$, amp^2 sec	del $W_1/(I^2R)t$ $*10^{-8}$	del W_2 6-17	$(I^2R)t$, amp^2 sec	del $W_2/(I^2R)t$ $*10^{-8}$
outer anode	7.07	0.35*10**8	20.2	0.71	0.2*10**8	3.55
inner anode	10.4	1.4*10**8	7.4	2.36	1.0*10**8	2.36
inner cathode	12.0	0.9*10**8	13.3	5.44	0.8*10**8	6.8
outer cathode	10.7	0.4*10**8	26.75	2.51	0.2*10**8	12.55
total	40.17	3.05*10**8	13.2	11.03	2.2*10**8	5.0

this indication after run 6-17.

After replacement of the flowguide, several other data points were taken. These are plotted as a function of I^2t in Figures 18 and 19. Figure 18 shows that the total copper loss for the anodes is on the order of 3 grams for the 30 minute test 6-17. During post-test inspection of the heater assembly 1.85 grams of copper or copper oxide were recovered from the rear shell and rear isolators. Total cathode copper loss was approximately 8 grams as shown by Figure 19 for the thirty minute test. Some undetermined portion of this copper loss remained inside the heater as with the anode.

Based on the electrode copper loss method, test run 6-17 freestream contamination levels at 1200 amperes were less than 50 ppm when part of the residual copper in the heater was subtracted from the total copper loss. This is significantly lower than the contamination levels of Huels heaters for similar conditions, but somewhat higher than values previously reported for other segmented heaters [70]. These data were taken using the method of measuring changes in electrode assembly weights. This method is inherently less accurate than weighing the electrode liners because of the possibility of residual water in the assembly.

It is important to note that the electrode copper loss method represents an upper bound on the freestream contamination level. As an example, much of the copper from the electrodes remains in the flow boundary layer and has no effect on the material sample. Other methods of contamination determination such as mass spectrometers, collection

probes or impact probes may provide a more reasonable indication of the material sample's exposure to copper contaminant.

Measured electrode liner weight loss after test 6-19 provide additional insight into the factors affecting electrode erosion. The arc chamber pressure for test 6-19 was 16.5 bar whereas the chamber pressure for test 6-17 was only 4 bar. Table 11 is a comparison of weight loss, incident current, and I^2t from 6-19 and 6-17. Even though the current on each cathode was 10 to 40 % higher for run 6-17, the normalized cathode weight loss was three to eight times greater on run 6-19. At higher pressure conditions the overall loss of electrode liner copper was approximately 10 times greater than the lower pressure condition. This is true despite the fact that the fractional heat loss to the cathodes was approximately the same between tests 6-19 and 6-17 as discussed in sections which follow.

From reference 66 the amount of erosion increases with increasing gas pressure. This is primarily because the rotating arc attachment area decreases in diameter as pressure increases. As a result the heat flux to the surface becomes more localized and more intense. The approximate relationship between pressure, current and arc attachment diameter is given by:

$$I / (p_{to} d^2_{arc}) = \text{constant} \qquad (24)$$

Table 11 Comparison of Electrode Weights after Runs 6-19 at 16.5 bar and 6-17 at 4 bar

Electrode	6-19 I, amp	del W_1 6-19	$(I^2R)t$, amp^2 sec	del $W_1/(I^2R)t$ *10^{-8}	6-17 I, amp	del W_2 6-17	$(I^2R)t$, amp^2 sec	del $W_2/(I^2R)t$ *10^{-8}
out anode	0	0	0	n/a	550	0.71	0.2*10**8	3.55
in anode	1000	8.25	0.2*10**8	41.25	725	2.36	1.0*10**8	2.36
in cathode	407	1.84	0.06*10**8	30.7	655	5.44	0.8*10**8	6.8
out cathode	608	3.7	0.05*10**8	74	585	2.51	0.2*10**8	12.55
total	1000	13.79	0.31*10**8	44.48	1200	11.03	2.2*10**8	5.0

Division of Current between Electrodes at DLR

One of the significant achievements of the L3K commissioning effort was the successful division of current between dual electrodes at each end of the heater. This division of current was a necessary measure in the development of a low contamination facility. Previous attempts to divide the current between electrodes have been unsuccessful at all arc facilities except NASA-Ames. The division of the arc between electrodes was critical to the success of the DLR project. No other arc facility has achieved division of the arc at pressure levels of 17 bar.

Attempts during test phases 2 and 3 to divide the current between the anodes were unsuccessful. In general, the anode region was far more sensitive to changes in gas distribution and ballast resistor settings than the cathode region, because the plasma is less ionized in this area. On several occasions attempts to force the arc to divide between anodes resulted in arcing in the gaps between segments and electrodes. Since these parts are not designed for the extreme heat flux of direct arc contact, damage resulted. In some cases water leaks developed.

Initial problems were caused by attempts to inject air in the anode assembly as a means of controlling the position of the arc relative to the anode surface. Early concerns about potential arcing between the anodes and the rear shell assembly had been alleviated by injecting approximately 5% of the air or 5 g/sec into a gap upstream of the outer anode. Removal of the air from the anode assembly and argon injection between the electrodes provided an environment that allowed the arc to attach to both electrodes.

More arcing problems in the anode assembly occurred in later tests as a result of attempts to increase the air flow into the converger. Higher enthalpy for a given mass flowrate may be achieved by injection of the air far upstream in the heater. Initial performance predictions had been based on a large percentage of the air injection just downstream of the inner anode. However, experiments proved that cold air injected tangentially into the converger has enough vorticity to create a core reverse flow into the anode assembly as illustrated by Figure 20. This creates a higher electrical resistance in the arc column, makes attachment of the arc to both anodes more difficult and creates a strong potential for destructive inter-segment arcing. Work performed in the UTSI water tunnel demonstrated a multi-cell flow regime or reverse flow in the anode assembly/converger of a similar geometry heater-see reference 55.

As a result, air injection in the converger during test phase 4 and 5 was limited to prevent air intrusion into the anode assembly due to flow vorticity. Approximately 75 percent of the air flow was injected in the converger and the first three packs of the constrictor. The remainder of the air was injected somewhat uniformly throughout the downstream portions of the heater constrictor. Two percent of the total gas flow or two gm/sec of argon were injected between the anodes. Argon was also injected upstream of both cathodes.

During phase 6 tests, stability of the arc attachment to the anodes again became a

problem. With improved electrode liner cooling, the arc wear pattern was not as well defined on the elliptical surface and, as a result, was more sensitive to other changes. Additionally, better heater alignment reduced the overall gas injection area and caused a proportional increase in air input to the converger region. Further attempts to increase performance by injecting larger amounts of air in the converger section resulted in anode region instabilities that again damaged inter-electrode segments and electrode liners. This problem was eventually solved by further reducing the converger air input.

One of the design and test goals was to achieve division of currents so that no more than 60 % of the total current was carried by a single electrode. The goal of achieving at least a 60/40 current split at each electrode assembly was achieved by careful adjustment of the ballast resistor as well as selection of a suitable gas injection plan. Typical ballast resistor settings for the four resistors were as follows: outer anode: 0.035 ohms (minimum setting), inner anode: 0.114 ohms, inner cathode: 0.096 ohms, outer cathode: 0.035 ohms (minimum setting). These settings were determined experimentally.

Verification of successful current split was achieved by review of the electrode current measurements and by visual inspections of the electrode liners. Figure 21 shows typical current vs. time averaged data for the anodes during 1800 second test run 6-17. The arc current naturally prefers the inner anode because of the shorter arc length. Attachment to the outer anode was achieved by increasing the resistance of the inner anode ballast

resistor.

Figure 22 shows the anode liners after 40 to 60 starts and a total run time of more than 30 minutes on each liner. The resultant wear patterns are typical for the anode region. The wear band is approximately 20 mm wide on each anode. Each liner wear band has a distinctive swirl pattern in a direction consistent with the spin coil magnetic field direction. Portions of the liner outside of the wear band are relatively free of wear. Because the downstream face of the inner anode is bathed in cold air, the wear on the inner anode is centered slightly forward of the electrode crown. The wear on the outer anode is on the downstream edge. The arc preference for the downstream position on the outer anode is attributable to the injection of argon at this location between the outer anode and the inter-electrode segment. The downstream face of the inner anode is bathed in cold air.

As reported by references 48 and 63 and illustrated by Figure 23, the arc column tends to constrict near the electrode surfaces because of the cold boundaries. At the anode electrons leave the plasma and enter the anode material. Electrons are provided to the anode in an exothermic process similar to condensation of a vapor. Actually, it is a recombination process whereby ionization energy is given up. Reference 64 explains that a space charge limited electron current provides continuity between the anode and the plasma at the anode. Because of the lighter mass of electrons, an equivalent saturation current exists in the plasma at lower temperatures and electron density. As a result less

constriction is required as confirmed by the wide wear bands at DLR.

As illustrated by Figure 23 cathode attachment is a highly constricted, high temperature, and high-density plasma approaching the copper surface to within a distance of a mean free path. The constriction in this region is necessary to provide a sufficiently high thermionic emission from the cathode. Each electron must overcome the binding energy to the copper solid. This is called the work function and is of the order of a few volts. The necessity to produce free electrons with a sharply constricted arc near the cathode creates a very high and localized heat flux on the surface of the cathode.

Furthermore, Durgapal's analysis in reference 67 found that the arc foot is likely to terminate at the left (or upstream) corner of a ring cathode. The following sections discuss the effects of this highly concentrated heat flux.

Figure 24 shows the division of current between the cathodes at an arc chamber pressure of 16.5 bar during test run 6-19. The inner cathode is carrying the higher current throughout this test as well as others. Total current is 1000 amperes through 350 seconds of this test. At this point the arc current was slowly increased until the end of the test. The presented data is sampled at 25 samples/sec.

Localized Cathode Wear

Information on three plasma systems are presented in this section: Mitaka's 0.75-MW arc heater, the DLR 5-MW system and the 1-MW ISAS arc heater. Table 12 presents a brief comparison of these facilities. Lessons learned from the Mitaka heater design and commissioning were incorporated in the testing and to some extent the design configuration of the DLR heater. As an example, after problems with cascade arcing occurred in the checkout of the Mitaka arc heater, voltmeters were used to perform diagnostic measurements of voltage between segments. These voltmeters were used at DLR to minimize cascade arcing effects. Similarly, experience from both the Mitaka and DLR heaters was incorporated into the design and testing of the ISAS heater.

Table 12 Summary of Mitaka, DLR and ISAS Arc Facility Characteristics

Facility	Oper Date	Po, bar (max)	Throat Dia, mm	L/D (max)	No. of anode/ cathodes	Current, amp (max)	Cooling water Pr, bar
Mitaka	1993	1.1	25	23.6	Single	750	20
DLR	1995	17	29/14	40	Dual	1700	40
ISAS	1996	10	10	40	Single	750	20*

*Cooling water pressure for the ISAS cathode is 40 bar. Other components are cooled with a 20 bar system.

The initial design of the Mitaka arc heater cathode was a toroidal shape with a circular surface liner as indicated by Figure 25. A cross-section of the Mitaka heater with cathode assembly is shown by Figure 26. After several tests with incident current on the cathode surface of 500 to 750 amperes and an arc chamber pressure of 1 bar maximum, localized areas of cathode wear occurred on the upstream surface. Post-test sectioning of the cathode liners confirmed nonuniform wear as indicated by Figure 27. Borescope inspections of the heater during the commissioning tests revealed heavy copper deposits on the diverger segments near the cathode. These inspection results suggested that nonuniform wear on the upstream side of the cathode may have been

caused by a flow stagnation region at the intersection of the diverger and the cathode assembly. An elliptical surface liner as indicated by Figure 25 was designed for the Mitaka heater as a solution. After approximately 2 hours of run time, the cathode liner was removed and sectioned as before. Figure 28 shows that the wear on the elliptical liner was very uniform with apparently no tendency for localized erosion. This liner had the old flowguide configuration and water velocities of 10 to 12 m/s.

The localized Mitaka cathode wear can be attributed to three factors: a) unequal electrode cooling water distribution, b) stagnation flow on the upstream toroidal surface and c) nonuniform argon bathing of the cathode. Based on the results from tests with a lower profile liner, elimination of the upstream stagnation region appears to have a strong remedial effect on localized wear.

Results of the Mitaka commissioning tests were not available until late in the fabrication and assembly of the DLR heater. Based on the Mitaka experience the elliptical cathode liners were always used at DLR. The only other change in the DLR heater design was associated with the spin coil. The Mitaka spin coil was a ten turn coil with a design point of 600 gauss at 600 amperes. Each DLR cathode spin coil assembly consisted of six turns. For both Mitaka and DLR heater designs, the spin coil is in series with the power supply.

Problems with localized erosion on the DLR inner cathode were first noticed at the end of phase 4 tests. It is reasonable to assume that localized wear problems did not occur prior to this point because the heater was operated at currents less than approximately 500 amperes on each cathode for short time periods. Problems persisted in every test phase afterwards despite the redesign to the electrode coolant flowguide and other changes. On three test runs the inner cathode liner developed a pinhole size water leak as a result of burn-through.

After test 6-12A the inner cathode liner was measured at 8 radial locations at each of 6 axial locations. The results were plotted as Figure 29. These data show that wear on the cathode is very uniform except for a single location near the upstream corner of the liner. Felderman reports that possible methods of electrode copper loss include: a) surface evaporation from the rotating arc spot, b) mass loss from subsurface nucleate boiling, c) scrubbing by viscous forces, and others. These data and visual examination of the cathode

surfaces indicate that the predominant cathode loss mechanism is that of scrubbing by viscous forces. However, copper loss from the localized erosion spot appears to be evaporation possibly due to diminished arc rotation or a preference of the arc for this location.

Efforts to minimize this localized erosion problem were hindered prior to test phase 6 by the poor cooling affected by the old flowguide. However, redesign of the coolant flowguide did not solve the problem. Several other investigations and remedial actions were implemented in an effort to eliminate the localized erosion. These actions included:

a) increased air injection in the diverger. Additional air was injected near the inner cathode to enhance the arc spot movement and rotation. These efforts did not prove effective and in general were disruptive to the arc splitting between cathodes.

The intent of these changes was to make the arc attachment to the cathode rotate faster. Careful examination of the worn cathode liners does not reveal any indications of swirling flow and suggests that swirling components of the air flow injected in the first three heater packs have been dissipated over the length of the constrictor and diverger sections. Further the results of fractional heat loss calculations as presented in later sections show that internal heat flux to the constrictor segments were well within the limits for nominal water flow conditions. This suggests that the constrictor bore diameter could be decreased to diminish the viscous dissipation effects on swirl without compromising the integrity of the constrictor segments.

b) inspection of the cathode assembly for water leaks. Some internal water leaks were

found and repaired.

c) a new spin coil assembly. S/N 4 spin coil assembly had 15% more magnetic field strength and would thus rotate the arc a little faster decreasing the arc spot residence time at any location. This made no difference. Ten turn coils were designed for testing in phase 7, but were not tested. The increase in magnetic field strength for these coils would have been an increase of 67%. Some experience from higher mass flow facilities have shown that too much magnetic field may result in arc control problems.

d) arc heater assembly alignment with laser systems. The purpose of this alignment was to preclude an arc attachment preference for the upstream face of the inner cathode. Alignment measurements showed that the heater was misaligned by approximately 5 mm in a direction consistent with the spot of localized erosion.

Appendix C details the work performed as a part of this effort as well as the results.

The precise cause of the localized cathode wear at the DLR facility was never determined. Based on the disappearance of the localized erosion problem at DLR during the 6-15B to 6-16C testing and then the reoccurrence of the problem after disassembly and reassembly for 6-17 without other changes, the problem must be due to inconsistencies in the installation of the cathode assembly and alignment of the heater. An off-nominal installation or alignment could bias the location and distribution of argon injection or create a water leak. Either of these could attract portions of the arc to a concentrated area on the inner cathode upstream corner.

Following the design and commissioning of the Mitaka and DLR heaters a new segmented

facility as described by Chapter II was designed for ISAS. Based on lessons learned from the previous efforts, design improvements to the ISAS heater cathode included: a) reduction of the cathode inner diameter to increase the plasma swirl momentum and decrease the average heat flux to the cathode, b) increased water velocity based on higher (40 bar) water pressure, c) redesigned flowliner d) additional structural supports for the heater packs and electrode assemblies to aid with alignment e) the o-ring between the spin coil and the electrode housing was eliminated to preclude water leakage at this joint f) argon was not injected upstream of the cathode. No argon injection was used to bathe the cathodes or anodes. Incident current to the ISAS cathode surface was 500 to 700 amperes with arc chamber pressures of 1 to 10 bar. Preliminary results indicate that cathode wear has been reduced as a result of these changes.

Figure 30 is a photograph of an electrode package from the NASA-Ames facility. This figure clearly shows a groove on the cathode crown. The electrodes are recycled for repair of this condition when the groove depth reaches approximately half of the wall thickness. Since the NASA-Ames electrodes are 0.1 inches thickness, recycling would occur when the groove depth reaches 0.050 inches. AEDC has also verbally reported problems with localized erosion on cathodes.

The DLR arc facility has operated recently up to 90 minutes at 1000 ampere without problems. As reported by chapter II the facility is actively supporting ESA test programs.

Internal Arc Heater Heat Flux Distribution

The average heat flux to selected portions of the heater was determined by the energy balance method using the difference between inlet and outlet temperatures from each of nine water manifold circuits. Figure 31 shows the correlation between water manifold circuits and the arc heater segmented packages. A time period of 160 seconds was chosen to allow the temperature sensors to equilibrate. These losses are presented in fractional form in Figure 32 for the 1800 second test run 6-17. This test was performed with the 29 mm diameter throat and a mass flowrate of 100 gm/sec. The resultant arc chamber pressure was 4 bar. Current was 1200 amperes and the voltage was 3150 volts providing an input power of approximately 3.8 MW. The total power loss to the heater was 1.8 MW.

Figure 32 shows that the fractional heat loss increases as the heater length increases. The increase in heat loss along the constrictor assembly is seen by comparing losses from manifolds 4, 5, 6 and 7. The highest losses occur at the downstream end of the heater. The total heat flux to the internal arc heater surfaces consists of both radiative and convective heat flux with the convective portion dominating the downstream stations. The heat loss to upstream packs 2 and 3 is 69% of the heat loss to packs 4 and 5. These data show good agreement with measurements of relative heat flux to upstream and downstream sections of the NASA-Ames Panel Test Facility for similar mass flowrates [71].

The calculated constrictor heat flux compares well with design predictions for test 6-17 conditions as well. The SHARC predictions for heat flux in packs 2 and 3 are 90% of the calculated values. In packs 4 and 5 the SHARC predictions are approximately 33% higher

than the calculated values.

Comparison of heat loss to the anodes and cathodes can be made through examination of water circuits 2 and 3, outer and inner anodes, and circuit 8, inner cathode. Water circuit 9 serviced the three nozzle isolator circuits as well as the outer cathode. As a result, a direct comparison of heat flux to the outer cathode is not possible. The electrode heat flux is a function of the combined radiative and convective terms. The heat loss to the inner cathode is three times that of the inner anode despite the fact that the indicated currents to these electrodes are approximately the same. This difference can be attributed to the larger convective heat flux in the downstream section of the heater as well as the highly constricted arc attachment zone at the cathode.

Figure 33 shows the same kind of comparison for test run 6-19. Test run 6-19 was a 360 second run with the 14 mm throat. As before, a time period of 160 seconds was chosen to allow the temperature sensors to equilibrate. The mass flowrate was 100 gm/sec as before, but the resulting arc chamber pressure was 16.5 bar. Current was 1000 amperes and the voltage was 4090 volts providing a total power input of approximately 4.1 MW. The total power loss to the heater was 2.3 MW. A modified gas injection distribution plan was used for this test; i.e. a larger percentage of air was injected in the converger pack to increase the arc chamber pressure. Test 6-19 and all of the other 14 mm throat diameter runs were performed with a single anode. Test 6-19 heat losses to the individual packages in the constrictor assembly are roughly equivalent because of the change in gas distribution as noted above and the decrease of the constrictor flow velocity.

As before there is good agreement between the calculated constrictor heat flux and the

prefabrication predicted heat flux for test 6-19 conditions. The SHARC predictions are approximately 80% of the calculated values in packs 2 and 3. The predicted values for packs 4 and 5 are approximately 25 % higher than the calculated values based on measured quantities.

There was no measurable heat loss to the outer anode, as expected, since all of the current was on the inner anode. Comparison of test run 6-19 to test run 6-17 inner anode fractional heat loss is of the order of experimental uncertainty or 20%. Test run 6-19 and 6-17 cathode fractional heat losses are approximately the same.

Failure Analysis of DLR Arc Heater Constrictor Segment 46

As discussed above, the average heat flux to portions of the heater were determined. Although actual heat flux to specific segments was not measured, failure analysis of segment 46 provides some additional insight into internal heat flux and cooling requirements .

Manufacturing and Test History

Segment 46 was made from OFHC copper. The manufacturer designated the segment as 46. (This number does not refer to its location in the constrictor bore.) The segment passed x-ray inspection and water flow tests. Measured water flow through the segment was 2.6 gpm or 9.84 liter/min at 55 psi water pressure. This was a very normal flow in comparison to all the other segments tested the same way. This segment was assembled in the 5th position from the upstream end of the pack.

DLR assembled this pack as the 5th package in a six pack heater. Water connections were made to the heater from the DLR manifold and total system flow checks were performed. Segment 46 was used in a series of 85 hot tests beginning in April 1994. The tests conditions were as follows:

mass flow rate : 50 g/s to 300 g/s

current : 600 to 1200 amperes

test duration : 170 seconds maximum

arc chamber pressure : up to 3.6 bar

Based on the energy balance method segment 46 was exposed to heat flux up to 13 MW/m^2 during these tests. Borescope inspection showed that this segment was a little rougher than all the others. Some mild surface scaliness was observed, but the segment remained completely functional and there were no flow anomalies attributed to this condition.

Description of Test Run 6-10Q/6-10R

The 86th run was test 6-10Q. This run condition was more severe than other runs as shown below:

mass flowrate : 95 g/s

current : up to 1720 amperes

arc chamber pressure : 3.86 bar

test duration : 148 seconds

Based on the energy balance method the maximum heat flux to segment 46 was on the order of 18 MW/m^2. We stopped this test when the flow began to show unusual fluctuations. Post-test analysis of the video showed green flashes in the flowstream near the point of test termination, but the post-test vacuum condition of the heater was good-reaching a pressure of approximately 1 torr. The conditions for the next test 6-10R were similar:

mass flowrate : 95 g/s

current : 1600 amperes

arc chamber pressure : 3.8 bar

test duration : 75 seconds

estimated heat flux : 18 MW/m^2

This test was terminated by the manifold 6 outlet temperature interlock. The absolute value of the bulk temperature in this manifold exceeded the limit of 40 degrees C. Post test analysis showed that the bulk temperature rise across the 32 segments serviced by this manifold was 19.7 degrees.

Post test inspection revealed a water leak inside the heater. Borescope inspection showed

that segment 46 was the source of water leakage.

This package was removed and disassembled. Segment 46 damage was localized in the upper half of the segment over an arc of approximately 15 mm length. The damage was located on the downstream or outlet side of the flow passage as shown by Figure 34. The segment wall was thinned in two locations by the overheating process.

The segment face was machined to inspect the water passage for signs of blockage. Inspection showed no blockage or signs of obstructions in the water passage. Measurements of the segment wall thickness showed that failures occurred in cusps which had a thickness of 1.3 mm. The thickness of other cusps are 1.5 to 1.7 mm. These measurements are within drawing tolerances.

Subsequent Test Results and Analysis

This segment was replaced and hot testing continued. An additional 10 runs were made including one run of 30 minutes duration and conditions of mass flowrate = 100 g/s, current = 1340 amperes, arc chamber pressure = 4.1 bar. After this run the heater was inspected again and the same segment showed scaliness and roughness unlike other segments in the constrictor.

Cooling water flow measurements were made using an ultrasonic technique. Water flow to this segment were restricted to 10 l/min. -other segments had 12.5 to 14 l/min. Additional investigation demonstrated that the DLR manifold had a weld slag buildup on the stub connection that feeds segment 46. The opening diameter was restricted to less than 4 mm.

The overheated segment was replaced. The water manifold connection was reworked by removing the weld slag. No further problems were experienced with overheating at this or any other location in the constrictor.

Explanation of the Failure Process

The restriction in the DLR cooling water supply manifold reduced the segment water flowrate and velocity. This in turn lowered the critical heat flux (CHF) level or burnout point to a level that was below the heat flux imposed on the surface by the run conditions. Consequently, local boiling occurred and the surface melted.

Researchers have shown that CHF is a function of many different parameters including water velocity, pressure, gas content, subcooling, surface roughness, turbulence and acceleration, wall thickness and material, geometry and others. Based on actual measured water flow of only 10 l/min, calculation of the critical heat flux using an empirical relationship derived by Van Huff and Roussar, [72]

$$q_{chf} = 5.1 + 0.00086\ u\ (T_{sat} - T_w) \qquad (25)$$

showed that the critical heat flux was 22 MW/m^2 +/- 30%. This relationship is valid for pressure from 10 to 2000 psia, velocity of 7.5 to 205 ft/sec and bulk fluid temperature from 76 to 470 degrees F. This is a relatively close correlation with the estimated segment 46 failure point, but the Van Huff/Roussar correlation was obtained in flow passages that are not cusped.

A cusp-shaped water passage induces a centripetal pressure gradient that sweeps away nucleate boiling bubbles from the copper surface. By contrast these bubbles will adhere to the surface in a conventional i.e. non-cusped design [73]. Data from NASA-Ames indicates that cusp-cooled segments can withstand heat flux up to 140 MW/m^2 at one atmosphere arc chamber pressure and full cooling capability.

It is possible that the onset of boiling conditions on one side of the water passage causes an increase in resistance for that half of the passage and forces more flow to the other passage. This in turn would decrease the CHF for the upper segment half lower and lower until finally burnout occurred. Note that the lower half of segment 46 has no damage.

Diagnostic Techniques during Arc Heater Development

Development of a new plasma system requires utilization of several diagnostic techniques. These techniques are used as a means of health monitoring while the heater operates in unexplored performance regions. Despite the fact that three different means of protecting the DLR heater were used, the arc heater was damaged by internal arcing between electrodes and/or adjacent segments on several occasions. As an example Figure 35 depicts damage that occurred between segments in the converger during test 6-1A. Nevertheless, in this case and for several others the amount and degree of damage was minimized by power cutoff initiated by the flowfield or voltmeter observers. Some runs were also terminated by the photocell.

The photocell is an automated cutoff whenever voltage readings exceed limits. The voltmeter readings could also be automated in the future when the heater has very well-

defined operating characteristics. During the development phase automation of the voltmeter readings would result in many unnecessary cutoffs and is not recommended.

This section presents a brief description of diagnostic techniques such as voltmeters between segments, photocells, visual monitoring guidelines and interlocks. These are presented as an aid to future heater development efforts.

Voltmeters between Segments

Approximately 12 segment-to-segment voltages were measured during the DLR test program. These were primarily located in the anode and cathode assemblies. However, the clip-on connections could be easily relocated between tests if desired. Voltmeter ranges were 0 to 100 or 0 to 300 volt instruments. The voltmeters were recorded and displayed real-time on video.

In general the voltages were very stable with time and read 10 to 20 volts for most heater conditions. If the voltage decreased to zero and remained at this point for a sustained time period, this was an indication that the gap had shorted. Several of these shorted gaps in sequence may indicate incipient cascade arcing that will damage the heater. The diverger gaps near the inner cathode shorted on several occasions during the runs because of copper material residue from the localized erosion condition. Post-test efforts to clear these shorts included blowing air through the gaps and burning the copper out with a low-voltage power supply. The shorted condition in the diverger was never more than an annoyance.

Photocells

The photocell as utilized for the DLR system checkout is described by Reference 10. The photocell is typically not active until 3 seconds into the test because the starting process produces a very bright flash that would trip the luminosity limit. As the data in Appendix D shows, the photocell output is indicative of very smooth and stable flowstream conditions. Absolute values of photocell output vary with arc current and mass flowrate. Under duress the heater produced luminosity readings that were indicative of problems inside the heater. As an example, a water leak from an inner cathode on test 6-20E decreased the luminosity reading.

Flowstream Observations

The flowstream observer must monitor the freestream for signs of heater distress and terminate the tests if warranted. These decisions should be tempered with input from the voltmeters as well as the photocell luminosity meter. The flow may be observed by video camera or by mirrors if location of the control room does not allow a direct line of sight to the flowstream. At DLR control room equipment was positioned so that flowstream and voltmeters could be observed on video. The photocell meter was positioned so that the gain be adjusted during the course of the test, if necessary.

During startup with argon the flow may have a purple tinge. With the initial injection of air a very bright flash is common for a brief time period of 1 to 2 seconds. With air as the primary gas the flowstream for a low pressure heater should be a whitish color and relatively free of instabilities. Failure conditions are readily visible in the flowfield. As an

example, green flow is indicative of copper vaporization. Sharp increases in luminosity without corresponding changes in current or mass flowrate settings are indicative of problems such as cascade arcing. Cascade arcing is a condition in which the arc or portions of the arc travel from segment to segment jumping between the small gaps separating segments rather than arcing from electrode to electrode.

During tests 6-12A, 6-17 and 6-20E pinhole water leakage from the inner cathode created flow instabilities. Normally the test stream appears extremely stable as indicated by the traces of photocell luminosity in Appendix D. Initial indications of the cathode failure began with occasional appearances of glowing copper fragments in the test stream. These fragments caused small increases in the photocell luminosity trace, but the flow quickly returned to stable conditions. As the test continued sudden changes in luminosity or flashes occurred. These changes in luminosity became more frequent and more pronounced as the test proceeded. However, these increases in luminosity were never high enough to trip the photocell limit. In parallel the voltmeters indicated a shorting of the gaps near the cathode.

Interlocks

Several interlocks were utilized to protect the DLR heater. A typical list of interlocks along with the rationale behind selection is provided by Table 13. Interlocks were adjusted at my direction throughout the course of test phase 4-7 to protect the heater. The values of interlock limits were chosen based on review of the data from previous runs.

Table 13 List of DLR Interlocks for Test 6-17

Interlock	Value	Comments
arc voltage HIGH	3500 V	120% of the expected value
arc current HIGH	1400 A	protects electrodes from excessive currents and damage to the heater
forward chamber pressure HIGH	5 Bar	4 bar expected, protects against damaged parts clogging throat and raising the arc chamber pressure above safe limits
air mass flow LOW	80 g/s	protects the heater from air system failure
water inlet temperature HIGH	37 C	protects the heater from failed heat exchanger and effects of water above nominal temp i.e. boiling
water temperature rise HIGH	40 C	for each of nine water manifolds
water mass flow LOW	varies	90% of expected value for each of nine water manifolds
balance resister water flow LOW	50	80% of expected value, protects the ballast resister
arc voltage LOW	2500 V	90% of expected value to protect the heater from cascade arcs
photocell luminosity HIGH	5 V	protects the heater from many different anomalies

CHAPTER V

SUMMARY OF DESIGN AND DEVELOPMENT PROCESS

Design and experimental development of any plasma system requires an understanding and command of several engineering disciplines including mechanical/electrical design, heat transfer, materials science, thermodynamics, hypersonics and others. Beyond the opportunity for academic achievement, further plasma system development has potential value and contribution. As an example, continued development of plasma facilities is needed to support thermal protection systems development for both future reusable launch vehicles and space capsules. A primary focus will be better understanding of flow stream chemistry and interaction with the sample material through the utilization of non-intrusive diagnostic instrumentation. Based on an increased understanding of flow chemistry, adaptation of plasma arc devices to produce desired sample surface chemistry conditions is needed. In support of this need, the focus of this dissertation has been investigation of low-pressure multi-segment plasma arc heaters. The primary objective has been the development of guidelines for future design and experimentation for these systems.

The design and development of a multi-segment plasma system begins with a study and understanding of similar systems. This work includes a survey of existing operational aerospace and commercial plasma facilities. Changes, modernizations and trends for future improvements were identified and discussed. The status and history of analytical code development was also presented. These codes do a reasonably adequate job of predicting heater performance based on explicit methods. Some improvement to future heater

designs is anticipated when second generation codes based on CFD techniques or genetic algorithms become operational.

With an understanding of existing material test facility and numerical code capabilities, the design of a new facility or facility modification begins with definition of test program requirements. This will establish the size of the model and ultimately the facility power requirements. In addition, the sample surface chemistry, temperature and pressure requirements must be derived or provided by the vehicle flight trajectory requirements. Derivation of arc heater enthalpy and pressure requirements based on this information is explained by Chapter III.

Prior to numerical code analysis, facility acquisition limits such as cost and schedule constraints must be considered. The cost of the facility is proportional to the facility power. Often cost can be mitigated by utilizing existing nozzles, air systems, cooling water systems or power supplies. However, the utilization of existing hardware or other resources imposes boundary conditions on the design process that may not be desirable. Available floor space and building features may also impose limits on the design.

The desired material test productivity requirements must also be considered as a part of the design process. The multi-segment arc heater must be packaged so that maintenance and routine checks may be accomplished within time constraints. Cooling water supply and return lines should be located on either side of the segments at 3 o'clock and 9 o'clock positions. The air lines should be located at 12 o'clock. This arrangement allows the air manifold to be located above the heater and the water manifolds along each side for maximum space for maintenance. Anode, constrictor and cathode assemblies should be independently packaged and mounted on rails for convenient axial movement.

With a recognition of budget constraints and productivity goals, the selection of heater airlines and basic dimensions can begin. The SHARC code or other codes as identified in Chapter III are utilized together with the sonic flow relationship to establish the constrictor dimensions and operating current and voltage to meet the pressure and enthalpy requirements.

Heater dimensions must be chosen with a recognition of limits imposed by cooling and other constraints. As an example, both the NASA-Ames and DLR heaters utilize a constrictor L/D of 40. Enthalpy gain provided by additional heater length is offset to a large extent by decreased efficiency. As mentioned previously, electrode currents should be limited to 500 to 700 amperes if possible. After the heater and nozzle throat dimensions are selected and built, system performance limits are to a large degree set. The only means of achieving higher sample surface temperature for a given mass flowrate is increased arc current. Penalties for higher current operation include increased electrode erosion, higher contamination in the flowstream and greater vulnerability to anomalies. As a result, system design margin must be included to insure performance goals are achieved without resorting to higher current operation.

The derivation of constrictor L/D and operating envelope using the SHARC code must be based on realistic air injection distribution. For multi-electrode heaters, reverse flow along the arc column will not allow substantial air injection immediately downstream of the anode as demonstrated at DLR. As a result, primary air injection must be concentrated in the upstream portion of the constrictor.

As explained by Chapter III, SHARC outputs include heat flux to constrictor wall, voltage between segments, enthalpy and voltage. Code results should be checked against actual

data from the DLR facility commissioning to validate predictions.

The heater airline configuration will be completed by design of the anode and cathode assemblies. Experience has shown that the cathode inner diameter should be minimized to limit heat flux to the cathode and limit erosion. The optimum inner cathode diameter is a function of heater mass flowrate, throat size, magnetic field strength, constrictor L/D and operating conditions. In the limit as the inner cathode diameter approaches the bore diameter, the arc column may be blown through the throat and attach to objects in the test chamber prior to attachment to the intended cathode. A cathode inner diameter of 50 mm has been successfully used for a throat diameter of 10 mm and constrictor diameter of 25 mm for mass flowrates of 30 g/sec.

Design of heater components may proceed after SHARC runs and empirical checks have established the geometry and heat flux for each component. As an example, the constrictor segment should have a width of 1 cm for low pressure applications. Thinner segments may be required for high pressure applications where inter-segment arcing concerns begin to affect the design. Average heat flux to the electrodes may be derived from the DLR data base using the energy balance technique. The derived heat input should be applied over a band approximately 20 mm wide at the anode. At the cathode much smaller arc spots should be used as demonstrated by the data from DLR and other facilities. Cooling water pressure should be a minimum of 20 bar for the heater and 40 bar for the cathode. NASA Ames uses 65 bar. These pressures are necessary to achieve the highest possible velocities on the backside of electrode surfaces. Electrode cooling water velocities of 25 to 30 m/sec are recommended.

With the design of the heater complete, the heater is fabricated with close tolerances. After fabrication a number of acceptance checks are required to demonstrate component integrity. Each segment is flow checked and x-rayed to assure cooling passages are free and clear. The magnetic field strength of each electrode is tested to assure no coils are shorted. After heater assembly resistance tests are made with an ohmmeter to assure that no shorts exist between segments. Leak tests are also made to assure no external or internal water leaks. Borescope inspections can be used to demonstrate no gross internal water leakage.

Initial development tests concentrate on establishment of a safe system starting procedure. An argon starting technique is preferred to limit electrode erosion. Introduction of air and current ramp time must be coordinated in this process.

Several diagnostic health monitoring techniques are needed in arc heater facility development. As an example, voltmeters between segments or other heater components offer an effective diagnostic aid during tests. If segment-to-segment voltages decrease to zero for sustained periods of time, this is indicative of a shorted gap. A progression of shorted gaps may signal an incipient cascading arc that can damage the heater. As a result, voltmeter monitors must terminate the test if this condition occurs.

An observer must also monitor the arc heater exterior and arc heater flowstream. Careful flowfield monitoring by an observer was one of the primary means of assuring the safe operating conditions for the heater. The number of cutoffs because of flowfield or voltmeter observers far outnumbered the interlock cutoffs at DLR. The flowfield observer must cut off power to the heater when the flowfield indicates the heater is under duress as indicated by green flashes in the flow, wide and random oscillations in the flow luminosity,

arcing external to the heater, and flow collapse in the vacuum test chamber.

A photocell to monitor flow luminosity or laser system to monitor copper in the flow stream is an important tool in heater development. A properly calibrated and sensitive photocell will often reduce the damage to heaters under changing conditions. Gain adjustment is a desirable feature. The gain may require adjustment as heater current and mass flow conditions are changed.

Experimental plasma system results from DLR and other locations show that effective reduction of electrode erosion can only be achieved by careful attention to several details. These include:

a) Division of current between electrodes in a dual electrode heater is strongly dependant on both the heater gas distribution and ballast resistor settings. The anode assembly was much more sensitive to changes in these parameters as demonstrated by several runs that damaged the heater when the balance of gas distribution and resistor settings was disturbed. An argon flowrate of 2 g/sec in the anode area was adequate to achieve stable current division at pressures up to 4 bar when air was removed from the anode assembly and limited to 15 g/sec in the converger assembly.

Division of current between cathodes was achieved at pressures up to 17 bar for the first time anywhere. This suggests that higher current operation may be possible at even higher pressure levels. Cathode coolant flow must be uniformly distributed to prevent localized erosion.

b) Off-nominal installation of multi-electrode assemblies may cause nonuniform gas

distribution over the surface of the electrode. Although an argon bath over the surface of the cathode has been proven as a means of reducing erosion, nonuniform argon injection may negate associated benefits, i.e. localized erosion may result if argon is not uniformly distributed over the electrode surface.

Results from weight loss measurements of the DLR replaceable liners suggest that previously reported results from electrode assembly weights may be inaccurate. As a result the material testing community's perception of segmented heater contamination levels must be altered. The measured contamination level of the DLR heater operating at 1200 amperes and 100 g/sec was approximately 50 ppm based on electrode liner weight measurements. Previously reported results from NASA Ames heaters at similar operating conditions were 7 ppm based on electrode assembly weights.

Weight loss data from runs at arc chamber pressures of 16.5 bar and a mass flowrate of 100 g/sec are approximately 10 times larger than those for the heater operating at 4 bar and the same mass flowrate.

After heater tests are completed, a number of checks and maintenance tasks are appropriate. A thorough heater borescope inspection should be performed after test runs that operate the heater in new operating regimes, after flowstream or other anomalies, or at the end of the testing day. This inspection should look for localized electrode erosion, scaling or roughness of segments, unusual wear on any internal surface.

The electrode liner inspection will be useful in establishing a plan to replace the liners. Replaceable electrode liners proved to be an asset to facility maintenance. Numerous liners were removed and replaced so that testing could continue. After removal the liners were

electroplated and re-machined to the original dimensions for future use. During the course of testing there was one instance when an electroplated liner failed after only 3 minutes of testing at mild conditions. All other electroplated parts appeared to function normally.

Evidence of roughness on the internal surface of segments may be indicative of inadequate cooling. Off-nominal water flows to individual heater segments can result in cusped segment failure due to overheating at levels as low as 18 to 20 MW/m^2.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

The primary focus and contribution of this work has been experimental and analytical investigation of low pressure segmented arc heaters with emphasis given to producing guidelines for the design and developmental process. A summary of contributions, guidelines, and results based on tests performed at DLR and other locations is presented below.

a) An up-to-date and accurate assessment of existing arc heated facilities status, capabilities and plans for future changes or improvements was presented. Evaluation of existing facility capability is the first step in the process of designing a new facility or facility modification.

b) A summary of the arc heater design process was presented by chapter III. This includes a method to infer the required heater enthalpy and pressure requirements from given sample surface temperatures and pressure requirements.

c) A data base for future heater development was created with currents up to 1700 amperes and mass flowrates up to 300 g/sec. This data base includes video record of the flowstream and voltmeter readings for a variety of nominal and anomalous conditions.

d) The design and development process must recognize the following guidelines:

1. The constrictor L/D should not exceed 40. Longer heaters offer marginal

enthalpy improvements with associated penalties for loss of efficiency, additional maintenance time and cost.

2. Low pressure (<10 bar) heaters operate at higher efficiencies with larger throat diameters. The throat diameter may approach or equal the constrictor bore diameter. At low pressure conditions the heater is less susceptible to anomalous operation due to arc instabilities in the constrictor.

3. Electrode design is normally the limiting factor in determining the plasma system test duration. A single electrode may operate up to 1000 amperes for short time periods. As an example, a single DLR anode operated for 6 minutes at 1000 amperes and a pressure of 16.5 bar. At the same arc chamber pressure the cathode current was limited to 600 amperes for six minutes.

Division of the arc at the cathode was demonstrated at pressures up to 17 bar. This was a significant achievement since all other facilities except NASA-Ames have been unsuccessful in dividing the arc. Ames has demonstrated arc division to pressures of 10 bar or less.

Arc current for each electrode should be limited to 500 to 600 amperes or less via arc division techniques, if long-1 hour or more-test durations are required. Backside cooling water velocities of 25 to 30 m/sec are required to minimize electrode wear.

Division of the arc between electrodes was achieved by careful selection of ballast resistor settings and gas distribution. Guidelines for ballast resistor settings for DLR acceptance conditions are as follows: outer anode-minimum setting, inner anode-0.1

ohms, inner cathode-0.09 ohms, outer cathode-minimum setting. An injection of up to 2% argon in the anode assembly was sufficient to achieve arc division. Argon was also an aid to arc division in the cathode assembly.

4. Precise measurements of electrode mass loss as a function of current and time was reported for each electrode. These results demonstrated that previously published results for low pressure segmented heater contamination may be biased low.

5. This work demonstrated the feasibility and advantages of replaceable liners at each electrode. No other facilities have utilized this concept.

6. Selection of electrode liner inner diameters relative to the constrictor diameter should be guided by evaluation of the total system mass flowrate, arc chamber pressure, throat size, magnetic field strength and other parameters. A cathode inner diameter to constrictor diameter ratio of 2 was successful for 10 bar, 30 g/sec conditions with a 10 mm throat diameter.

7. Constrictor segments with off-nominal water flow conditions may overheat at heat flux as low as 20 MW/m^2 . The DLR heater cooling water supply and return systems were divided into multiple manifolds. This innovation allows the calculation of internal heat flux based on energy balance methods as a function of position in the heater assembly.

8. A photocell is a desirable diagnostic instrument to monitor the arc heated flowstream. Adjustable gain is a desirable feature for this equipment. Gain should be adjusted as test conditions change, if possible. A delay of 2 to 3 seconds for photocell

activation is required to avoid cutoff because of start transient conditions.

9. Segment-to-segment voltages should be monitored to assess internal heater conditions and avoid damage to the heater. Expected segment-to-segment voltages are a function of operational conditions i.e. heater voltage, and gas injection flowrates. For a 4000 volt heater condition, voltages between segments with 1 to 5 g/sec air injection flowrates were 10 to 20 volts at DLR. Manual monitoring is recommended.

If segment to segment voltages indicate zero, a shorted condition exists. Sequential shorted segments may be indicative of incipient cascade arcing. The heater operation must be terminated to avoid damage due to this condition.

10. Guidelines for interlocks to protect the plasma system are presented by Table 13.

Recommendations for future work to improve these plasma systems include:

A) development of a modern two-dimensional code that will address the current code deficiencies as listed by chapter III. As a example, the code must model total heater assembly geometry and should include modern turbulence models.

B) development of a flexible low pressure arc heater laboratory that would allow variation and characterization of all parameters. As an example this laboratory would measure system performance changes as a function of variation in electrode magnetic field strength, gas injection distribution, heater L/D and geometries. Variations in sample surface chemistry would be assessed as the heater conditions and configuration is changed.

C) exploration of innovative approaches to arc division between the electrodes. As an example, power supplies may be used and dedicated for each electrode pair rather than a ballast resistor.

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APPENDICES

Appendix A

Figures

Figure 1 Comparison of High-Temperature Tunnel Capabilities

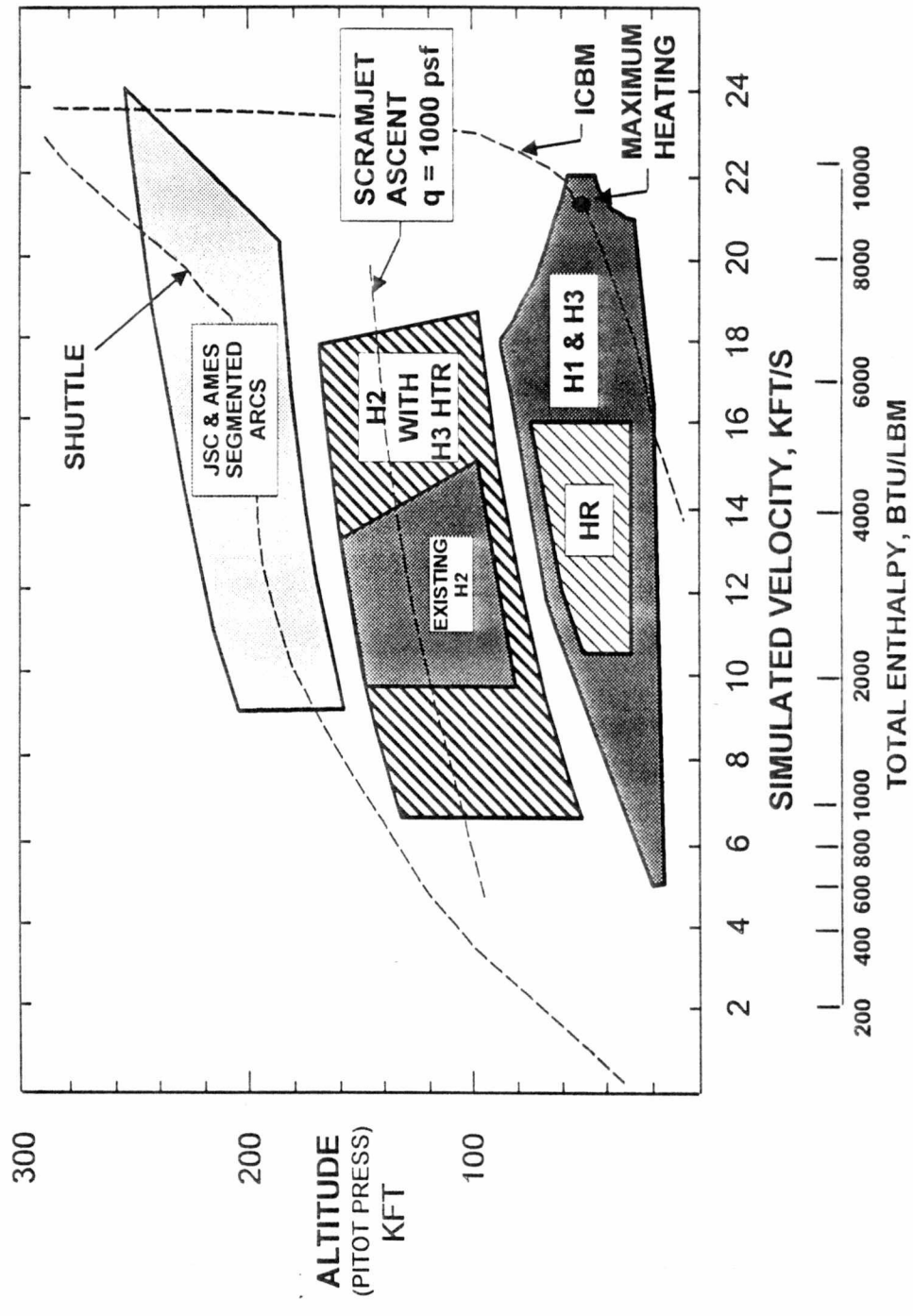


Figure 2 Comparison of Arc Facility Simulation Capability with Spacecraft Descent Trajectories

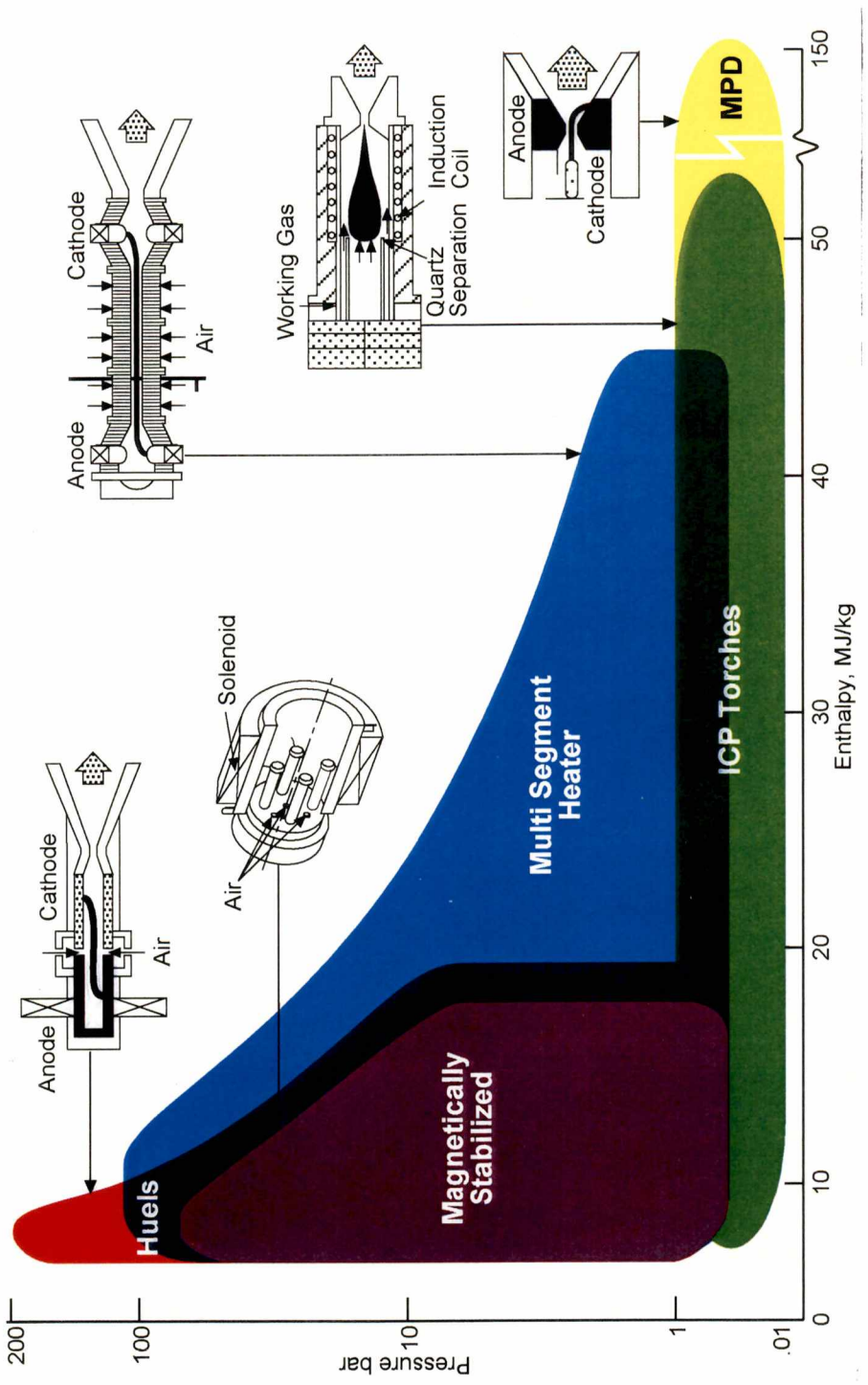


Figure 3 Pressure Enthalpy Envelopes for Arc Heaters and Other Plasma Devices

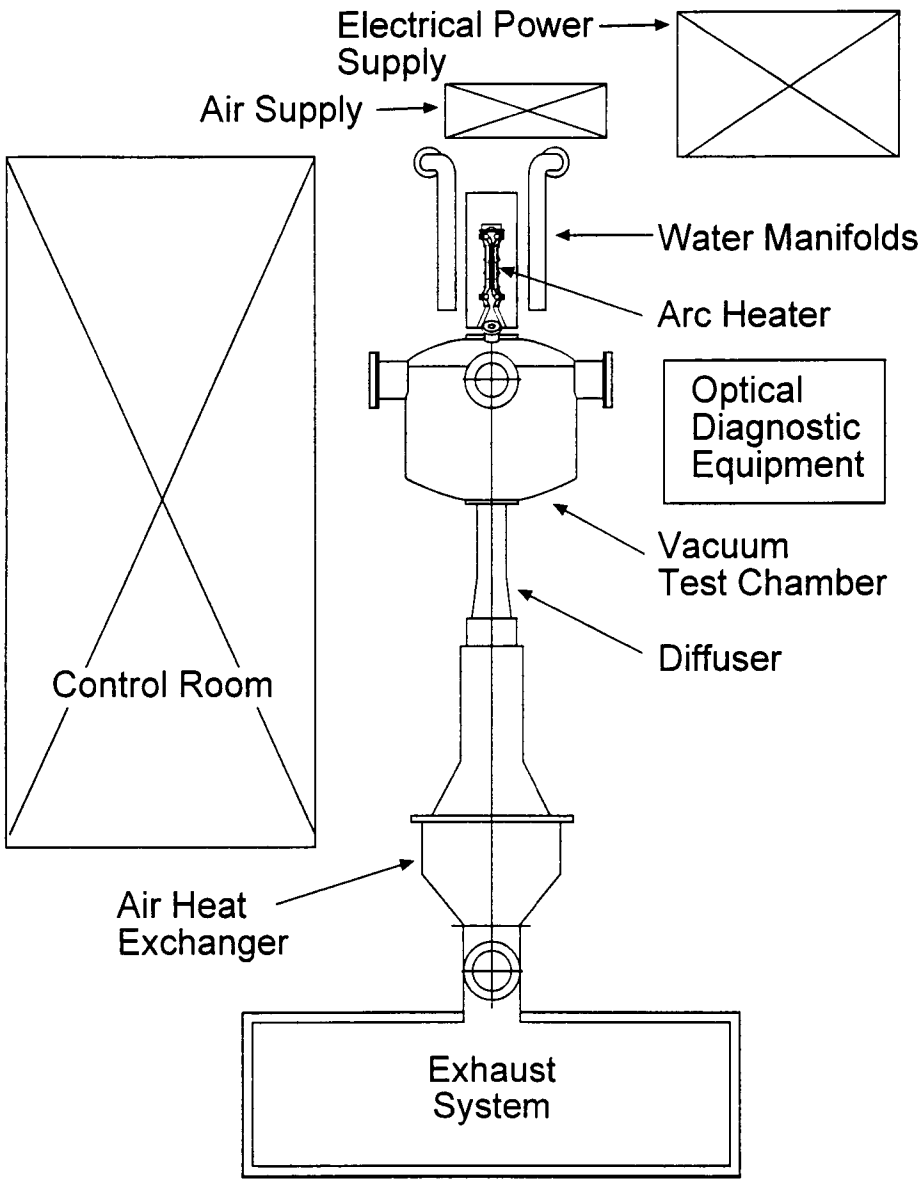


Figure 4 Typical Aerospace Arc Heater Facility Diagram

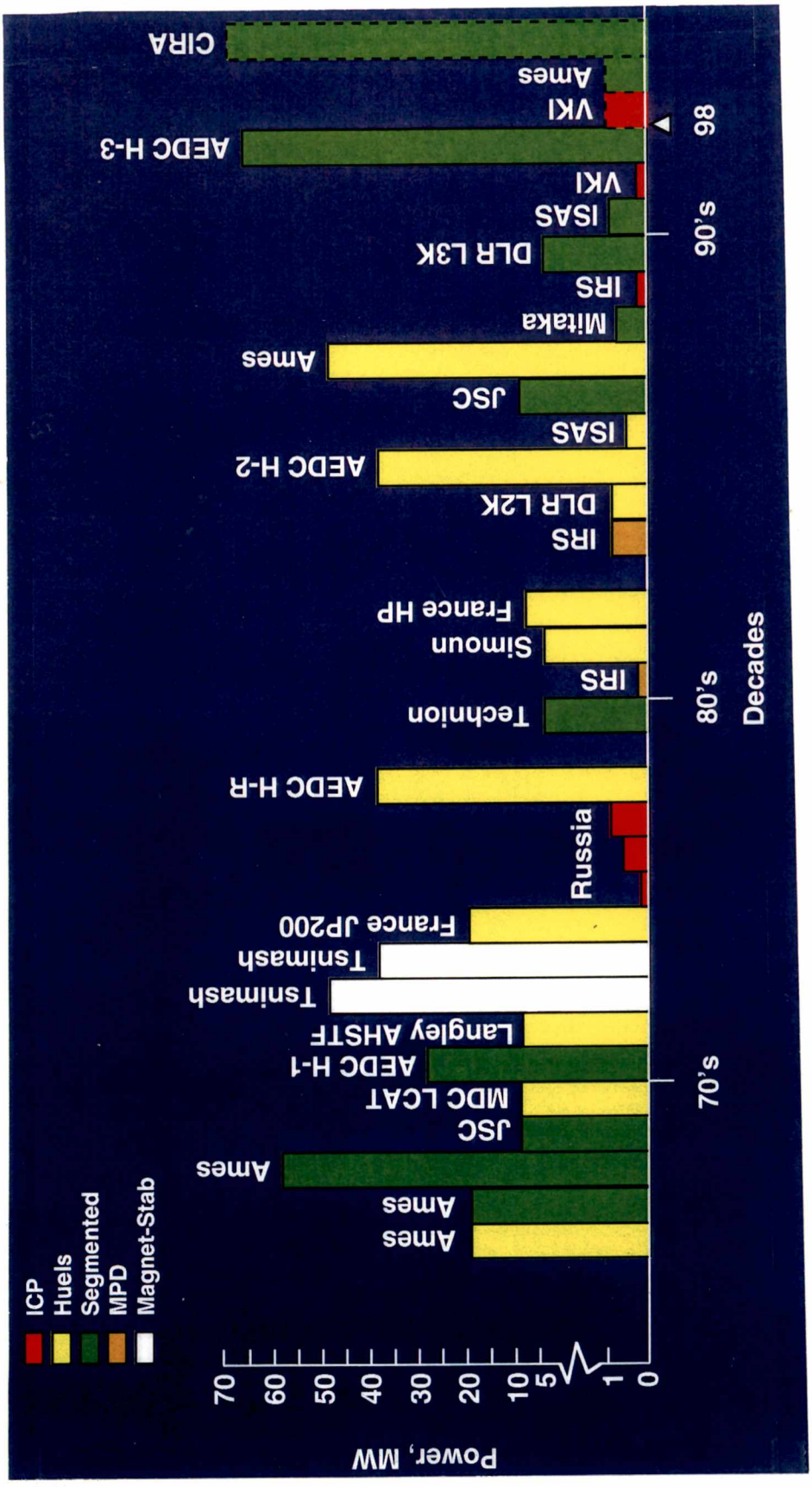


Figure 5 Time History of Aerospace Plasma Facility Development

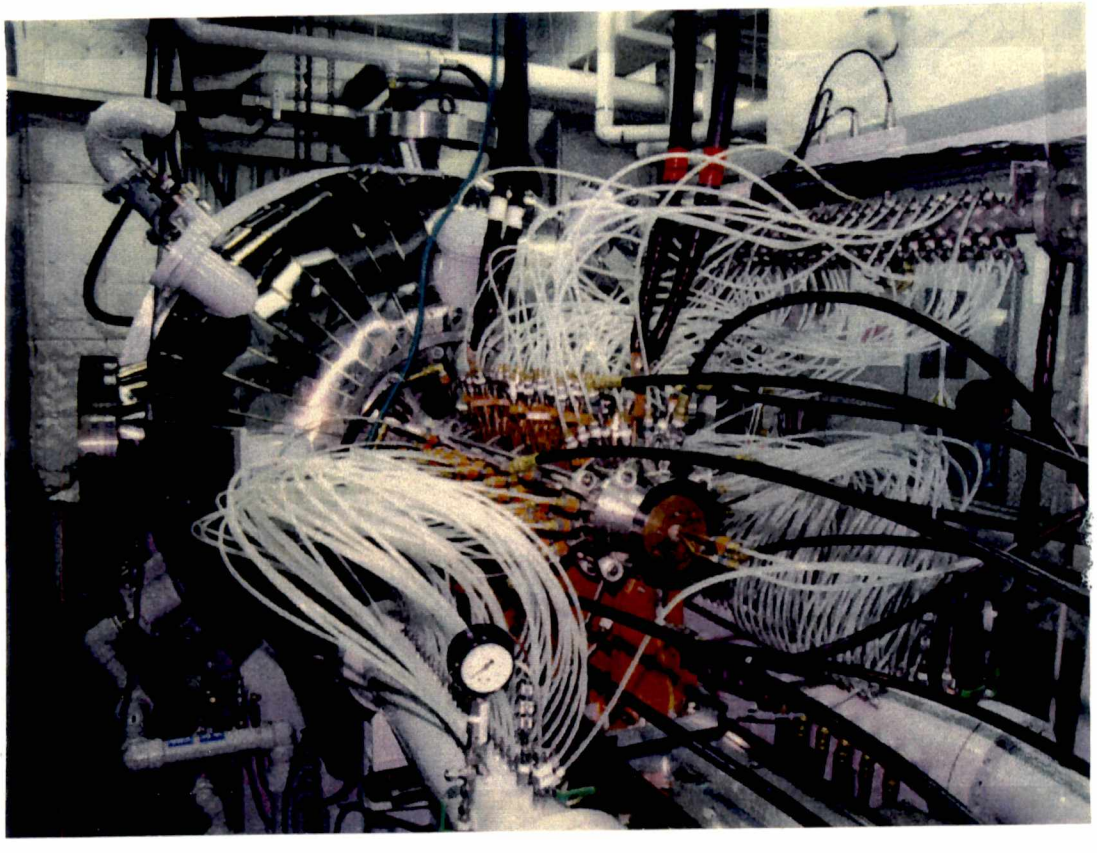


Figure 6 ISAS 1 MW Segmented Heater Facility

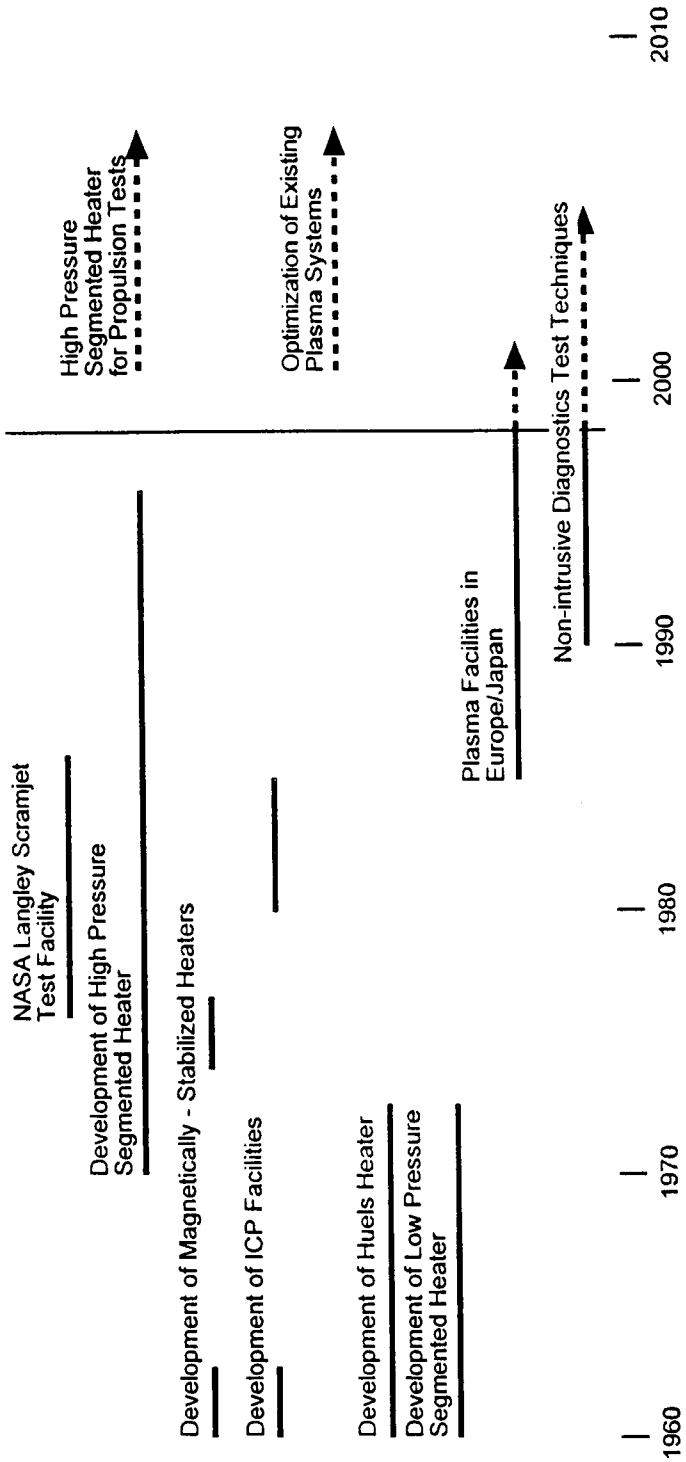


Figure 7 Timeline of Significant Progress in Aerospace Plasma Systems

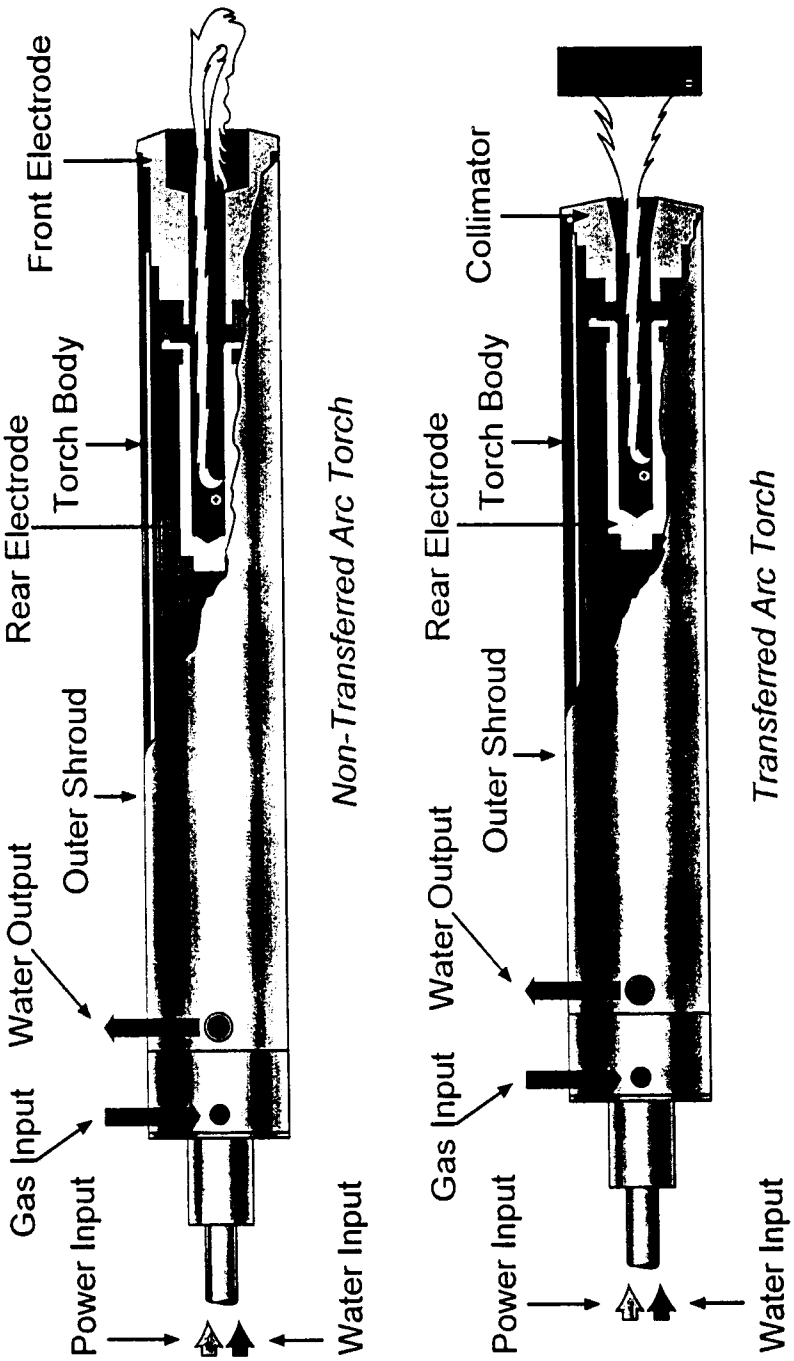


Figure 8 Typical Commercial Plasma Torches

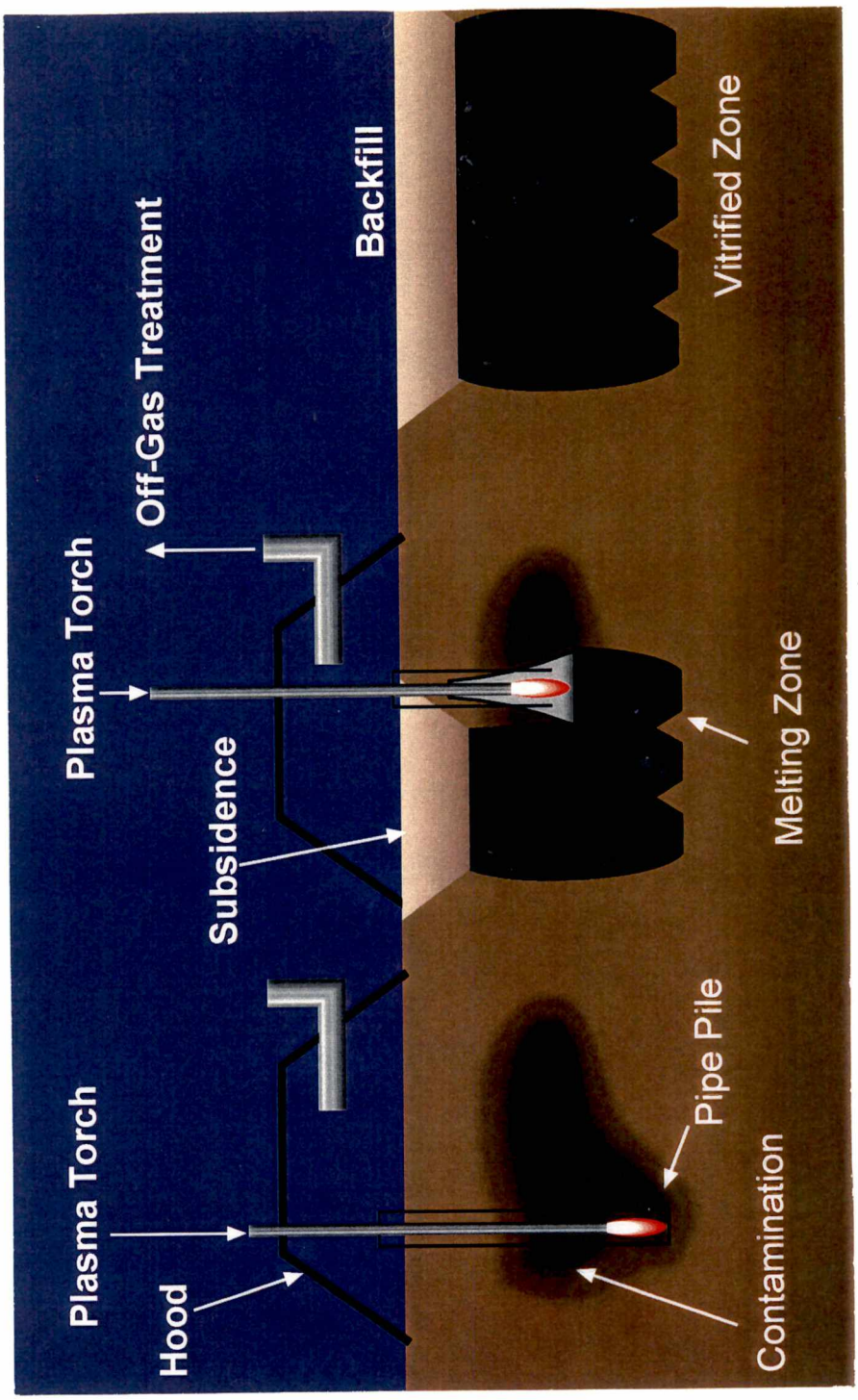


Figure 9 Plasma Remediation of In-Situ Materials

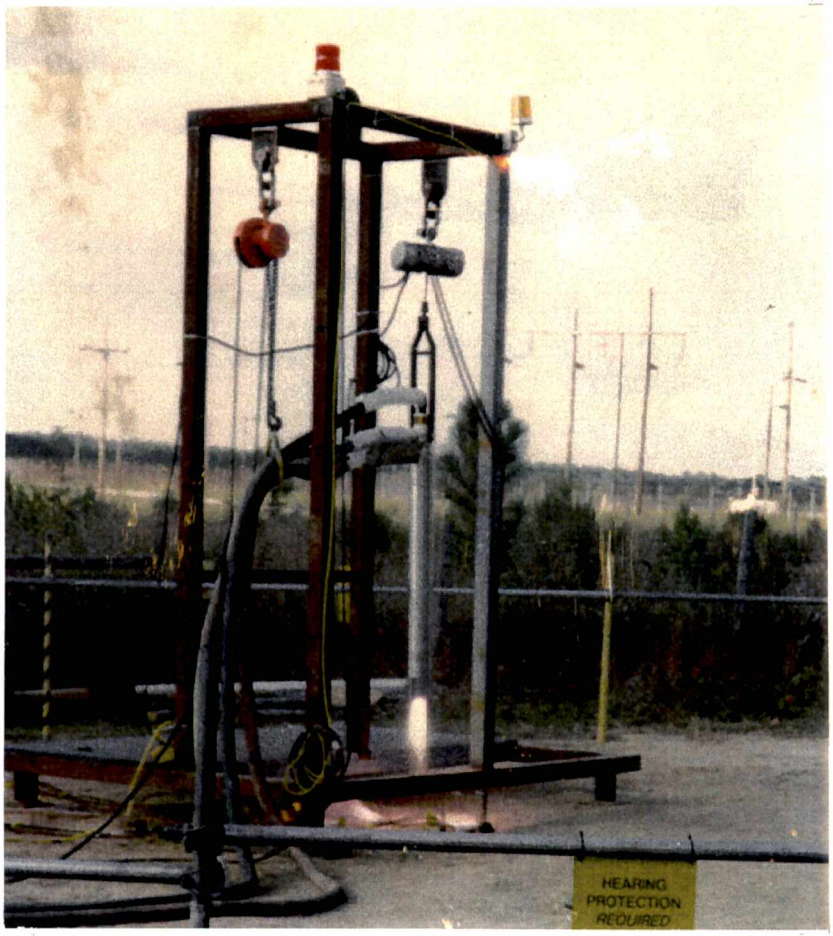


Figure 10 Commercial 1MW Plasma Torch During In-Situ Operation

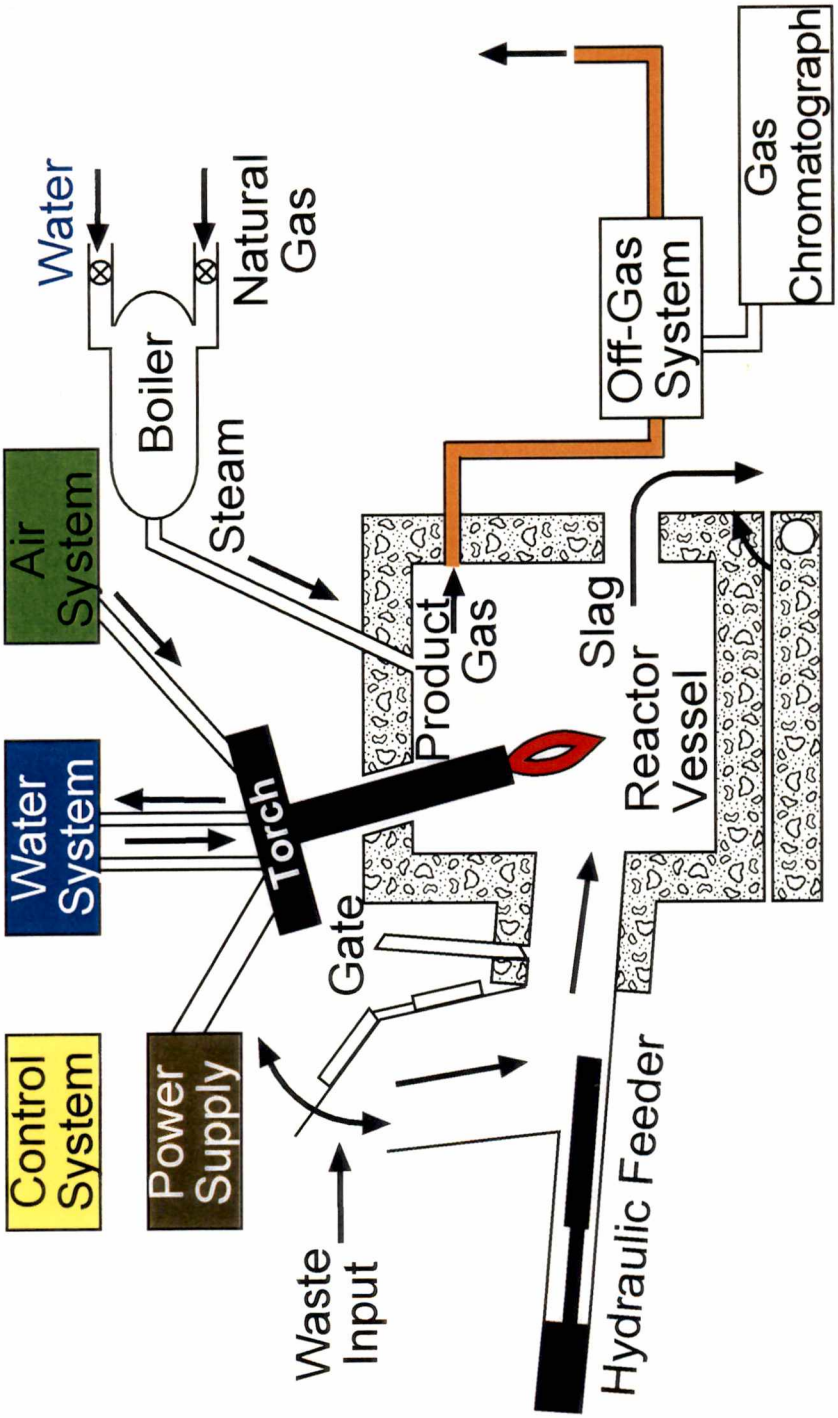


Figure 11 Typical Commercial Plasma System Process Diagram

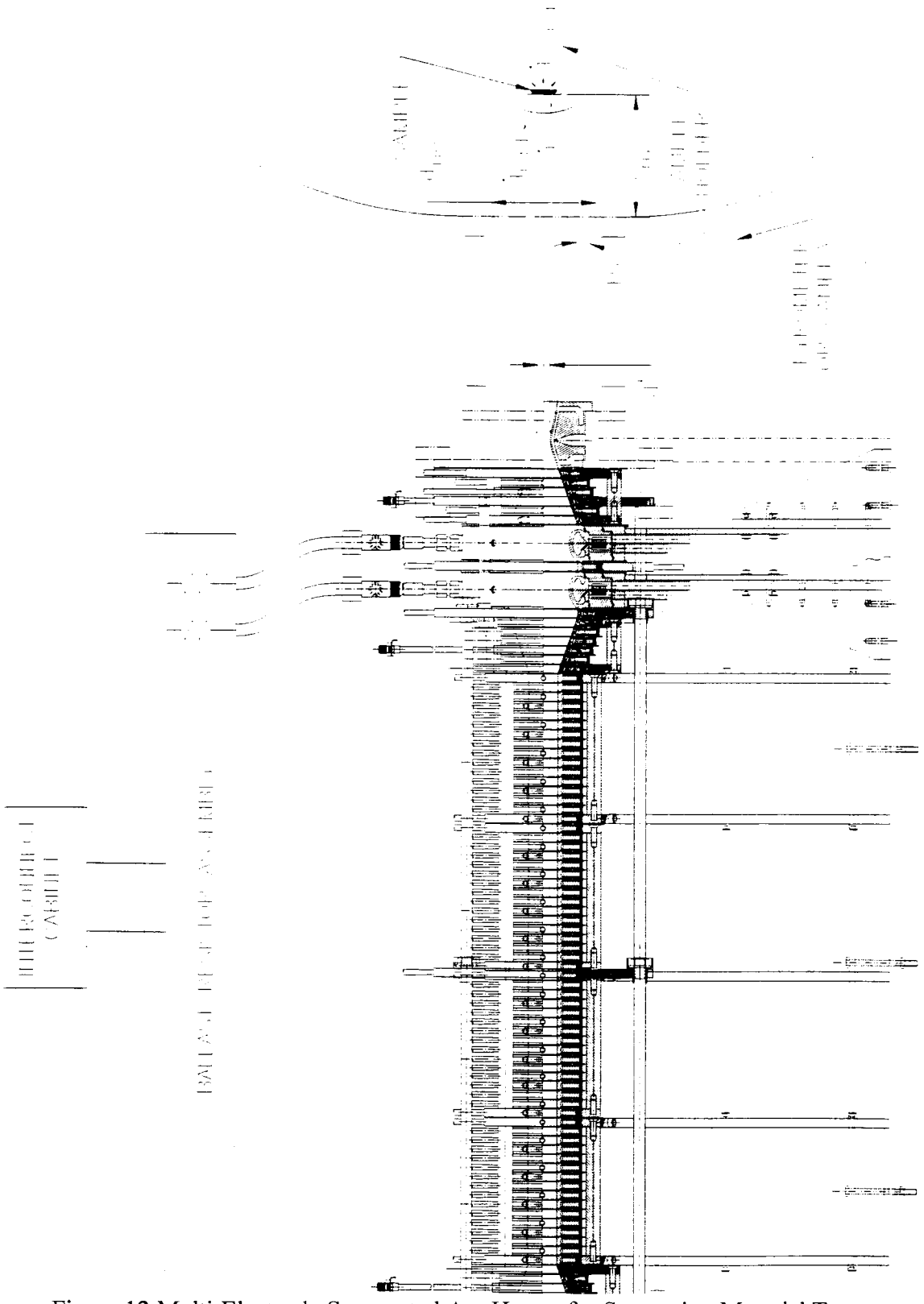


Figure 12 Multi-Electrode Segmented Arc Heater for Stagnation Material Tests

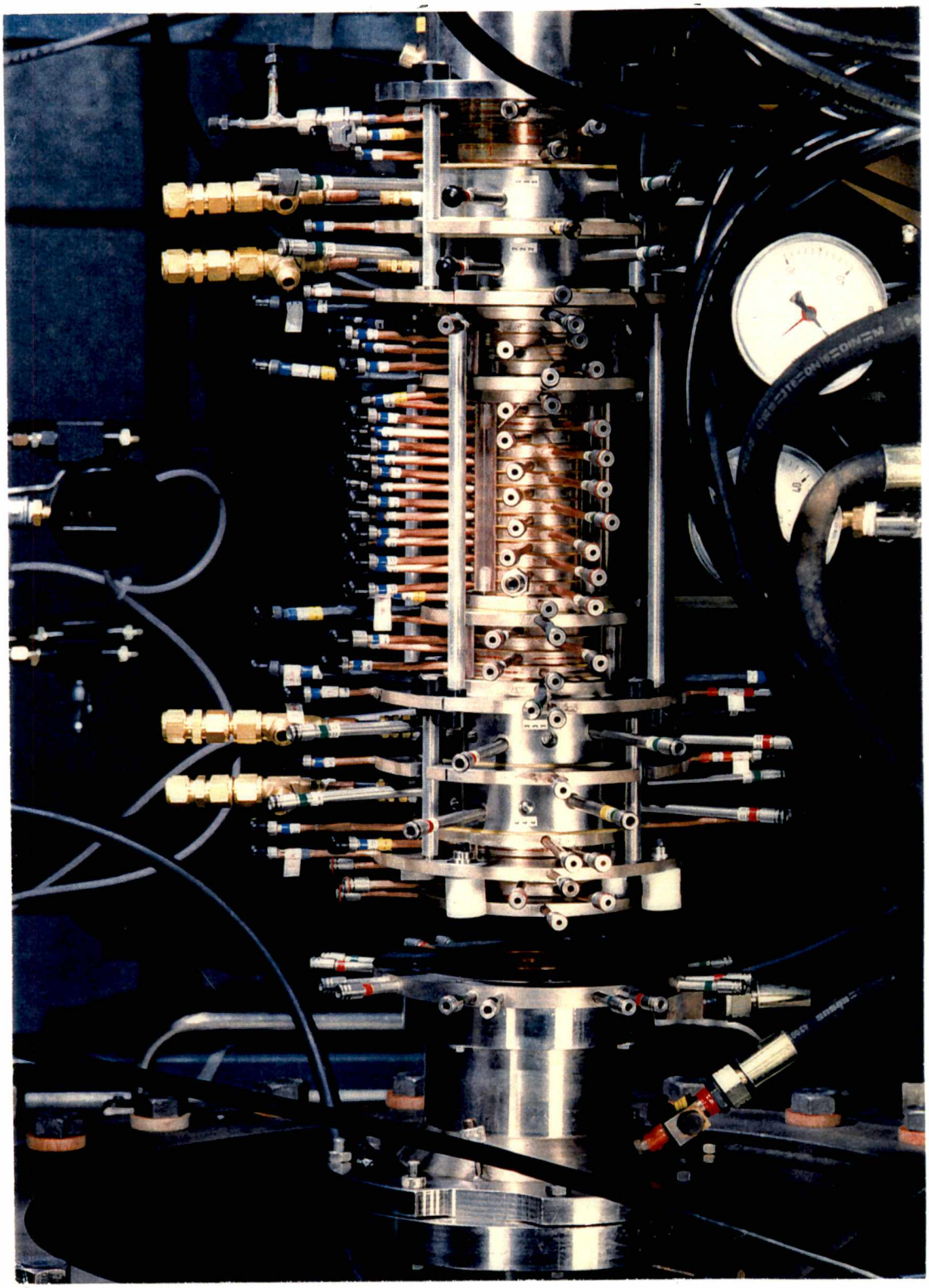


Figure 13 One-Pack DLR Arc Heater

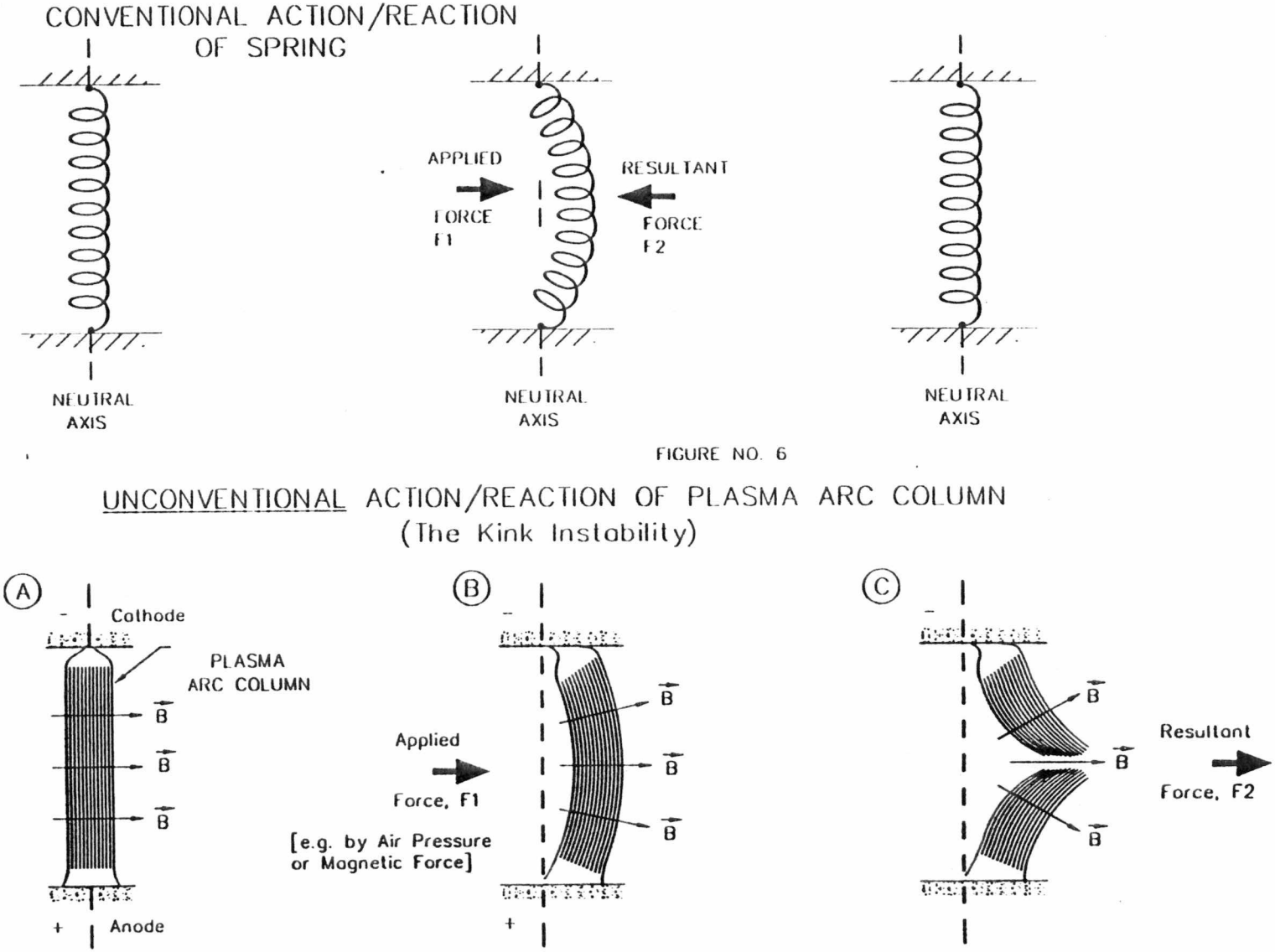


Figure 14 Comparison of Off-Axis Arc Column Behavior with a Helical Spring

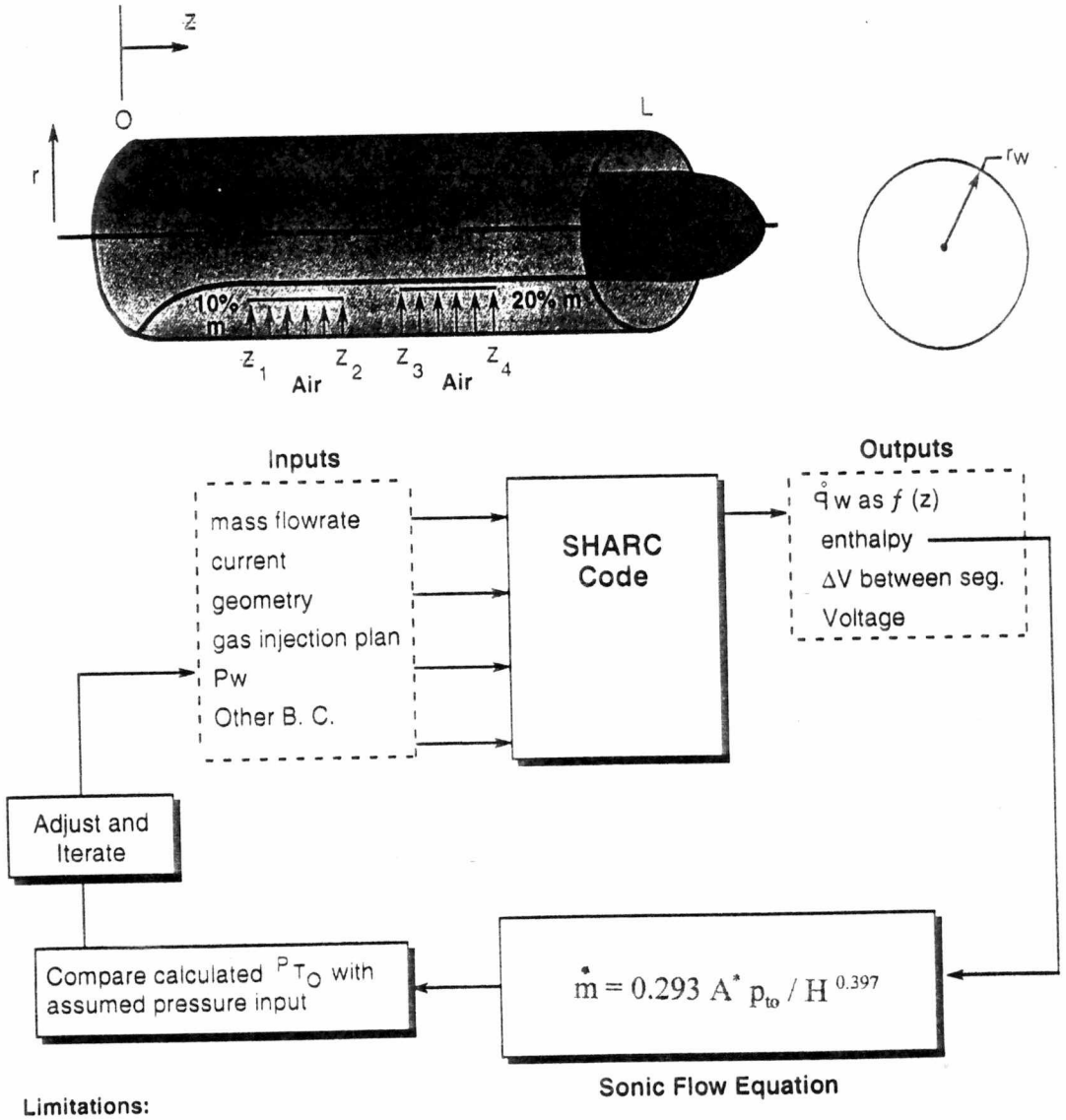


Figure 15 Algorithm for Arc Heater Design using SHARC and Sonic Flow Equation

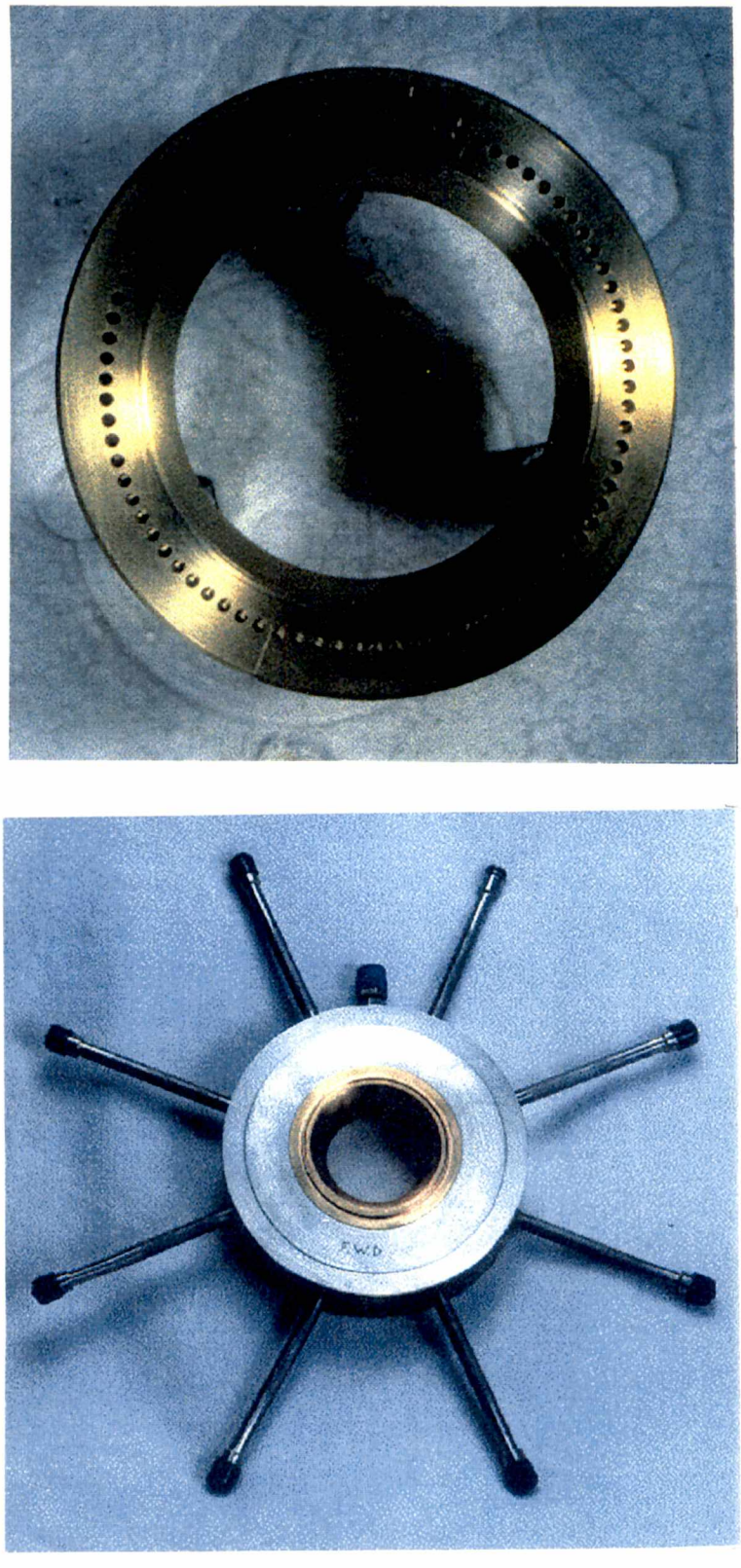


Figure 16 Electrode and Coolant Flowguide



Figure 17 Cathode Liners after Run 6-12A

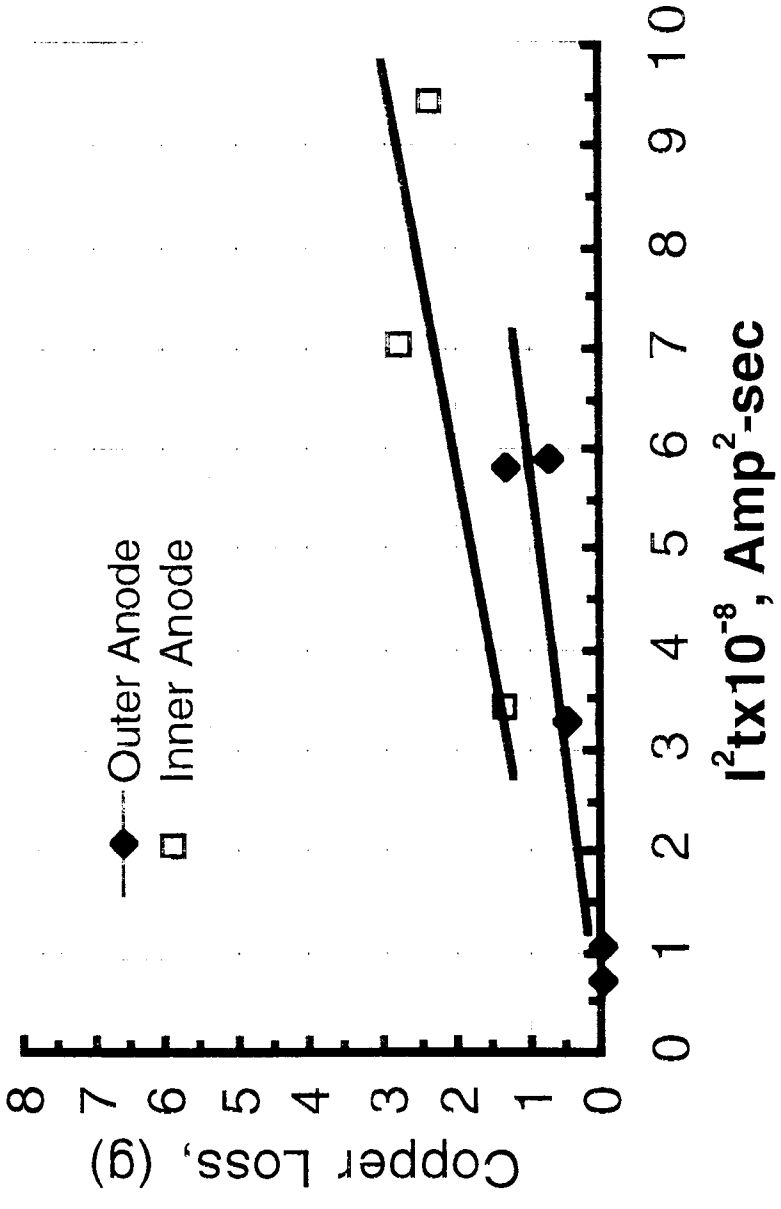


Figure 18 Anode Copper Loss as a Function of Current and Time

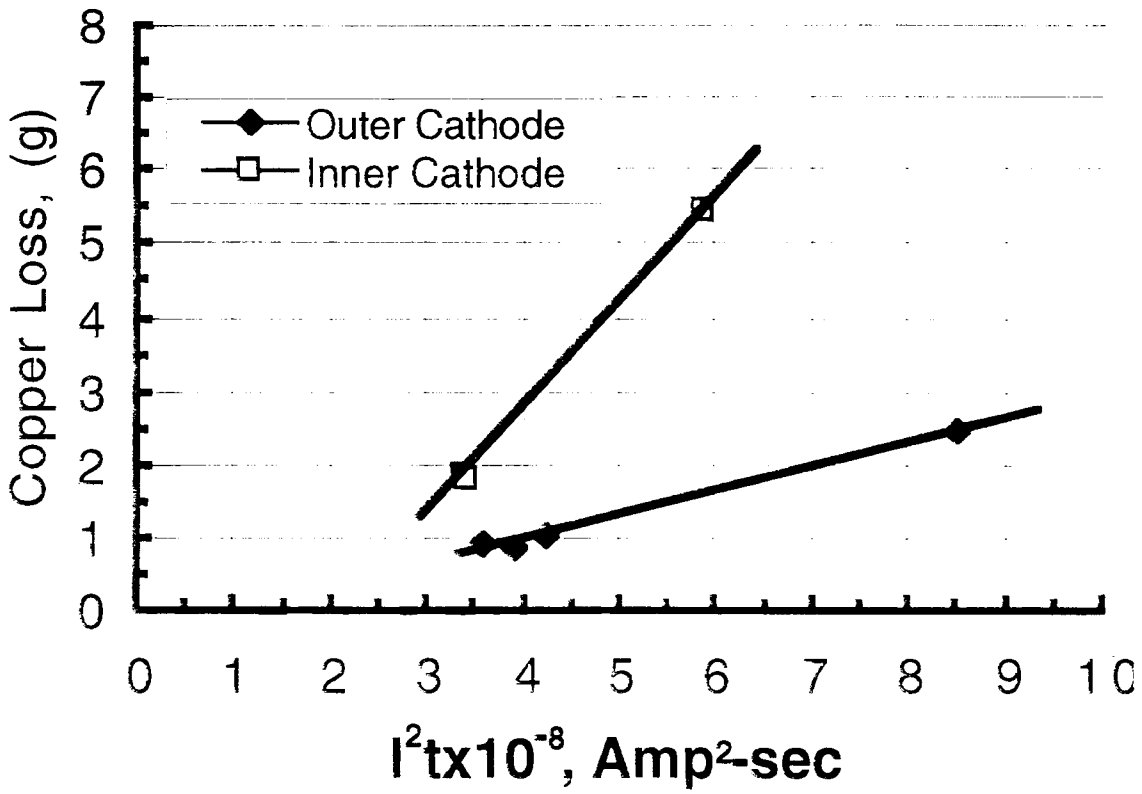


Figure 19 Cathode Copper Loss as a Function of Current and Time

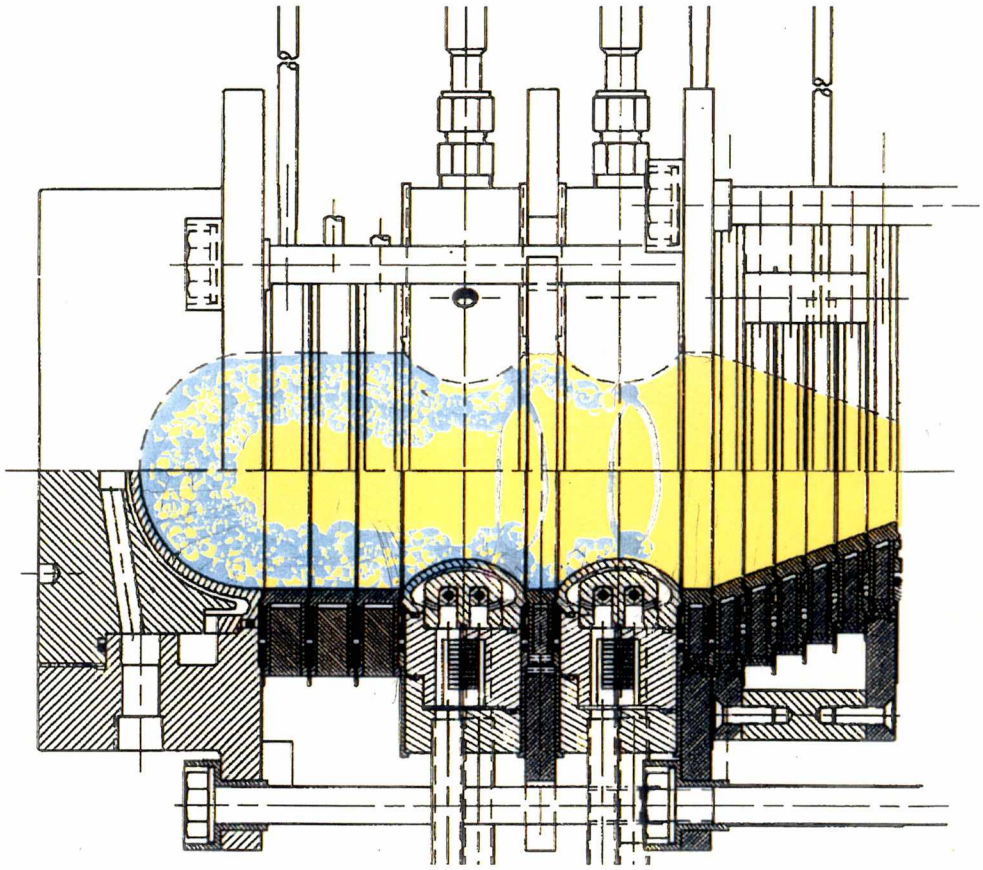


Figure 20 Anode Assembly with Plasma Arc Attachment to Both Anodes

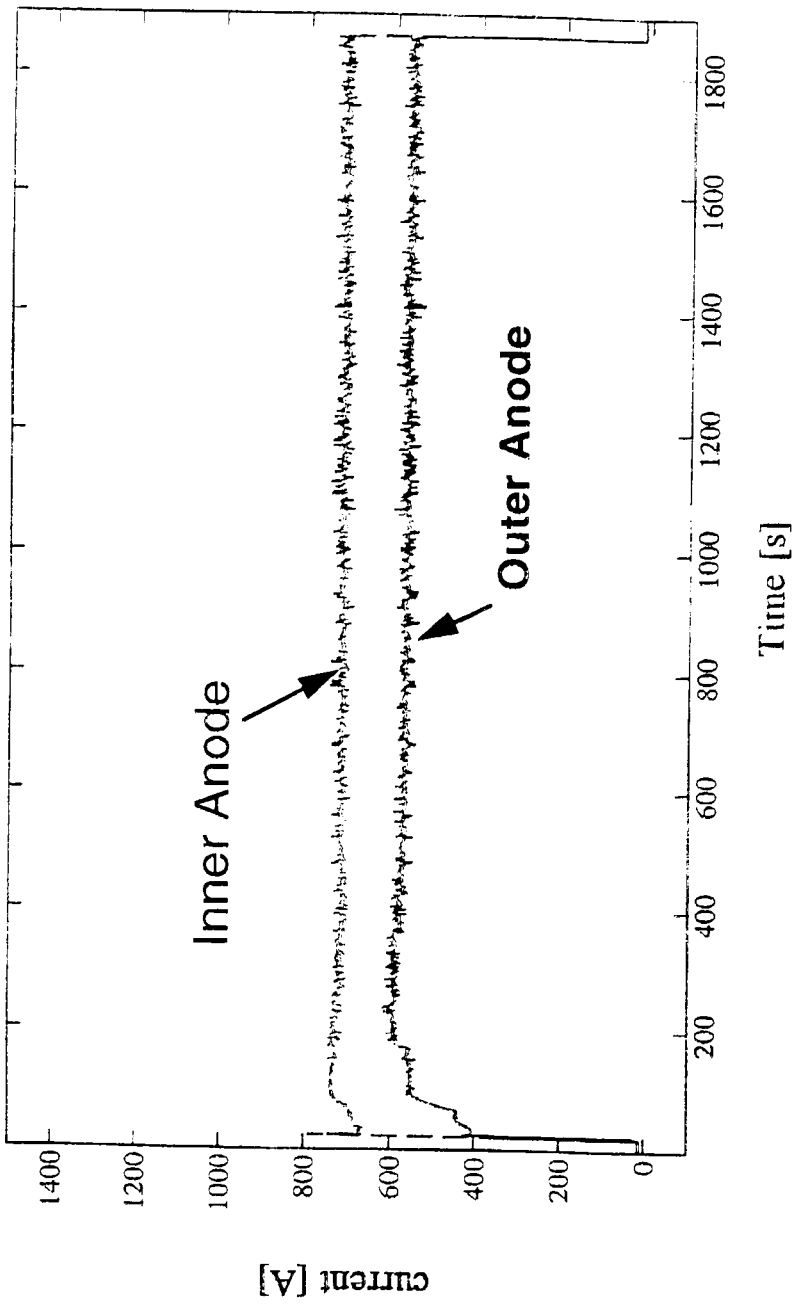


Figure 21 Inner and Outer Anode Current vs. Time for Run 6-17

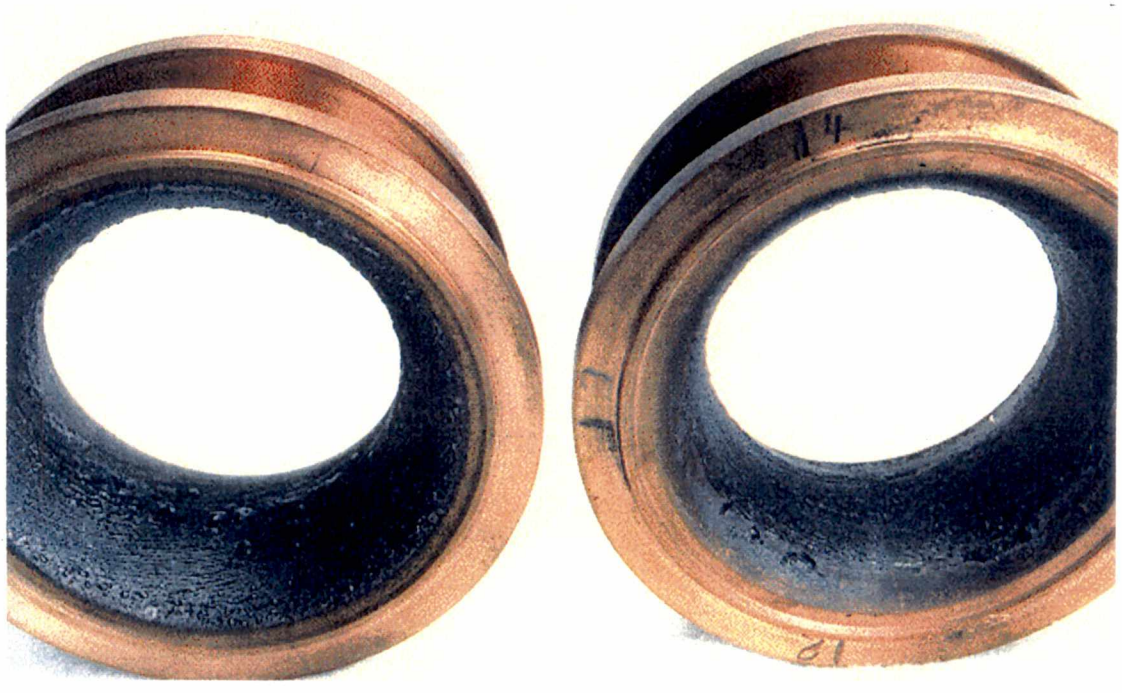


Figure 22 Outer and Inner Anodes after 30 Minutes of Operation

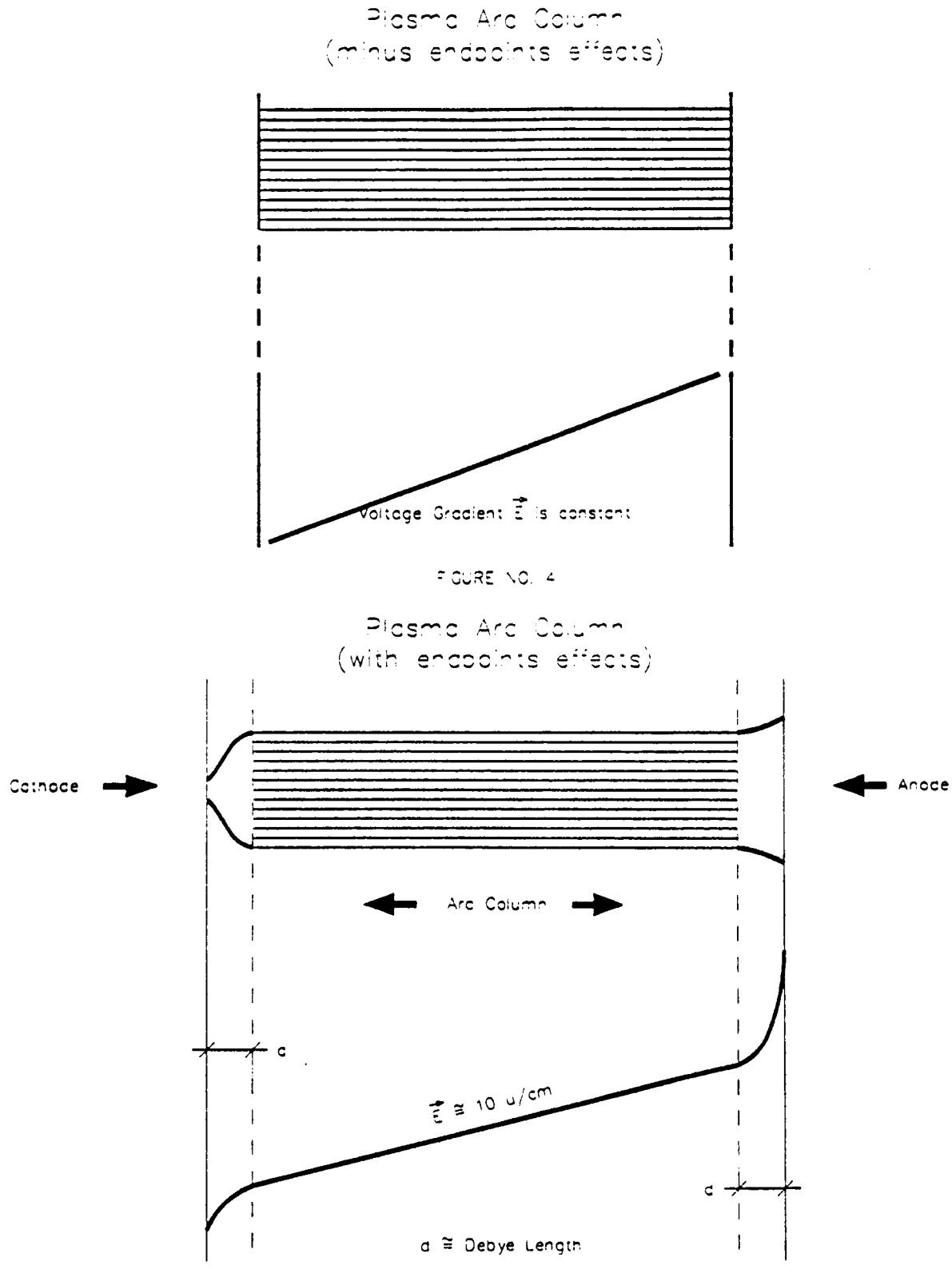


Figure 23 Typical Electrode Attachment Schematic

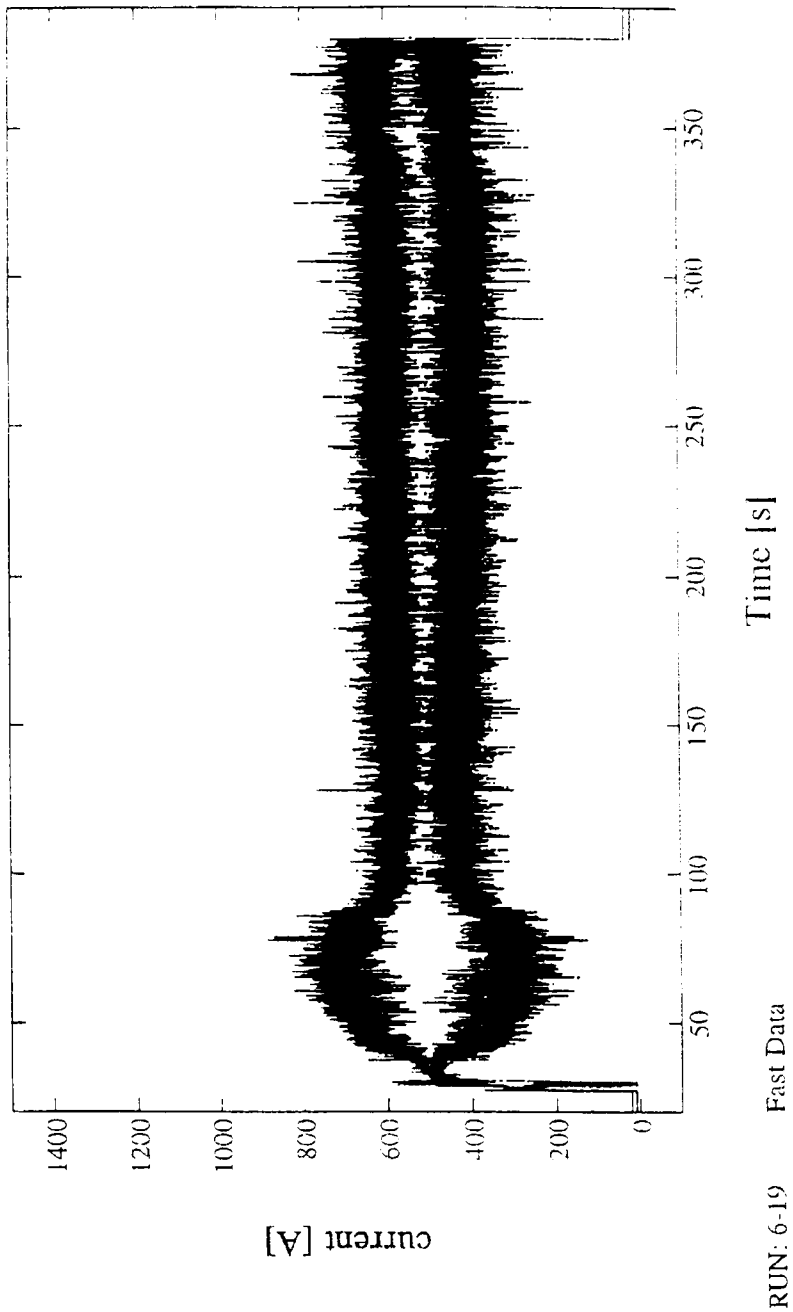


Figure 24 Inner and Outer Cathode Current vs. Time for Operation at 16.5 Bar

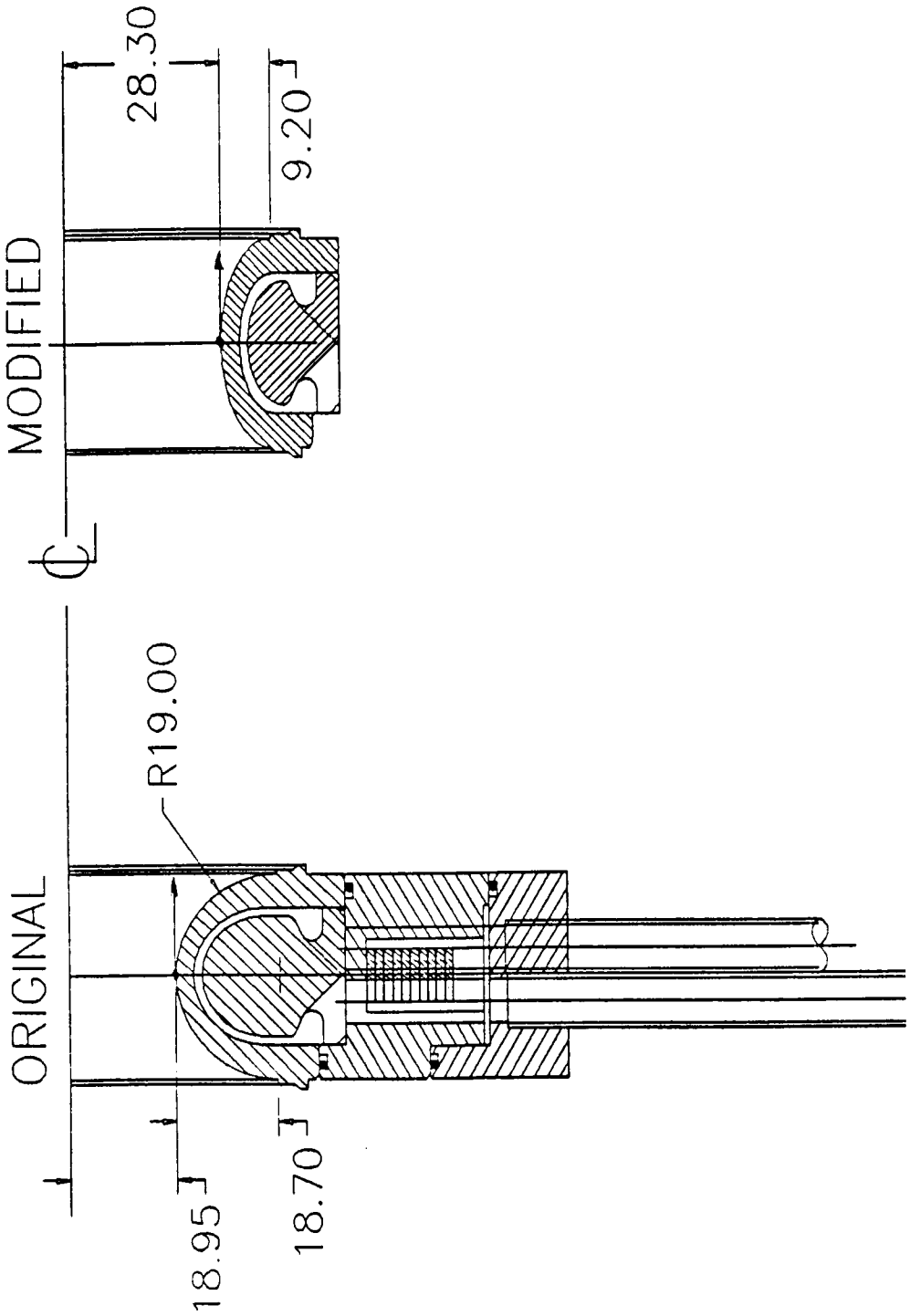


Figure 25 Comparison of Original Toroidal Cathode Liner with Ellipsoid Liner Configuration

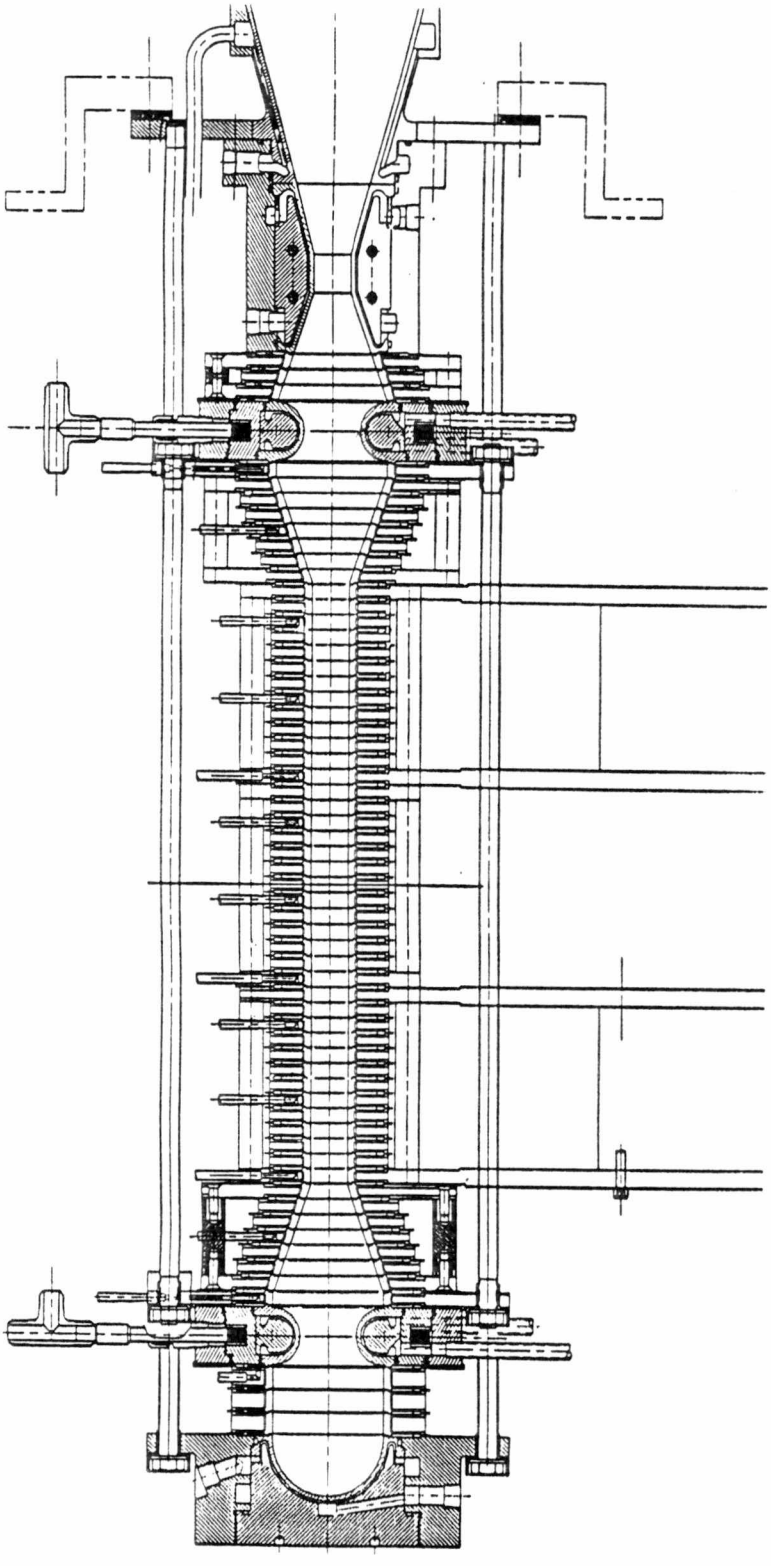


Figure 26 Cross-sectional View of Single Electrode Arc Heater

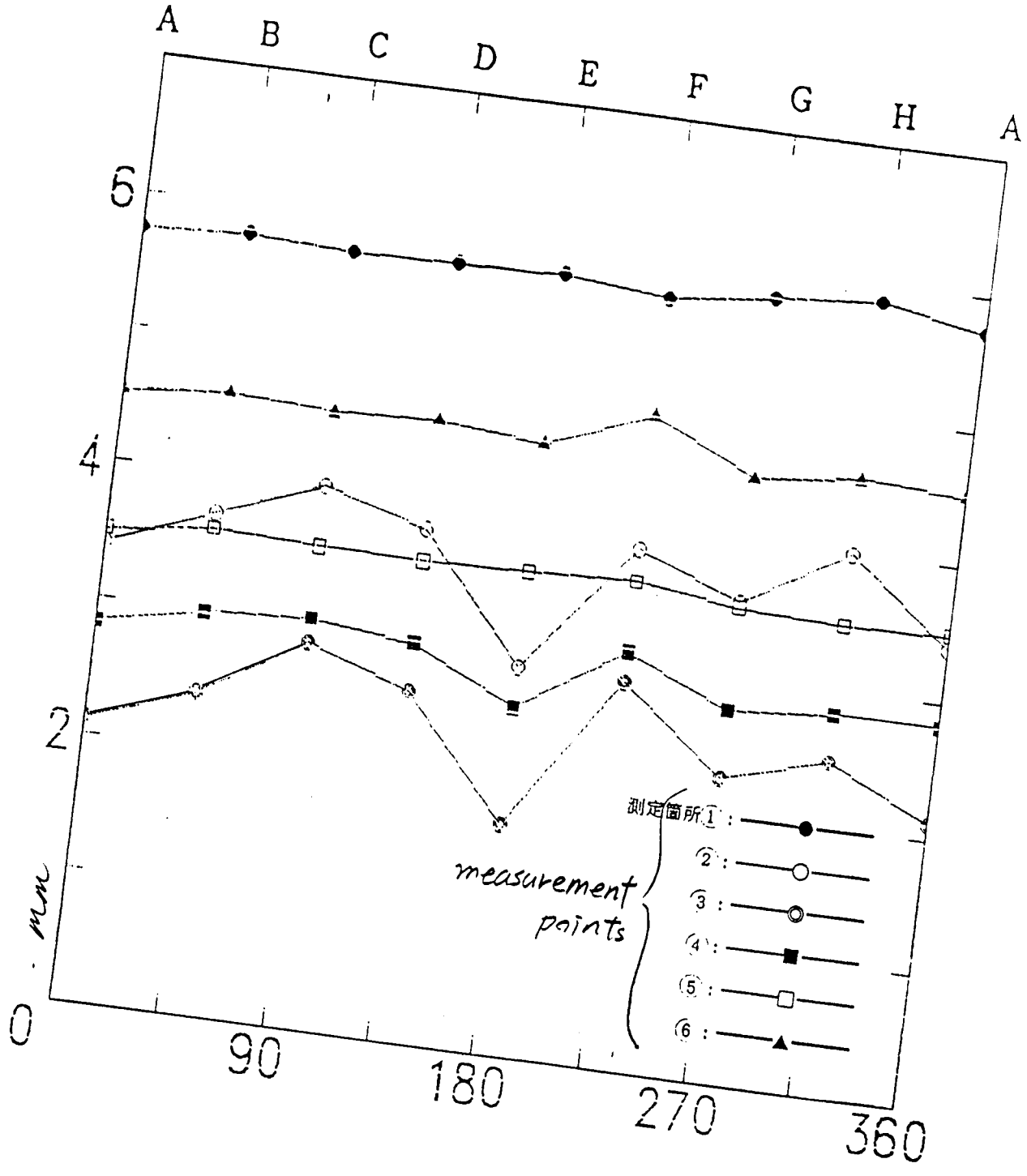


Figure 27 Typical Variation in Toroidal Liner Thickness After 2.5 Hours at 500 Amperes

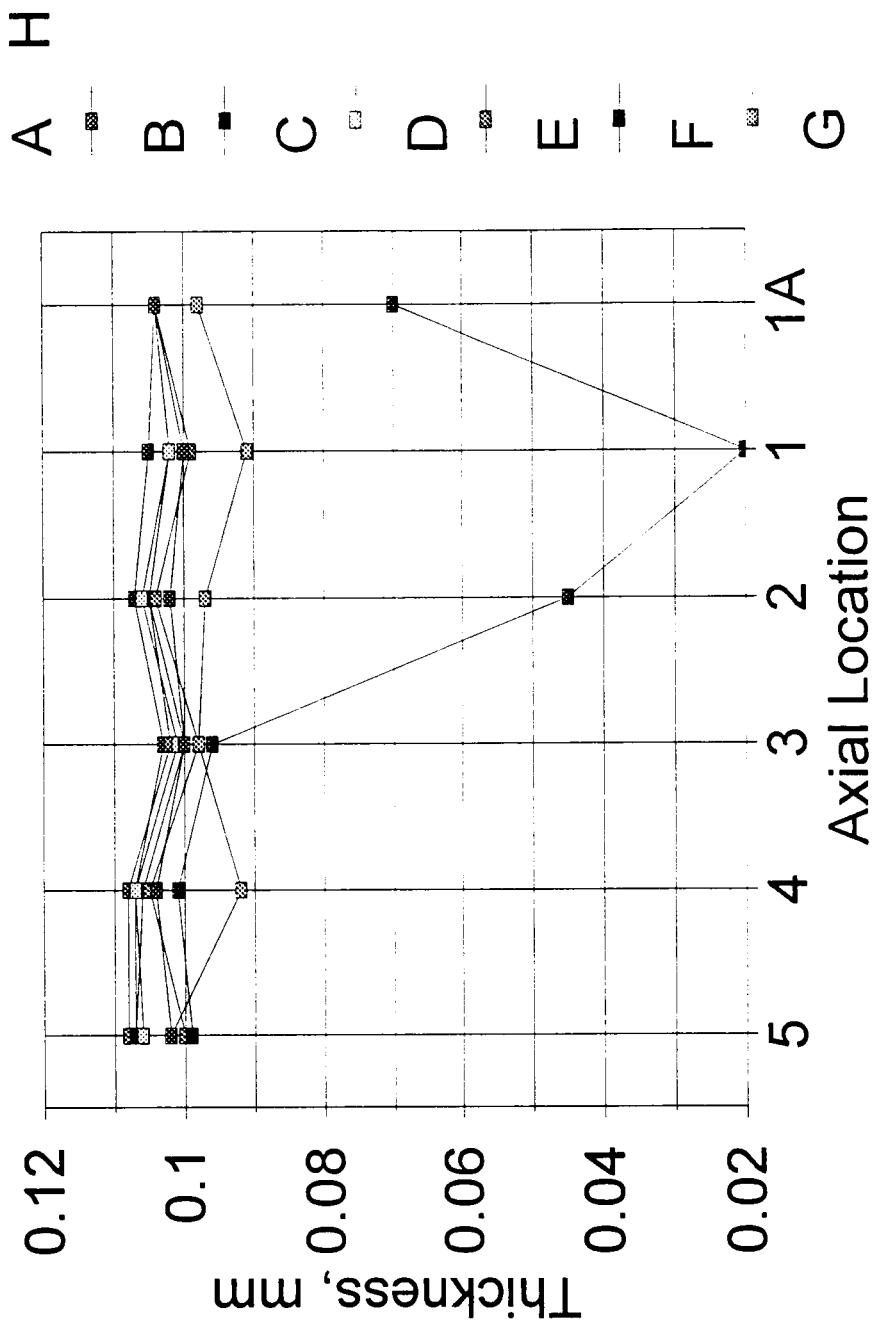


Figure 28 Variation in Inner Cathode Liner Thickness After Run 6-12A

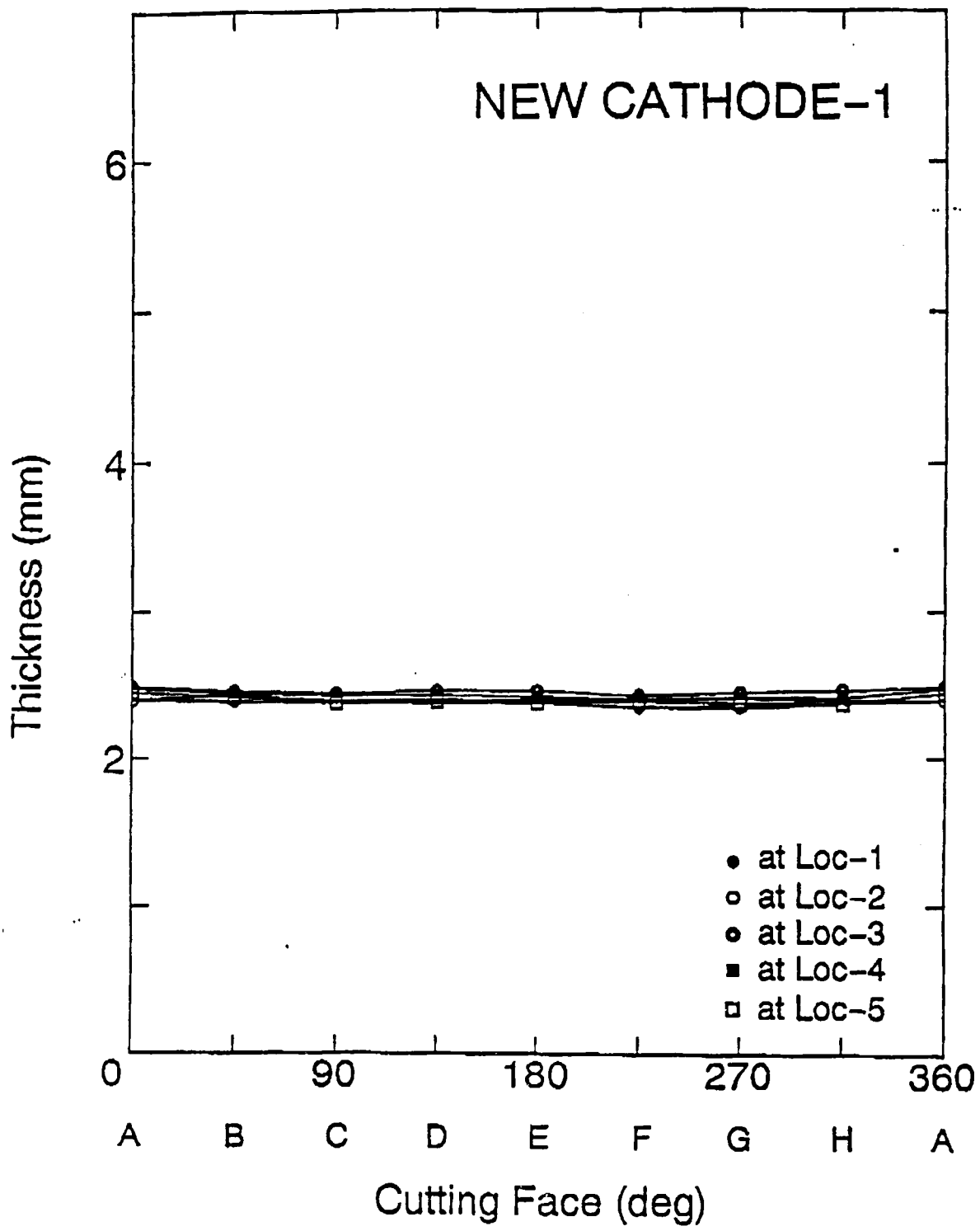


Figure 29 Typical Variation in Elliptical Liner Thickness After 2.5 hrs at 500 Amperes

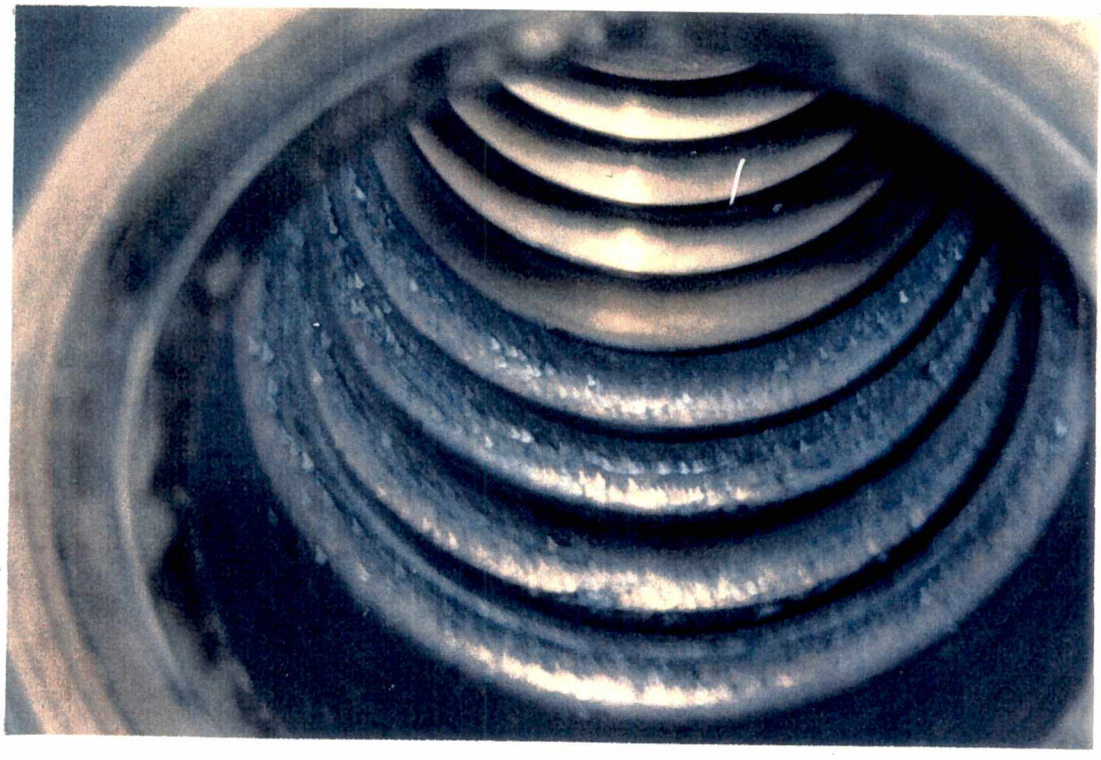


Figure 30 NASA-Ames Electrode Package February 1993

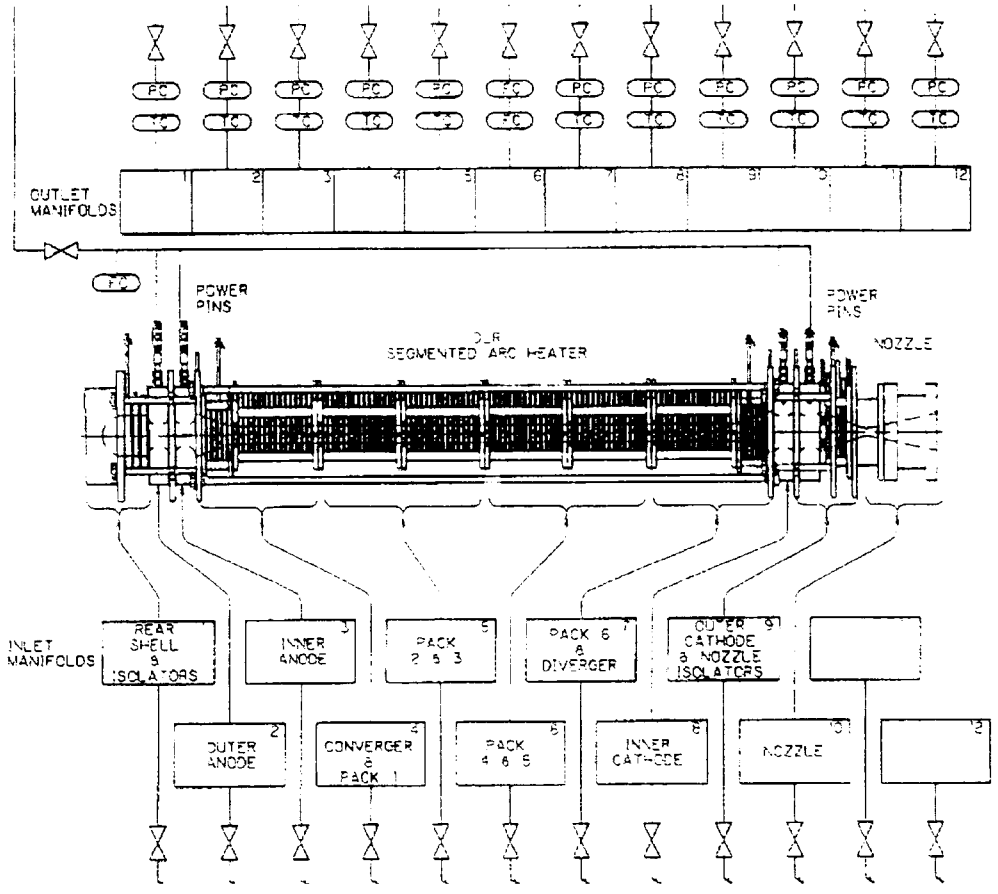


Figure 31 Schematic of DLR Arc Heater and Supply and Return Cooling Water Manifolds

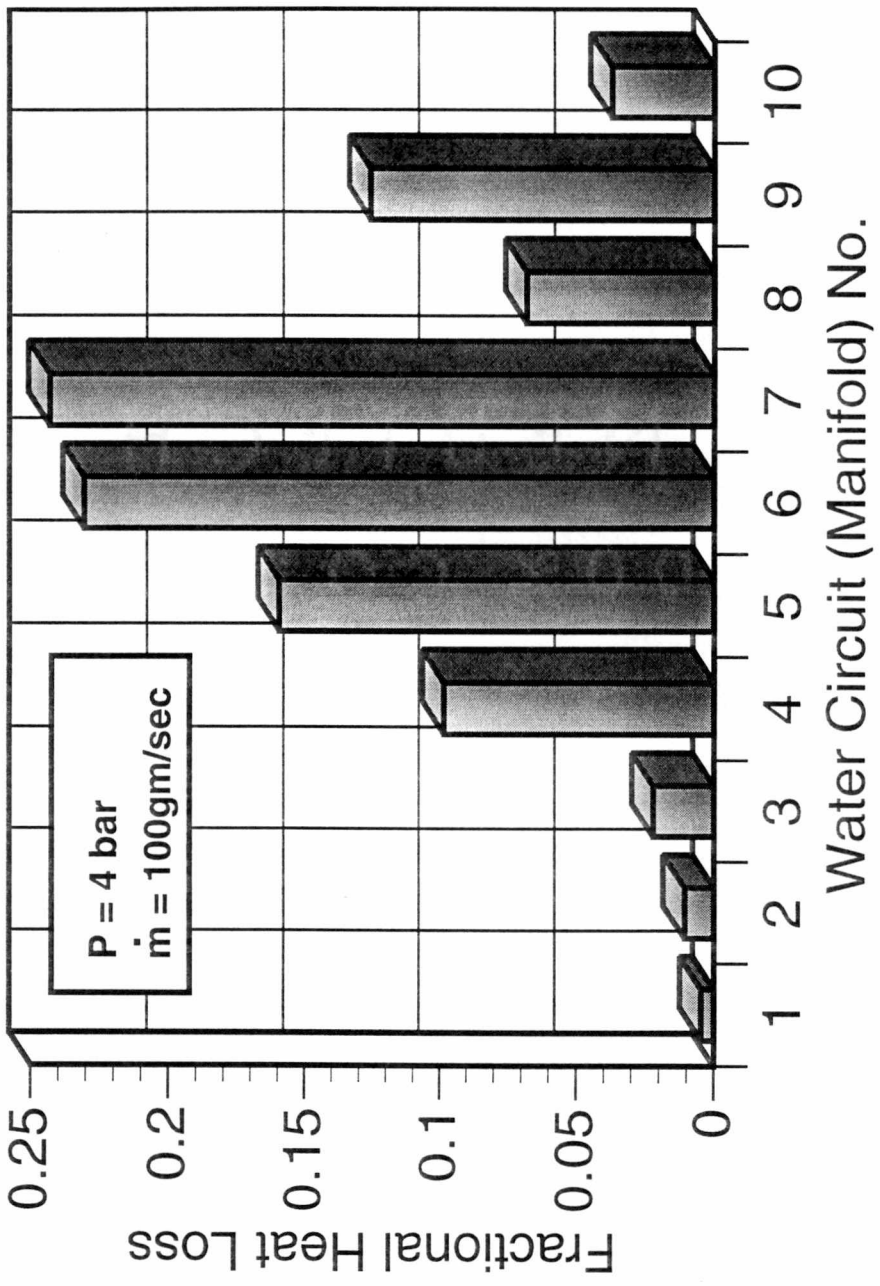


Figure 32 Fractional Heat Loss for DLR Segmented Heater at 4 bar

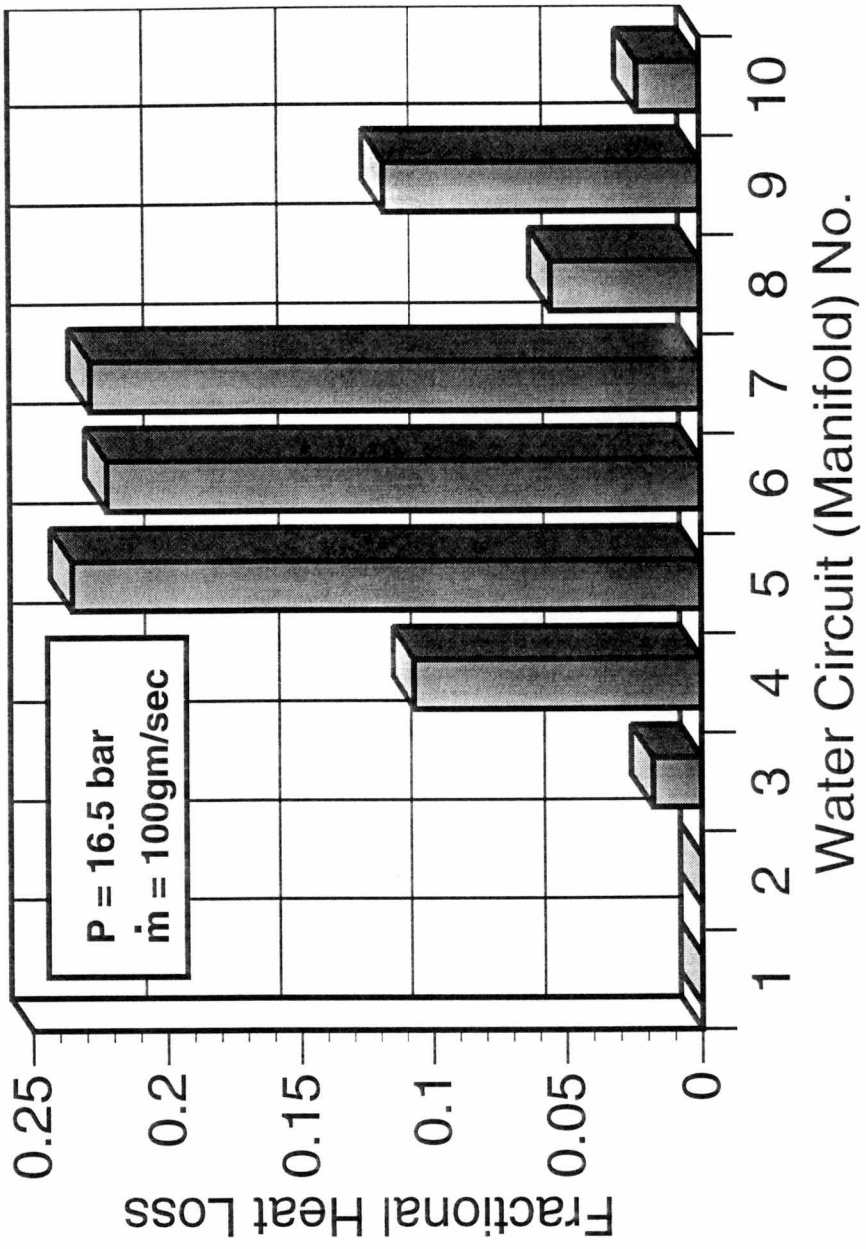


Figure 33 Fractional Heat Loss for DLR Segmented Heater at 16.5 bar

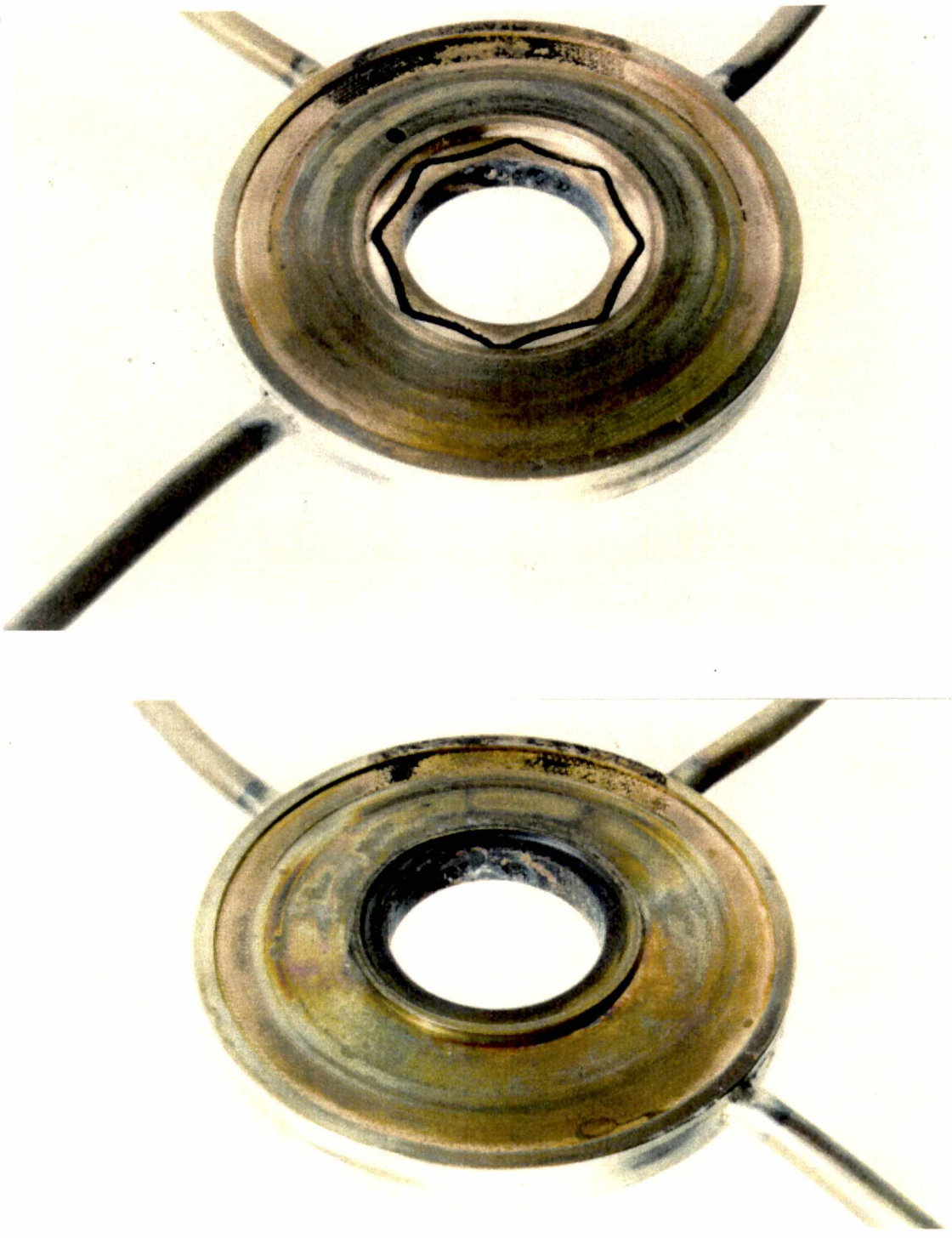


Figure 34 DLR Segment 46 after Failure on Run 6-10R

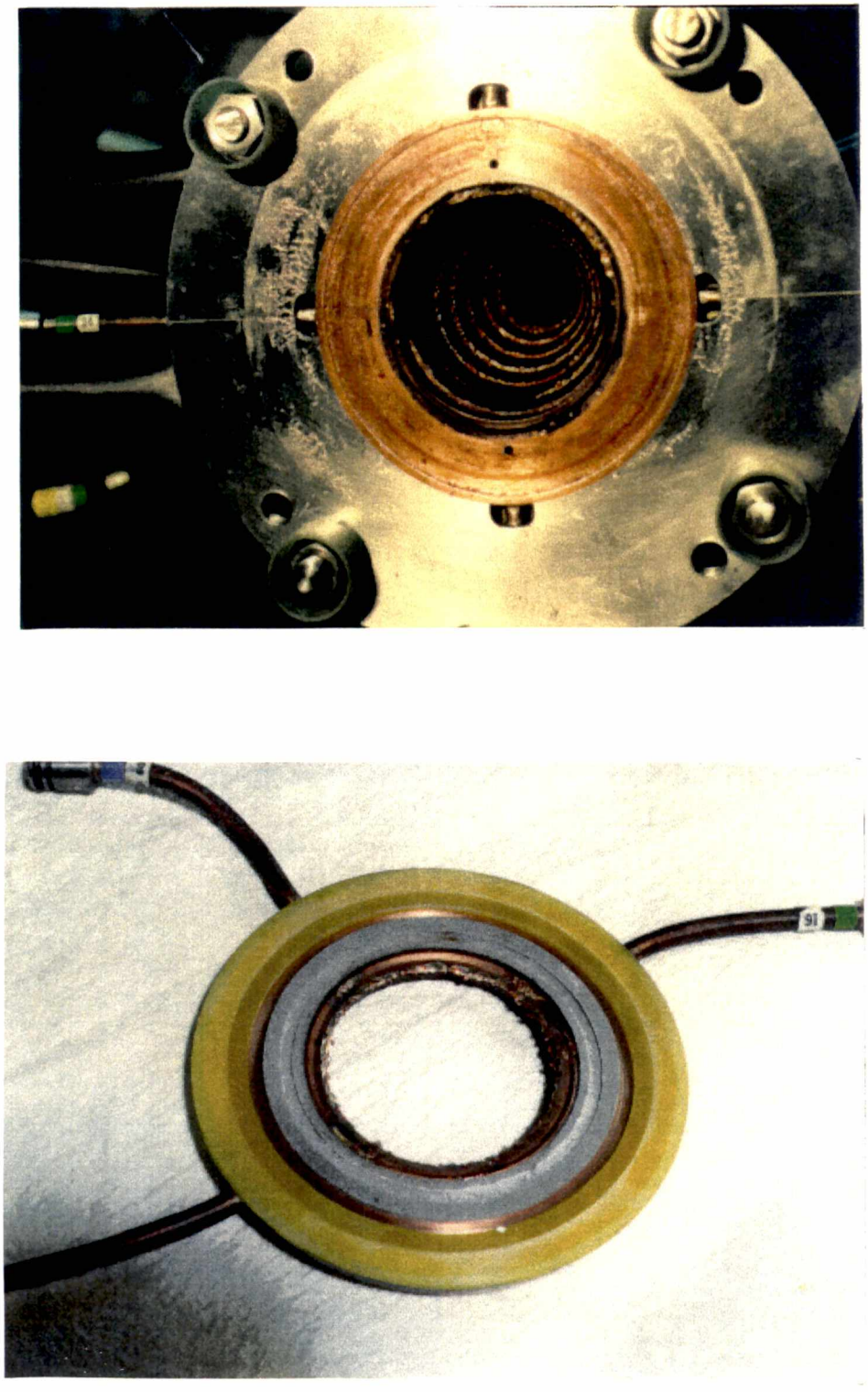


Figure 35 Damaged Converger Package and Segment after Run 6-1A

Appendix B

Calculations

OBJECTIVE:

CALCULATE Critical heat flux for DCR segment 46.

Methodology:

Use empirical Relationship from AEDC-TR-93-3

$q''_{CHF} = 5.1 + 0.00086 \cdot V \cdot \Delta T_{SUB}$

from Van Huff and Rousar. This correlation is valid for the following conditions

pressure: 10 to 2000 psid

Velocity: 7.5 to 205 Ft/sec

init fluid temp: 76° to 470°F

CALCULATION:

Measured flowrate of water was 10 l/min

$\text{Velocity} = \frac{10\ l/min}{\text{Flow area}} = \frac{10\ l}{min} \frac{1\ min}{60\ sec} \frac{m^2}{8.966\ mm^2} \frac{1000^2\ mm^2}{m^2}$

$= 10\ m/sec$

Convert 10 m/sec to Fps: $\frac{10\ m}{sec} / 0.3048 = 32.8\ Fps$

Water pressure = 465 psi on Run 6-10Q

bulk fluid temp = 16°C to 36.7°C

= 61°F to 98°F

Run 6-10Q conditions for segment 46 are consistent with correlation boundaries:

Calculate ΔT_{SUB}.

Assume T_{water} = 20% higher than bulk manifold outlet temperature.

T_{water} = 1.2 × 37.0°C = 44°C (111.3°F)

Then measured water manifold pressure upstream of the flow restriction was 31.5 atm. Measured pressure drop is 12.5 so that best estimate of pressure at the last cusp would be 19 atm.

At 19 atm, T_{SAT} = 409°F

Then ΔT_{SUB} = 409 − 111.3 = 297.7°F

Substitute into correlation:

$$q''_{CHF} = 5.1 + 0.00086 \cdot 32.8 \frac{Ft}{sec} \cdot 298°F$$

$$= 13.5 \frac{BTU}{in^2\text{-}sec} \times \frac{144 in^2}{Ft^2} \times \frac{3600 sec}{hr} \times \frac{3.155 W}{BTU/hr} \times \frac{MW}{10^6 W}$$

$$= 22 \frac{MW}{m^2}$$

Appendix C

1995 DLR RUN LOG

Report from DLR on Monday March 6

I arrived this afternoon and had a meeting with DLR. I inspected heater to confirm that all argon is moved to the back of the heater and orifice is still installed at primary 2.
We ran another cold flow test.
I borescoped the heater. All segments look clean.
Gave DLR voltmeter settings.

Diffuser centerbody
The new design is incorporated. They are worried about hot spots on the diffuser from shock impingement and have installed an air manifold around the diffuser entrance section. Dlr will monitor the outlet temperature from the cooling water effluent. They want to cut the test if the temp rises 30 degrees

Plan is to have a meeting tommorrow at 0900 to discuss changes since the last test.

Inner cathode wear
This part is worn approximately 2 mm near the base of the liner.
I will return to AJTuck for electroplating. Need to provide discussion on cause and prevention for future

Report from DLR on March 7

Summary of the 0900 meeting:
DLR presented changes since phase 4 tests. These include:

- -new vacuum pump
- -redesigned cooling system for the diffuser centerbody
- -argon system change effective for AP #2 tests

discussed the cathode wear. I sent this part to Tullahoma on March 8. please route this part to AJTuck in Connecticut for replating. Return for remachining.

Discussed the redline observor responsibilities. DLR has added thermocouple readout to the diffuser centerbody and will stop the test if temp exceeds 30 degree delta.

DLR has notified me that development testing has begun since we have changed the configuration of the gas rings in the first pack. Development will continue until we reach 3.6 bar in the heater(same pressure as last test 6-7)

Summary of test activity on March 7

Ran tests 6-8b thru test 6-8h. 6-8d was the longest test at 3.2 sec. This test showed that the voltage has increased to approx. 3750 volts. This is a larger increase than

anticipated156 and is in the right direction to solve the performance problem i.e. allows us to achieve A.P.#1 with lower current and lower contamination.

Problem is that the heater is unstable with this gas distribution at the starting condition of 600 amp in 4S*2P configuration. After several attempts we could not find a current regulator setting that would allow the heater to run more than 3 or 4 seconds.

March 8 log

Discussed the results of yesterdays tests with DLR. We will decrease the gas flow into the first 2 packs by reconnecting hose to the last three packs and repeat the 600 amp test with the pre 6-7F current gain setting in 4S*2P configuration. This will make available to us 24 blank fittings that can be used to orifice the pack 1 flow if required.

DLR continues to resist running the power supply in the 8S*2P configuration. There are two problems:

a)warranty considerations if we need to run dc currents greater than 1000 amp please pull the memo from Halmar -Robicon that addresses this issue and fax a copy to the hotel. I believe this memo states that there are no warranty problems if we run continuously at these currents. Please confirm.

b)damage to the facility harmonic filters may occur if we use 8s*1p with arc heater voltage less than 3800 volts.

Test 6-8I ran for approx. 1.5 sec then current went unstable. There was no apparent improvement by this change.

Plan is to run a 75 g/sec test in the 4s*2p configuration and establish best current regulator setting. This point should be far enough away from the power supply stability limit to allow stable operation. Then go to 8s*1p and run for less than 30 sec.

March 9,10 log

no testing due to K. Smith illness. Went home after lunch on Mar 8

March 13 log

ran test 6-8K. Test ran for approx 1.5 sec. in the 4S*2P configuration. this test was intended to be at 75 g/sec but actual flow was higher due to the facility bypass system.

ran test 6-8L. Test ran for approx. 2 sec. in the 4S*2P configuration. We started with 700 amp for this test but result is still the same. current oscillations are too high

ran test 6-8M. Same test as above was planned except power supply was changed to the 8S*1P cofiguration. Test ran for less than a second. arc was extinguished due to current oscillations. An external arc occurred between the contrictor pack tie rods when power supply went to open circuit voltage 10,000 volts.
Based on video and the photocell the heater appeared to relight for a short time period.

Results of borescope inspection
there is some relatively minor signs of copper displacement between the IES and the anodes. Anodes and cathodes both show signs of fresh copper removed(probably due to the 700 amp starts)
there is a surprising amount of copper flow on the flange segment upstream of the inner cathode.
In general the internal surfaces of the heater look acceptable with dissasembly and cleaning.

March 14 log

1)as of noon we have finished dissasembly of the heater and are photographing all of the damage prior to the cleanup. two anode liners and the IES were sent to the shop early this am. these are available for our use later today. Other parts that must go to the shop include the cathode IES, liners, and M13-2. The radiation shields on some of these parts will be slightly diinished when rework is complete

transferred two new liners and an IES to DLR so that the buildup of the anode assembly could begin. This is in work prior to lunch.

Orifices of 0.5 mm diameter are being machined for the first pack. These will provide a flow that is similar to December test series. As of this time we only have available 7 orifices. We are looking for others. we need 16. An order for 16 additional blank fittings should be placed with ESPE today. I sent him a request for quotation. DLR is building more also.

we looked at the pulsations in the gas flow. there are approximately 15 cycles in 1.5 seconds during test 6-8M. These pulses grow larger in amplitude as time progresses.

we are looking at the rise rate of air during start.see attached plot. would like to decrease the rate of rise for next test.
need discussion on attached requirement to bring the air up within 1.5 sec

cathode assembly is in work

March 15 log

Diverger and converger assemblies were also dissassembled to replace damaged retainer rod and to clean the parts. Reassembly and retest of these are in work. Work to be done includes assembly of the heater and retest. We will make a pressure test of the heater at 20 bar to insure that there was no damage to o-rings or internals of the hoses.

Based on current rate of progress we will be ready to begin again on Friday morning.

We had a meeting to discuss the next test. We will install the orifices and return the heater air distribution to the 6-7F configuration. After a sucessful run we would gradually remove orifices from the first pack to increase the voltage in the heater. With each removal of orifices we would adjust the facility air system to reduce the rate of increase of air flow into the arc chamber during start.

received a memo from DLR

March 16

responded to DLR memo

gave DLR new gas distribution and run sheet with interlock settings.

heater has been reassembled and leak checked. M13-1 has a water leak. we will replace it with a spare. The requested dial has been installed on the power supply
orifices are being drilled

March 17

we took two parts to the shop for repair of leaks-M13-1 and M13-3
DLR told me that this is the first day of development that Sverdrup must pay for. They gave me a form that provides a way to keep track of costs. I gave them a memo that provides groundrules for the development time period
orifices have been installed and all pretest checks have been made as of 1300. The required air manifold pressure is a function of the water manifold pressure-same as December. they say this was not true for the tests performed earlier this month.

ran test 6-9 for approximately 8sec. test was terminated by INITIATION OF INTERLOCKS. Voltage measurement did not perform correctly from the beginning. Prior to the beginning of this test we the power supply had a reoccurrence of the

ran test 6-9A for 26 sec at 1000 amp and 100g/s.removed two of the 0.5 mm orifices after this test

ran test 6-9B for 4.5 sec. test ended when voltage measurement went to zero for one

sample rate

ran test 6-9C (same conditions as above) for 50 seconds. test ended as the current was increased to 1050 amp because of current oscillations. O'scope was not connected properly.
ran test 6-9D for 102 seconds. sucessfully increased current to 1235 amp and achieved >3.6 bar in the heater. Adjusted the gain of the power supply to approximately same location as last December. Development test period is finished with this test.

borescoped the heater.everything looks ok except that the arc attachment zone on the inner cathode is too close to the u/s face

March 18

had a meeting with DLR and discussed the next test. We will restore air to the diverger and argon to the u/s face of the cathodes in an effort to adjust the location of the arc attachment on the inner cathode

ran tests 6-10-had to adjust the gain because arc did not start
ran test 6-10A for 35 seconds 6 orifices were removed
ran test 6-10B for 84 seconds with 10 orifices removed
ran test 6-10C for 84 seconds with all orifices removed
borescoped the heater at this point-the arc attachment zone has moved to aft of the center on the inner cathode. I do not think the erosion region on the upstream face is larger

ran test 6-10D for 99 seconds with every other hose removed from the last three packs reached 3.8 bar by increasing the current to 1400 amperes

installed 0.5 mm orifice at the prim 1 location and ran test 6-10E for 185 seconds. reached 3.92 bar(acceptance point #1) by increasing the current to 1600 amperes

voltage for all of these tests is only 2980

March 20

reviewing data.have asked DLR to give us 2 larger(0.8 mm dia)
orifices for use at prim 1/2/have also asked him to measure the torque on the tie bolts and to increase the torque 20 to 25% before next run/we are looking at the resistor setting for the anode in an effort to get a more even split between anodes

tie-bolt torque was only 2.6 n-m. we measured air manifold pressure to achieve 100 g/s with and without water pressure. results were:
without water pressure-16.4 bar

with water pressure -20.6 bar
torqued the bolts to 5.2 n-m and repeated air tests.results were
without water pressure-19.2 bar
with water pressure -22.0 bar
torqued bolts to 9.2 n-m(approx.80 in-lbs) and repeated air test
without water pressure-21.7 bar
with water pressure -22.8 bar
this condition is reported by DLR to be consistent with the heater configuration that we had for the March 7 test

March 20 (cont)

measured resistances and performed limited megger tests after torquing-found one low resistance-anode to M13-1 cleared this with air flow all resistances are good

we asked DLR to delay the initiation of air flow approximately
0.2 sec so that the voltage can reach a higher value prior to the intiation of air flow.this should decrease the need to adjust the power supply gain during each run

ran test 6-10F for 50 seconds to measure the effect of increasing the torque. test was inconclusive because the DLR air system had significant oscillations.DLR will adjust their system and we will try it again

ran test 6-10G for 75 seconds. Voltage increased to 3080 at current of 1000 amp. Manifold pressure remained the same at 26 bar. We increased the torque on the tie bolts to 12 N-m(110 IN-LBS) after this test.

ran test 6-10H for 13 seconds test stopped when the current gain was adjusted too low.
Ran test 6-10I for 100 seconds. we ran 58 seconds at 600 amperes to measure the voltage level-3350 volts
difficult to say if the voltage increased any more because the
air manifold pressure contiues to oscillate.

ran test 6-10K with a larger orifice(0.8mm) at the prim 2 location. This test ran for 60 seconds. there was no detrimental effect on the anode voltages also no noticable change in performance but again this is difficult to judge because of the air system

March 21

borescoped the heater. continues to look good. some evidence of copper splatter downstream of the cathode. I asked DLR to adjust the air system to decrease the amount of inital air that the heater sees during start.DLR will also look at the 5 degree rise in inlet water temperature from 6-10E.

Next test is 6-10L with the orifice removed from the prim 2 location. test ran for 7.4 seconds. we stopped the run because the anode assembly voltmeters indicated that arcing was ocurring in the IES region. resistance measurements were good and borescope indicated no damage to the hardware.

readjusted the inner anode resistance to 0.96 ohms/installed the 0.8 orifice in primary 1 and 1.4 mm orifice in primary 2 and we will run again

We were delayed from 1300 to 1700 because of facility water system valve malfunction and because we had to wait for power to become available.

Based on discussions with DLR, we will reduce the air mass flowrate to 97 g/s for the next run to comply with his understanding of the contract(101 g/s of total gas flow)

power supply anomaly reocurred. cleared it by tapping on the board. We will call Robicon tonight to notify them that we need another board.

ran test 6-10M. Test was stopped by voltmeter observor after 8 seconds because of fluctuations in the anode assembly. post test inspection shows that the requested 1.4 mm orifice was not installed at the correct location. Resistance measurements indicate no problems in this area.

ran test 6-10N for 44.25 seconds. voltmeters are quiet
we will drill the primary 2 orifice to 1.6 mm and try it again

ran test 6-10O for 71 seconds. test was stopped by observor when the diffuser cooling gas(70 g/s) was initiated. caused flow field to collapse

ran test 6-10P for 62 seconds. went to 1200 amps and initiated the diffuser cone cooling flow of 20 g/s. no problems

March 22

talked to Robicon and explained the intermittent anamoly. We will arrange for the service representative to bring a replacement board after accaptance testing. I will call them today to discuss cost

we inspected the heater. looks good. splatter continues to build up downstream of the cathodes but gaps are clean

We have decreased the argon flow to 2.5 g/s so that we can run 99 g/s of air. disconnected the argon from the u/s face of the outer anode so each gap flow rate changes from 0.8 to

0.625 g/s
moved the center pressure tap to the front slot in the diverger in an effort to find a higher pressure point in the heater

inlet water temp measurement is in the storage tank u/s of the cooling water pump. also the losses in the ballast resistor must be taken into account when the energy balance enthalpy is calculated.

Italian representatives arrived today

Ran test 6-10Q for 148 seconds. Pushed the current up to 1700 amperes. shutdown when flow began to fluctuate. current split on the cathode needs adjustment at 1600 amperes. we have changed the inner cathode resistance to 0.07 ohms and will test again. also moved the center pressure tap back to downstream of the cathodes

borescoped the heater. splatter u/s and d/s of the cathodes.

inner cathode is not wearing around the whole circumference. wear is mainly on the lower 1/3 of the surface. resistances are good

ran test 6-10R for 75 seconds at 1600 amps. flow is steady and photocell quiet. test was terminated by arc heater cooling water system 6 interlock setting. Interlock was 40 degrees C absolute temperature
we will change this limit to 70 degrees C for the next test
cathode current split was good 700 to 760 but anode currents changed to 750 to 900. we will adjust the inner anode resistance to 0.111 ohms

DLR reported a water leak at the o-ring that seals the nozzle to the throat. After more checking DLR says that the leak is in the heater. I borescoped the heater and found a segment in package 5 that is damaged. Review of the video shows green flashes for the first time at DLR when we went to 1720 amperes. Dissasembly of the heater is in work to remove the bad segment(s) at 1600.

segment 46 is the 4th segment in package 5. this segment has damage in the upper half of the ring apparently due to overheating. downstream segments have spots of copper displacement, but can be cleaned up and reused
we looked at the original X-ray and there is no sign of blockage problems. water flow was 2.6. tommorrow we will try to machine away the copper to check for contaminant in the water passage.

March 23

machined the segment 46 away to inspect the water passage. there are no indications of

blockage problems of any kind. The wall thickness appears to be thinner at the failure location-1.3 mm compared to 1.7 mm at all other places

pack 5 has been reassembled and is under vacuum check. The other downstream packages have low resistance-probably due to water contamination. we are trying to dry these out with air.

calculations show that the bulk enthalpy is higher than the measured sonic flow enthalpy. this cannot be and may indicate a problem. We will install a thermocouple in the inlet water manifold to measure the water inlet temperature for the next test

March 24

Heater has water leaks at the inlet QD's. DLR is brazing these joints to fix the leaks.

The resistance between outer anode and u/s segment is near zero after attempts to blow gas and use of the power supply. We will accept this condition for the next test. borescope inspection shows a small bead of copper in this gap.

tie-bolt at the 4 o'clock position has failed the megger test. We changed the insulator boot and megger is ok. Boot has a crack or small defect.

DLR says they cannot work this weekend because of power availability.
We had a meeting to discuss the calibration of the air system.DLR agrees to do this. They had already purchased some standard calibration test hardware from Mannesman. received amemo from DLR that says calibration cannot be done until Tuesday Mar 28

Measured the throat with a micrometer.three measurements were 28.99.29.01.28.98 mm.
We had a discussion with Marcus to summarize power supply issues.Marcus will install and retest the Robicon board when it arrives in about 6 weeks.

March 27

Germany changed to daylight savings time Saturday night.
Preparation of the calibration equipment is in work.
Heater has been run a total of 33 minutes in the 6-pack configuration since Dec 1. Of this time 21.8 minutes are with the same electrode liners. Tabulated (I**2)*time function for each electrode. Received performance comparison of DLR heater and NASA Ames heater.

March 28

Performed air system calibration per DIN 1952 using sharp-edged orifice technique.

Discussed need for a 15KV megger test equipment with Marcus. gave him a copy of Jim C's memo on this subject.

todays calibration confirms that the previous mass flowrate was 5.28% low. see attached results
have asked DLR for a 2% correction on the indicated pressure based on the area ratio at the measuring location.
we are preparing for the next test at 100 g/s and current needed to reach 4 bar

Ran test 6-11 for 10 seconds. stopped the test because video was not working. found loose connection.
ran test 6-11A for 125 seconds. reached forward chamber pressure of 4.0 bar at 1540 ampere. test stopped because SPS system didnot have correct zero value for current. exceeded the current high value of 1600 amp. we reset the current high limit to 1700 amp and will run again. gain was 115 for this test. reset the gain to March 28(cont)

112 for the next test. test 6-11B was only 7 seconds long terminated by current oscillations. we rest the gain to 115 and will try again.
test 6-11C was terminated by current oscillation after 8 seconds
Adjusted the damping control 30% put the gain back to -- and tried again.
test 6-11D ran for 23 seconds. voltage oscillations occurred
reset the the damping control to zero and the gain control to 140
test ran for 32 seconds. test stopped because of current oscillations.problem seems to be one of coordination between operators. increasing the current while adjusting the gain. we will try the next test with Marcus adjusting both parameters simultaneously.

March 29

had a meeting with DLR. They want to test the diffuser air cooling during the next test. Diffuser centerbody cooling circuit reached the 30 degree C limit. DLR now says the limit is 40 degrees.
Based on the results of 6-11A, I recommended that we run the acceptance test at 1500 amp. DLR has recommended that we run the test at 1570 amperes. He refuses to correct the pressure 2%

ran test 6-11F for 6 seconds at gain setting of 140. test stopped due to current oscillations.reset the current regulator gain to 115 and this time we will increase current faster to 1000 amp.

test 6-11G made all smile.ran for 246 seconds with normal(planned shutdown) after approx. 100 seconds at the acceptance point#1 condition. DLR tested the diffuser cooling flow and reports that diffuser temps decreased. flow was steady. split between electrodes is within the 60/40 goal.

dissasembled the heater to weigh the liners. wear on the anodes is very even. we oriented the liners in the same position as prior to removal. weight loss was: inner anode-9.48g/outer anode-1.23g reassembly is in work

during the pack 5 removal and rework last week, apparently DLR allowed the converger pack to slip. this created a nonsymettric openingbetween the converger and constrictor. no damage except for the gas ring. we corrected this problem.

cathode liners are being removed for weighing. inner cathode looks good wear is around the bottom 240 to 270 degrees. outer cathode has an area that has some depth just upstream of the crown. we will try to measure this and evaluate. ingeneral all 4 liners are in good shape.

acceptance test will be tommorrow

March 30
groove in the outer cathode liner is approximately 1mm deep at one point-gradually decreases to no depth over a 25 mm arc. it is 2.5 mm wide. We changed this liner. the other cathode liner has even wear, but we changed it also to insure that the current would split evenly.
gave DLR a memo addressing acceptance point 1 and another requesting 15KV megger equipment for acceptance point 2.

reviewed interlocks. opened up the margins on some of these including(cw flows was 90% now 80% of current value, etc)
DLR has added a test cabin pressure high interlack(12mbar)

heater is reassembled, but DLR has shifted into slow gear.

at 1445 found that DLR has disassembled the diffuser nosecap and is evaluating a water leak. apparently there will not be an acceptance test today. DLR has told me that we will do the test tommorrrow.

March 31

0900 had a meeting with DLR to discuss in detail the procedure for the acceptance test and the interlocks for this test. see attached minutes.
1000 checked the progress of work in the test area. diffuser nosecap is still laying on the floor and DLR is welding on the centerbody.
Gave DLR copies of memo addressing the acc pt 2 electrical changes. Marcus will receive a proposal early next week for a 15KV megger device.
At 1530 on a cold and rainy day at DLR the diffuser centerbody is still in a state of

dissasembly and technicians are inside it. It is clear there will not be an acceptance test today.
At 1645 the diffuser is back together the test cabin closed and we are checking resistances. checked to confirm that the argon lines are hooked up properly.

acceptance test began at 1830. we had a clean start. test ran for almost 6 minutes. we were cutoff by the failure of the rear pressure transducer to the high position. only the forward pressure transducer was supposed to be interlocked but DLR interlocked all 3. We will delete this interlock for the next test and reevaluate the others.
Borescoped the heater and everything looks ok. I looked at the outer cathode closely. There may be an indication that uneven wear is beginning but it is not conclusive with the borescope.
DLR centerbody has another leak-9 drops per minute
outer flange temperature reached 200 deg C and was still rising when the test ended. they will cool it with water for the next test.

April 3

Reviewed the data from the last test. Performance has improved. We reached more than 4.08 bar at a current of 1420 amp. The manifold pressure has increased by 1 bar. this indicates that the gas injection area has decreased. The only change we made was replacing the damaged ring between the converger and constrictor pack. Apparently we had radial injection at that point on previous tests. We should be able to run most of the test between 1300 and 1400 amperes. will adjust the balancing resistors for 1400 amperes before the next test. gave Marcus the new settings.

over the weekend DLR decided to remove the first cylindrical section of their diffuser centerbody. Cutting and welding is in progress to extend the nosecap water lines 680mm. This will probably move the overheating problems downstream. They have also added active cooling outside the flanges.

had a meeting to discuss the last test. they say next test will be tommorrow.

April 4

Ran acceptance point 1. Ran 1330 amperes and achieved 4.08 bar. Heater ran very smoothly for approximately 31 minutes. I stopped the test when the flow indicated a problem.(prolonged green).
The vacuum level in the heater indicates that we have a water leak in the heater.
Borescope of the heater: anode assembly looks fine. there is ice in the cathode region.
Anode and cathode assemblies are removed and dissasembled. Results are:

weight loss of inner anode= 10.39 gram
weight loss of outer anode= 7.07 gram
weight loss of inner cathode=12.0 gram
weight loss of outer cathode=10.65 gram
total =40.07 gram
also recovered and weighed debris from the anode assembly-located in rear shell and isolator segments=13.84 grams. have not yet done this in the cathode region because it is wet total ppm (in the stream) based on two tests is 120 ppm

anode liner wear is very uniform and both liners look capable of mor tests. inner liner is beginning to show some flattening of the contoured surface

inner cathode has uneven wear on the u/s face at approx.
4 oclock wear was severe enough to cause a small hole. I believe this was the source of the green flash and photocell activity.
underside of the liner a change in color indicative of heat. water flowrates are as specified in our interface control document

outer cathode has a groove almost identical to the previous liner removed a few days ago. location is shifted a little downstream and over the center of the contour. underside also shows signs of heat

rest of the heater loks like new. DLR sustained a small hole in the water inlet line that feeds the centerbody. this line is exposed to the direct impingement of hot gas.

April 5

Had a long meeting with DLR. Told them that we need to reassemble the heater with new cathode liners and redistribute the water to increase the cooling to the cathodes as our first priority. More cooling to the anodes is desirable also. gave them a copy of memo minus the last paragraph.
I asked them to make measurements of the anode liner thickness and spare liners thickness. we have to decide which liners will be used for the anodes on the next test.
DLR says that:

a) the indications of heat on surface B of the liner(refer to attached sketch) are indications that the liner is not being cooled uniformly. As a result we should redesign the flow guide.

b)heat transfer from the electrode to the water is not good enough.again, Sverdrup redesign the flow guide. Tangential flow should be employed.

c)DLR wants more input about how we will solve this problem.

From the data it appears that we should be running a slightly lower current. Chamber pressure is 4.05 to 4.1 throughout the test. Requirement is 4.0 bar.

Noticed that DLR has reversed the water inlet and outlet connections on the electrodes from those indicated by the drawing. Water comes in on the upstream end and goes out on downstream side.
Reassembly of the cathode is in work at 1430. Anode liner thickness is being measured.

Converger has low resistances and copper in some gaps. We will remove the converger and clean. Low resistance in D/S packs due to the cathode water leak.

April 6

Wrote a long memo addressing electrode erosion at DLR
DLR reassembled the cathode and we adjusted the water system to increase the water flow through the cathodes. Responded to Svt requests

April 7

Had a discussion with DLR about the course of future tests. They do not want to continue testing until we provide new electrode liners. Told them that we were reviewing the design and would provide an input to them early next week for the schedule to deliver new flowguides.

Suggested that
1)we measure the pressure drops through the arc heater components
2)inspect the gas ring at the cathode diverger interface.
3)DLR write a memo that descibes the installation process for the cathode

measured the flowguides. The width is 3 mm less than the drawing. this causes the water passage in the corners to be too large.

we inspected the gas injection ring at the interface between the diverger and the cathode. There is no damage due to dissassembly. Damage is due to thermal expansion of the copper radiation shield. We need more tolerance on this diameter.

May 2

arrived at DLR with redesigned flowguide and liners this afternoon. Reworked liners are available, but o-rings for the flowguide are a problem-may not be available until Thursday. 2 key technicians are on vacation this week

May 3

received the replacement board from Halmar-Robicon yesterday and installed and

calibrated it yesterday. We will retain the old board here until we run the power supply a few times and then return it to Robicon.

Water system IES hoses have been reconfigured.

one or two inlet side holes in each flowguide have chamfered exits like the outlet holes.

I asked DLR to rework the remaining liners at DLR to the M10.2 configuration.also to photograph the anodes

I had a long meeting with DLR. gave them the attached sheet to describe test plan for acceptance point 1. Following are the results of this meeting and other discusssions.

1)nozzle isolator cooling-we will leave these connected to manifold 9 and orifice the flow so that they each receive 15 l/min. Water tests will be run to measure the pressure drop downstream of the inner cathode.

2) proposal is to run the tests 6-13 to 6-13C as shown by attached sheet. Then run a 4 or 5 minute test and measure the electrode liner weight loss. Based on these results decide between additional heater length,more changes to the air system or running the 30 minute test. Told him that we should try again to put more air in the converger on test 6-13B since the assembly problem has been solved. We will think about running an additional 4 to 5 minute test..

3)DLR will build up a spare segment package. Some segments need to be reworked by their shop. DLR does not have spare ports available on their water manifold for an additional pack-these would have to be added. Spare hoses are available.

Discussion about acceptance point 2

a)DLR wants argon gas rings(4) with .12mm slots. we will fill existing ring slots with epoxy and remachine grooves

b)DLR wants to share the cost of new higher voltage hi-pot tester

c)told DLR that I would give them a detailed test plan for acc pt 2

d)need P.O. for tie bolt boots

DLR schedule for next two months
testing in L2k facility-mid June
no testing after the end of June for 2 months

May 4

Inspected M17-1 DIVERGER flange segment that DLR has concern about. The radiation shield has some localized wear and there is minor wear or deposits on the internal surface after cleaning, but the part looks good enough. I will check with ESPE on availability of spares.

gave DLR purchase order for tie rod boots.

May 8

we checked the water flowrate through the overheated segment 5. the inlet pressure is 31.5 bar with manifold pressure at 39 bar. flow through this segment was measured as 14 l/min. We switched the inlet hoses and measure 15 l/min.

new segments 5 and 7 were installed and pack 5 was reassembled, tested and reinstalled. The converger has slipped down slightly as a result of this activity and DLR will correct this problem.
They are also checking the alignment of pack 5 and will make it right.

May 9

HAD A MORNING MEETING WITH DLR. We agreed on time charges of previous day and planned the work for today.

all problems are resolved except the fast data system. The system has too much noise and we are looking for another board. we will not run today.

May 11

new board for DAS arrived this AM. hand carried. We are now installing and checking at 11:30. Some programming changes may be necessary.

went back to manifold 6 and checked the diameters of welded connections with rods. This diameter should be 5 mm per DLR drawing, but position 5 will not allow a 4 mm rod to go through. A 2.5 mm rod will go through. Checked other connections. 4 will go through on all except #7(other location of overheating)
we disconnected the inlet connection and drilled the stub connection through with a 4 mm drill. also flushed manifold through open inlet connection to remove chips. checked new cathode and anode IES connections these also required same procedure.
checked cathode connections. these are supposed to be 8 mm by drawing. 6 mm rod will go through 8 mm will not. could probably gain a little inlet pressure on the cathodes if we opened up these holes but I am concerned about generating contamination that may cause a problem with the 1 mm gap downstream. we left these as is.

DLR IS working with new board. Problems continue and I do not believe we will test today. Is there a 15 channel 25 sample/second data system available in our lab?

power supply was switched on yesterday and the problem indication on front panel display

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power supply was switched on yesterday and the problem indication on front panel display LED'S reappeared. Marcus hit 'reset' and the problem went away.

May 12

results from daily morning meeting
recived photos of anodes. will send these to U.S. need slides or viewgraphs
of these. Data system problems continue. changing the A/D board did not help
they found a grounding cable that was damaged. will repair this and check the multiplexer.
If not sucessful will change the board again to a unit that provides 10 samples/sec and a less accuracy(12 bits on 0 to 9 volts-was 16 bits on 0 to 5 volts)

data system problem solved and DLR says ready at 1345. ran cold flow and looks ok.
ran test 6-13 for 20 seconds at current up to 1000 amperes. voltmeters in the anode region indicated some problems with the arc splitting otherwise everything looked fine. reached 3.6 bar forward pressure and was still increasing. Borescope inspection shows some minor damage to the anode IES due to arcing. resistance and vacuum checks are good. Data indicates that the inner ballast resistance was too high. We will adjust this resistance and run again.

ran test 6-13A for 20 seconds with a lower inner anode resistance(.080mohms). Effect was to make the current run on the inner anode. As time progressed the current began to split but there were occasional oscillations. Voltmeter observer cut the test. Post test resistance was good. we did not borescope.
adjusted the inner anode resistance again to .102ohms.

May 13

we will install 1.2 mm orifice in the converger and run again with 100 g/sec air to st-st conditions. we adjusted the position of the outer cathode current indicator to move it away from other cables.

ran 6-13E for aproximately 18 seconds. cutoff by the photocell when the DLR diffuser cooling system failed-caused the flow to collapse.post test DLR says they forgot to turn the water on-now they are pumping water out of the test cabin. resistances in the cathode assembly are a ok indicating no water intrusion

anodes did not split we will increase the converger air again with 1.4 mm orifice at pri 2. cathode currents now add to 1000 amp as they should and outer cathode indicates 550amp was 420 on last test.

time is 1500 DLR has removed the copper tubing that failed during last test and we have brought up water pressure, but there is a problem with the model support system circuit

finally ran again at 1800. Test 6-13F ran for 82 seconds. we stopped when the voltage and pressure appeared to be constant at 3450 volts and 3.82 bar. mass flow was only 97 to 98 g/s. The next test will increase the mass flow and current until we achieve 4 bar. The inner electrode ballast resistors will be adjusted to 0.095 mohms for the cathode and 0.117 mohms for the anode. Anode currents did not split.

ran test 6-13G for 165 seconds. Achieved 4 bar condition at 1200 amperes. splitting of current on both cathode and anode without problems.
Borescoped the heater and again the heater looks very good. Outer cathode has no sign of wear. inner cathode also looks good. one or two spots on the u/s face where copper loss is evident-but in general a big improvement over March/April tests.

May 15

DLR agrees that development is finished. we are back to commissioning. I gave DLR my recommendation for the allocation of time for the last 2 days.

We will adjust the inner anode and cathode resistances to 0.1 ohm and run again. Also put the 1.6 mm orifice back in primary 2 location.

Asked Marcus to get a quote from his machine shop for the ceramic gas rings

Test 6-13H was a no current test. Dlr did not close the disconnects.

Test 6-13I ran for 21 seconds. We stopped because all the current was on the inner anode. Will adjust the inner resistance to 0.112 and run again.

test 6-13J ran for 162 seconds with a normal shutdown. performance was a little less than test 6-13G. Achieved 3.9 bar with 3320 volts at 1200 amps.
current is running primarily on the outer anode. our goal is to have a higher current on the inner anode. will adjust the inital rate of increase in air as a first step.
adjusted the air system and also tightened the tie-rods. ran a cold flow and the manifold pressure increased 0.5 bar. There is an announcement that their is no water available at 1515-problem is outside DLR.

test 6-13K began at 1640. test ran for 2 seconds only and then went to open circuit voltage. review of the video shows that the start was a lot stronger i.e. more air. DLR's software change to the air system was intended to decrease the air Don't understand this but we will undo the software change and try again.

test 6-13L began at 1740. test ran for 82 seconds and was shutoff by the cooling water circuit 7 temperature interlock. Inlet temp has crept up to 22C over the course of the days tests. The data indicates the air mass flowrate was only 97 to 98 g/s. Start was normal. reached 1163 amperes

adjusted inner anode resistor to .098 ohms. changed cooling water temp limit to 60 and we will run again
test 6-13M began normally. did not have a current display on the power supply front panel and Marcus shutdown to investigate. we found a problem with the oscilloscope connection.
test 6-13N ran for 180 seconds and had a normal shutdown when we reached stable conditions of 3.92 bar in the arc chamber. split of anode current occurred when we reached 1125 amperes.
borescope results:heater looks the same as Saturday night inspection

evidently higher mass flow into the converger decreased the performance of the heater. we will reduce the pri 2 orifice size tomorrow and try again

May 16

agreed with DLR to use a 1.2 mm orifice in pri 2 location. ran test 6-13O for approx 2 minutes at 1200 amp. Forward press reached 3.92 bar but mass flow was 99.2 to 99.7 g/s. The currents did not split on the anodes. voltage was 3350 volts. Flow stability was less than previous tests.

we increased resistance on the inner anode to 0.108 ohms and ran test 6-13P. The test ran for 90 seconds. We reached 1200 amps but the anode current did not split. The mass

flowrate oscillated more than normal due to a change prior to the test. will return the setting to its previous value. We will increase the primary 2 orifice to 1.4 and test again with same resistor setting.

Test 6-13Q ran for 170 seconds. the split of current on both anodes and cathodes was near perfect. Chamber pressure at 1250 amps is oscillating between 3.93 and 3.96 bar.

The mass flowrate continues to oscillate around a value which I think is decreasing as time increases. Supply pressure has also increased since Saturday night test and the manifold pressure is slightly lower. DLR is now checking filters.

had a meeting with DLR and told them that we should remove the electrodes nad weigh them in preparation for the acceptance test. In parrallel they will try to fix their air system. Then we will reassemble and run a couple of tests to measure the effect of start transient and also determine if they have improved air system. Following reassembly, we would do the 30 minute test. Suggested to them that we set as a goal to accomplish this work by the end of this week.

The arc attaches to an area coincident with the same "hot" area as the inner cathode 3 oclock position. It crosses over the crown of the ring in a wear pattern that is 30 mm wide. At point A it begins a ccw sweep around the downstream face of the liner and gradually tapers to no indication of wear approximately 300 degrees from the beginning.

anode surfaces have wear patterns that are similar in appearance to the previous anodes but they appear to have less wear also.

May 17

had a meeting with DLR I requested parralel efforts to get cathode water flowrates and anode reinstalled. asked for more technician support.
outer cathode was dissasembled and liner weighed. back side of liner looks clean one faint dark spot near one of the attachment screws. area behind arc attachment is shiny copper color.
there were no broken gas rings in the cathode assembly.

Anode assembly was disassembled and inspected. no discoloration on the back side of the liners. wear pattern on each of these is wider than previous tests(25 to 30 mm was 20 mm). we cleaned up the IES minor damage over 1/2 inch length with sand paper and reinstalled. One gas ring has a crack thru near the point of IES damage but we reused it. cathode assembly is reinstalled and we are preparing for water flow tests. all parts were reinstalled in the same orientation as removed. We changed the inner cathode liner to a new one.

results of weight losses were as follows. There is approximately 1 gram of material recovered from the rear shell (see adjustment below*)and a substantial amount of copper

that is plated onto the diverger.I**2*t function for the 30 minute run will be approx. 6.9*10**8.

inner anode assembly/ liner	18	5770.7 408.8	5775.6 405.98	0 2.8	20	7.8	0 22 14*
inner cathode assembly/ liner	18	5889.5 400.6	5896.3 398.66	0 1.9	20	4.3	0 15
outer cathode assembly/ liner	18	5895.3 400.5	5903.5 399.59	0 0.9	20	4.0	0 7

time is 1445.water flowrates to the reassembled cathode assembly were measured. all inlet flows were the same. measured one outlet flow same magnitude. We did this test in parralel with vacuum test. posttest we have water in the test chamber from the cathode assembly. we will remove the cathode assembly and replace inner cathode with the spare cathode. this cathode was used for phases 2 and 3 tests. also plan to remove argon from the u/s face of the inner cathode prior to next test.

have discussed a tool fixture for removal of the electrode liners. With the change to the flowguide it is extremely difficult to remove the liners by hand. He said he was willing to give us a purchase order for this device.

May 18

resistances in the heater constrictor have degraded. evidently the anode assembly also has a leakage. we dismounted the anode assembly and are investigating.
DLR had an intermittent problem(pump shutdown occurs without warning) with the high pressure water pump yesterday . Electricians are coming this A.M. to troubleshoot.
Removed the liner and flowguide from inner cathode(3). o-ring in the spin coil housing is

cut. The spare cathode assembly (spin coil 4) will be reassembled. spin coil 4 was used successfully in phase 2 testing. it was removed from service after phase 3 because of a damaged power pin and the threaded block. spin coil 3 was installed prior to phase 4 tests.

anode assembly was dissassembled and o-rings changed. both electrode assemblies are ready for reinstallation by 1300.

DLR told me that they did not find any problem with the pump and the problem has not reoccurred. But unfortunately during this testing they forgot to limit the pressure on their nozzle to 19 bar. As a result the copper floguide was bulged and must be replaced. Their is no spare but they will change to a 30 degree nozzle and use that liner. This means the heater assembly will be pulled forward slightly. We are waiting for this work to finish before we install the electrode assemblies. Leak check of anode assy in preparation at 1415 using a spare IES on the downstream face.

reviewed data from acceptance testing of spin coil assemblies and sent fax requesting specific info to Tullahoma.

May 19

0830 cathode connection to the nozzle is not parallel. DLR will disconnect and correct. Resistances still indicate moisture in the heater. We will blow more air and place it under vacuum.

received preliminary electrode liner removal/installation sketches. comments are attached.

1300 DLR reattached the nozzle interface and we are checking the vacuum level. at 1.35 and decreasing slowly. the resistances between segments in the heater continue to increase but still indicate moisture. Marcus has not been here since Tuesday.

1500 DLR continues to have problems at the nozzle to heater interface. the joint leaks with positive pressure. they disconnected it again and o-ring is good. problem is alignment since they changed the nozzle yesterday

1600 DLR have opened the joint between cathode assembly and constrictor and working to get a good seal at this point. Amount of progress made since Tuesday night is not good.

May 20

0930 heater vacuum level is ok <1 torr. resistances down the column have improved. we will check them again before start.

1100 gaps on either side of the outer anode fail the 5 kv megger test. we have tried to blow air through the M05-1 to anode gap to clear this problem with mixed success. resistance between the isolator and the anode is changing as a result of this testing and troubleshooting. Blew air through the IES gap and now we have good resistance and good megger results. checked isolator to anode and resistance is good. still fails megger. we go ahead with condition after discussion. we have already run with no resistance based on ohmmeter in previous tests

1400 ran test 6-14 for 60 seconds. current reached 1200 ampere but anodes did not split despite the fact that we changed nothing in the anode region. only changes were removal of argon from the u/s gap on inner cathode and change of cathode assembly. cathode split was also not as good as before. stopped the test and we will adjust resistors.

borescope results
inner cathode localized erosion on the front face at 3 oclock is still present. there is evidence of copper oxide around the circumference on the front face. shiny copper on the downstream side of the crown.
outer cathode wear pattern is the same as before.
we did not borescope the anode assembly.

based on this result we inject air at the front slot location(0.8 mm orifice) in an attempt to increase the amount of swirl in the gas.
ballast resistors have been adjusted for both the inner cathode(0.09x) and the node(0.116)

Ran test 6-14A for 14 seconds. test was stopped because of low voltage on the outer anode to IES voltmeter. Anode current had split with most of the current on the outer anode.

borescoped the heater and damage to the anode IES had occurred.
dismounted the anode assembly and inspected damage. The IES to inner anode gap sustained most of the damage. the IES is not leaking. Liners have damage also but can be reused with some cleanup.

May 22

Took the IES to the shop and cleaned up damaged areas to evaluate reusability. Their is material that has been removed in the segment wall and we will electroplate this part at AJTuck before reuse. Spare part given to DLR. IES is in shipping. Shop is working on the liners.

Had a meeting with DLR and asked them to perform the following work.

1)reassembly of anode with repaired/reworked or replacement parts

2)check of heater constrictor and cathode assembly alignment using laser method or equivalent

3)removal of cathode assembly/removal of inner cathode liner/inspection and reclocking of worn spot

4)reassembly and installation of cathode

5)heater constrictor and cathode assebly alignment using laser method or equivalent

6)adjustment of inner anode ballast resistor to lower setting(0.080)

7)evaluate/prepare for spin coil magnetic field tests

Hot tests would follow this work at conditions that are similar to the phase 2 testing where localized wear did not occur. Also discussed using a milder start procedure where mass flow is increased gradually to 100 g/s.

told DLR that we would give them quotation to design/build the electrode liner removal/installation tool.

1445 Anode reassembly is complete using same liners and spare IES.

May 23

alignment check preparations for the heater/nozzle using laser method is in work this A.M.

alignment check using laser shows that there is good alignment between the converger inlet and diverger exit. There is an obvious misalignment somewhere between the converger inlet and the nozzle exit.(The rear of the heater needs to move toward the door) I believe the juncture of misalignment is at the cathode to diverger interface-the last joint connected)

DLR spent most of the day in meetings.

May 24

1130 A.M. We spent this morning establishing the control centerline using the nozzle exit plane and the nozzle inlet. After doing this we found that the converger inlet is misaligned

by approx 5 mm at 3 oclock.

Cathode assembly was disassembled. We rotated the worn spot on the inner liner to 9 oclock and measured the magnetic field strength at 10 amp. The results were the same (10 Gauss at 4 locations including 3 oclock)
the liners were removed and new weights established.

The diverger was removed and surfaces cleaned of copper slag from the cathode liner. Reinstallation is proceeding. DLR does not have any technician support today. Preparation for the test program in L2K is beginning and time is being shared with this activity.

Gav DLR a cost estimate for the electrode removal/installation tool.

May 25

DLR holiday

May 26

DLR finished the alignment process. They removed the center bolts and clamps for the heater. All of the clamps were loosened to position the constrictor. The heater connections are made and vacuum applied to the heater.

May 29

Vacuum check indicates a leak in the heater. DLR spent the morning looking for the leak without the blanking plate on the nozzle with no success. After installation of the plate Esser and I found the leak at the cathode to diverger interface. Insulator boot is loose at this location-I can move it back and forth with my fingers. They tightened the tie-bolts and we leak check again. It still leaks. DLR will disconnect the cathode and reconnect to the constrictor first-then connect to the nozzle. Will do this without disturbing constrictor position.

1530 Vacuum reading is now < 1 torr. water leak tests and other preparation for hot tests are now in work.

DLR changed front slot gas ring to a 10A(smaller slot) ring
water hose came off and wetted the exterior of heater. they dryed with air Megger tests are still good.

Ref. magnetic field tests gaussmeter is 0 to 500 gauss. so 10 gauss reading is only approximate.

May 30

DLR says they cannot afford the liner removal tool. also returned a liner to me that was damaged by their machine shop-needs electroplating to repair.
resistance measurements are taken. all values are more than the 50K limit. but some are lower than usual. We dryed the exterior of the cathode area(they had a leak at the power pin area) with air again and will repeat.

anode ballast resistor has been set to 0.94 ohms.
ran test 6-15 for 110 seconds. Current has more oscillations than normal. also flunctuations in flowstream seem more pronounced.
achieved 4 bar with 1200 amps. current split in the anode region with most current on inner anode.

post test inspection shows that the requested 1% gas was not installed upstream of the cathode. instead their was no gas injection in this gap as previous test.

inspected heater area post test. all water connections have magnetic connections. In addition the inlet copper lines have a magnetic field. We are discussing the possibility that these external magnetic fields may influence the angular velocity of the internal arc. also voltmeters are connected on the 3 oclock side of the heater.

May 31

had more discussions with DLR about changes for the next test. they have suggested that we equalize the gas injection at primary 2 location-currently all gas injected at the top tube-we will inject equal amounts in top and bottom.

will also try to clean-up the external wires attached to the cathode region. will disconnect the IES voltage divider and all the voltmeters except the 2 that monitor the IES gaps.

brought up water and found a leak at the cathode to constrictor flange(M13-2). leak is at 3 oclock. we disconnected the flange and took it to the machine shop for repair. we do not have a spare for M13-2 but we can use a spare IES without the radiation shield on a temporary basis if the shop cannot repair.

June 1

M13-2 was repaired by the shop. QD's had leaks when they came back to LBK so the part went back to the shop late yesterday.
after reinstallation of M13-2 the vacuum level of the heater was not good. we removed

the diverger and disassembled, replaced o-rings,cleaned these parts again and reinstalled. brought up water and found another leak at the outer cathode. this leak was at the spin coil to housing interface. removed cathode assembly and replaced this o-ring. we also rotated the inner cathode liner so that the worn spot is no longer at 3 oclock. Worn spot is less than 30 mm deep at deepest point.
sent a sketch of external magnetic surfaces to Tullahoma.
reinstalled the -10 gas ring per drawing for the diverger to M13-2 gap.
made a schedule for the month of June with DLR to accomplish acceptance points 1/2.

ran test 6-15B for 40 seconds stopped the test because of fluctuations on the IES to outer cathode. borescoped the heater and there is no new localized wear on the inner cathode.

Outer cathode looks the same and no copper on either the IES or the M13-2 flange. we have reconnected the IES voltage divider and will run again.

Ran test 6-15C for 130 seconds achieved 3.94 bar at 1200 amperes. normal shutdown. cathode voltmeter has less fluctuation. we borescoped the heater. no localized wear no signs of copper on the flanges-DLR says it is because we equalized the pri 2 flow(their suggestion)

June 2

asked DLR to adjust the gas flow at the diverger to 1%-was 5% for last test and voltmeters fluctuation is probably a result. DLR also adjusted the air system prior to this test.

ran test 6-15D for 50 seconds. stopped the test because the anode current split was unstable. borescoped the heater-says it looks ok no problem of localized wear. we have increased the inner anode resistance to 0.103 and will test again.

ran test 6-15E for 140 seconds. stopped because of instability in the anode assembly. borescoped the heater arc excursions in the cathode region drove some copper onto adjacent flanges both cathodes

met with DLR and discussed the data. next test we will remove all air from the diverger in an effort to improve anode stability.

test 6-15F ran for 100 seconds. Initially the flow stability was noticebly improved and current splitting was good. As the current was increased to 1200 amperes the current began to favor the inner anode with increasing fluctuations to single anode operation. data shows that as time increases the anode currents begin to diverge. we shutdown after 20 seconds of operation at 1200 amps.

conferred with DLR again and decided to try to repeat Test 6-13Q conditions. This test had very stable anode operation. We increased the inner anode resistance from .103 to .108 ohms and put the single 1.4 mm orifice back into the pri 2 location.

test 6-15G ran for 100 seconds. current split in the anode assembly was basically 50/50 after 30 seconds of operation with occasional fluctuations to single anode(inner) operation. these fluctuations began to increase in frequency and we shutdown.
we checked the resistances in the anode assembly and they are good-almost the same as beginning of the day.

data shows that the gas injection area is smaller now than 6-13Q-we have an additional bar of manifold pressure. We decide to connect 3 hoses in the constrictor-these were connected for 6-13 Q and run again.
test 6-13H ran for only 35 seconds. the anode current split after 20 seconds and fluctuations were more frequent and stronger than before.
we checked the resistance in the anode and IES is shorted to anodes. borescoped the heater and found significant copper flow onto the IES. however it does not leak. told DLR to remove the anode assembly.

June 3

anode assembly dissasembled at 1230 and cleanup begins. gave DLR new liners and IES spare. they built up the heater and reassembled. vacuum is not good. dissassembled anode and cleaned more.

Assesment of test results since May 12(phase 6 tests)

we made 2 changes to improve performance at the beginning of the 6-13 series. these were better cooling on the electrodes and removal of air from the diverger. after several tests we were able to run stable(6-13Q/6-13O/6-13G/6-13J,etc) with current split between 2 anodes and performance had improved-acceptance point conditions at 1200 amperes with reduced wear on all the electrodes.

a localized wear problem remained on the inner cathode at 3 oclock. we changed this liner and others were reinstalled as before. anode liner wear pattern was similar to March/April tests.

test 6-14 with reassembled heater and same test conditions did not produce same results-no splitting on the anode, but wear pattern on the cathode liner was still there. we added air to the diverger to try to correct the wear problem and also increased the inner anode resistance. result was damage to the anode IES.

the arc tracks were removed from the liners as a part of this rework. we reinstalled these reworked liners with clean surfaces.

we made some alignment checks and determined that the heater was not aligned as it should be. corrected this problem and began test series 6-15.

The laser alignment did not solve the problem at 3 oclock, but it did reduce the gas injection area. manifold pressure is higher. This in effect also 'changes the equation' i.e. stability in the anode assembly.
after 2 tests in 6-15 series we found the source of the problem at 3 oclock on the inner cathode-it was a water leak that was influencing the arc position.
From test 6-15C forward we are trying to improve the anode stability.

Summary

In March and April we ran 32 tests with no damage to the anode IES and current split on 26 of them despite the fact we were making several air distribution changes in this test series. There were unstable conditions in the anode assembly on 2 or 3 tests but there was no damage to the IES. In these tests the arc created a very distinctly defined wear pattern on both anodes-partially due to the hotter surfaces.

In May and June we have run 29 tests. there have been no current split on 8 of these. there was unstable conditions on 10 others and we have damaged the IES on 3 occasions. I believe the difference between these test series are:
1) with improved cooling the arc wear pattern is not as well defined on the toroidal surface. the position of the arc is more sensitive to other changes.
2)better heater alignment and no air in the diverger puts more air in the anode assembly. As we saw in phase 4 there is a point where this creates problems.
evidently we are at a point of instability as a result.

Plan for next test series(6-16)

Test Objectives

1)reestablish stable operating conditions
2)reestablish acceptance point 1 conditions

Spend more time wearing the arc tracks into the anode liners with reduced air in the converger.
reduce prim 2 orifice to 0.5 mm-same as pri 1
change the resistance of the inner anode to 0.94 ohms
run initially at 1000 amperes to establish arc footpoint on the anodes.

June 5

DLR Holiday

June 6

reassembled anode assembly and reinstallation is beginning at 1130 AM. damaged liners and IES have gone to the shop for repair. IES will need electroplating.

anode assembly installation is complete and there are no leaks. I asked to verify that the anodes do not leak with a bench test and this was done.

had a meeting with DLR and we discussed the course of action outlined above. they are worried about the vacuum level in the heater. it is not as tight as previous tests, but still pumps down to 1 torr. told them this has no effect on the anode stability.

has been assigned the task of contacting our material suppliers or finding substitutes in Germany for heater spare parts.

I do not have another spare for the IES. What is the status of all the parts that are currently at the electroplater?

argon orifices were cleaned prior to this test-manifold pressure was high
ran test 6-16 for 50 seconds at 1000 amperes. the current ran on the inner anode, but the heater operated stable. we checked the resistance(all ok in the anode assembly-some deviation from normal in the last pack). data looks good mass flow was low-96 g/s. We will run again at higher current.

ran test 6-16A for 175 seconds at currents of 1250 amperes. the anode current split at 60 seconds into the test. division was 400/800 O/I. reached 3.93 bar. flow was very stable. borescoped the heater and looks good.

June 7

had a meeting with DLR to discuss results. we agreed to run another test with a higher resistance on the inner anode. Problem with low resistance in the converger between 2 segments. Marcus cleared it with the small power supply. Inner anode resistance increased to 0.104.

ran test 6-16B for 147 seconds at 1200 amps. flow and voltmeters were very steady and current split on anodes was improved to 500/750 O/I. Reached 3.9 bar.
had another meeting with DLR. I recommended that we run the acceptance test next, but

they would like to adjust the inner anode resitor again and to reduce current on the inner anode. we will increase to 0.114 ohms. Marcus suggests tweaking the circuit 7 water flow up a little.
check of resistance shows reduction in resistance between IES and anodes to 51Kohms.
ran test 6-16C for 120 seconds at 1200 amperes. everything same as before except the current split between anodes was 540/730 O/I. DLR repaired the brush recorder so that we can see the anode behavior realtime.
1500 had another meeting with DLR to discuss next step. at this meeting they decided that they needed to have another internal meeting. I recommended that we prepare the facility for the acceptance test in parallel, but they prefer to leave everything as-is.
received 2 electroplated liners. shipping IES to electroplater today. DLR shop still working on 2 other liners.

DLR says they are ready for accept pt 1. There will be a written explanation from DLR.
Dissassembly of the heater begins at 1730.
June 8(1500)

0930 dissassembly of electrodes are complete.

The wear on the anodes is very uniform. removal of the converger air had the effect of widening the wear pattern. The wear is now across the front half of the liner. These liners will be installed in the same locations with the same orientation. There are some marks on the liner sealing surfaces-asked DLR to clean these up

The wear pattern on the inner cathode is the same as that observed prior to 5-15B. There is one localized wear spot that now has an approximate depth of 0.35 mm. Prior to 6-15-B the depth was 0.03. I believe the additional loss here was due to the large current oscillations during the 6-15 test series. Opposite this position there is another localized wear spot. Other parts of the cathode have very uniform wear.

I asked DLR to photo all 4 electrode liners.

Outer cathode wear has become more uniform with time. There are faint spots of discoloration on the inlet side of the cooling passages-this is true on the inner cathode also. The total accumalated starts on this cathode since May 1 is 41 and the run time is 41 minutes. total loss of copper is 1.95 grams.

DLR has made 2 suggestions. They want to remove the melt flow around the edges of the liners-I agreed. They suggest that we switch the outer cathode liner with the inner cathode liner-I agreed. We will maintain the same orientation for all parts during reassembly.
Vacuum checks of the constrictor bore are on-going.
I asked DLR to make an effort to dry the electrode assemblies after the acceptance test so that we can compare the electrode weight loss on the same basis as that obtained NASA-

Ames.
Based on the following assumptions: weight loss a linear function of I**2*T
no copper loss due to start process
no correction for the start transient period(2 min.)
some localized wear on the inner cathode
no correction for copper that is left in the heater(not in the flowstream)
weights made on the basis of the liners rather than the assembly

then the accumulated acceptance test contamination level will be 60 ppm. see attached data plot

1230 electrode assemblies reinstalled and vacuum test underway.

1500 vacuum is good. we have a low resistance between M13-2 and cathode 3(33,000 ohms s/b >50,000). also 5000 volt megger between cathode 4 and M17- is 0 but 500,000 at 1000v. resistance > 30Mohm

borescoped the cathode assembly with the water on and saw no indication of leak-also vaccuum level does not change when water is on.

June 9

was notified by DLR at 1130 that they agreed to the contract change ammendment 2 revision and that work would proceed on acceptance point testing.

actual work did not start until approx. 1315 because they were finishing work on L2K. shortly thereafter a problem with the high pressure water system was noted. the valve will not open. Then the DLR changedd out the valve with a spoolpiece. This took until approx 1500. argon system trouble-they cleaned the orifices and pressure returned to normal.

we revised the test procedure and discussed it. Acceptance test began shortly after 1700. the test ran smoothly for approx. 30 minutes. I stopped the test when flow and cathode current information indicated a problem. The post test vacuum results indicated a water leak in the heater.

borescoped the heater and a problem at 3 to 4 oclock on the inner cathode was evident.

we removed anodes and cathodes. I asked DLR to dry the electrodes before dissasembly. they did this on one anode (only) and weighed it.
results of the liner inspection and weights follow

	wt loss after 6-12A	init. wt. grams	final wt grams	delta wt loss after 6-17A	est.sum (I**2)*time amp^2-sec	ppm
outer anode	7.07	403.23	402.52	0.71	6.1*10**8	3.8
inner anode	10.4	387.8	385.44	2.36	9.1*10**8	12.7
inner cathode	12.0	398.44	393.00	5.44	8.3*10**8	29.3
outer cathode	10.7	386.04	383.53	2.51	5.6*10**8	13.5

we recovered 1.85 grams from the anode assembly but this is not all of the copper that is in the heater. there is significant other copper on the diverger flange which may be recoverable. then flowstream contamination including the start transient and the localized wear problem is probably less than 40 ppm.

comparing with the previous 30 minute test
weight loss reduced from 40.7 to 11.03
total ppm reduced from 220 to 59 ppm

wear patterns on the anodes are very uniform and wide.
wear patterns on the cathodes are uniform across the whole surface except at the problem point at the corner again. there is a small hole in the liner at this point.
Outer cathode has slight indication of the same groove that it had on previous test 6-12A. on the downstream side. other than that the wear is very uniform across this liner.

June 10

drafted preliminary version of the detailed test plan

June 11

finalized detailed test plan and faxed to USA for comment

June 12

had a meeting with DLR and reviewed the plan. We have general agreement and I have incorporated their comments. I will release a final version for signatures after receiving comments from the DLR distribution. I would like to have these comments by fax no later than tomorrow morning in Germany.

We inspected the constrictor-it looks like new.
the converger-it has some copper that can be easily removed in place wiyhout disassembly
the diverger-it has a significant amount of copper that requires dissasembly
Diverger is being cleaned and we will weigh the removed copper.

DLR has already changed the nozzle to the 14mm throat.

June 12(cont)

removed particles from the Diverger are xx grams

We measured the profile of the anodes in 3 locations. The outer anode has measurable loss of material in one location only=0.2 mm. The maximum inner anode loss of thickness was :

loc.1=0.6 mm
loc.2=0
loc.3=0.5 mm

We removed the edges of build-up copper and are reinstalling these liners for the anodes. Based on above results and our plan to run mostly on the inner anode, I asked DLR to

switch the inner and outer anodes. They have done this and the anode assembly build-up is complete.

June 13

Mr. Komatsu arrived today.

Cathode assembly is complete. We used a new liner for the outer cathode and a used one for the inner cathode. I have asked Doerfeld to modify his QA record form to record the minimum thickness of each liner after each installation.
We used a -10 ring for the slot upstream of the cathode instead of -10A.
Signed the detailed test plan and gave it to DLR for signature.

June 14

I traveled with Mr. Komatsu to see a potential vendor for the RF-heater and power supply.
DLR assembled the heater cathodes and anodes.

June 15

DLR holiday

June 16

There is a water leak at the constricter flange QD for pack 6(near the pack 5). Mr. Empt has rebrazed this morning.

DLR is working on an English report for ESA on progress of the LBK facility.
Received the electroplated IES from AJTuck. 2 of the copper tubes were severely bent as aresult of the shipping process. Evidently they did not adequately protect the tubes. Attached fax should be sent to them for future parts.Did not receive the liner M10.2 that was sent to them in May. Where is this liner? did AJTuck ship it?

DLR continues to maintain that smaller(0.12 mm depth) gas injections slots for the argon positions would be desirable, but they are willing to go ahead with the present setup. verbally indicated that 15 or 16 bar would acceptable instead of the desired 18 bar if we have stable operations in the anode and cathode regions.
Cold flow tests at 50 g/s are ongoing. the rebrazed joint is leak free. we checked to verify no braze blockage in the flow.

Megger test at 5kv is ok. we do not have the new boots yet. resistance checks in work at 1430

June 16 (cont)

ran test 6-18 for 3 seconds. we stopped the test when an unusual sound of gas flow was heard. inspected the heater and found that 2 QD's had blown off. one of these was opposite the center pressure tap in the cathode region. the other was in the anode region. no damage was observed.
reached 7.2 bar at 50 g/s. cathode current appears unstable. anode did not split but this was expected. the sps system did not function-post test checking showed that the disk was saturated.
borescoped the cathode region and there is no evidence of a problem.

ran test 6-18A for 6 seconds. test was stopped by voltmeter observor-the voltages between cathode and IES were zero.
the data shows most current is on the outer cathode.
borescoped the heater again and this time there is evidence of some arcing in the gap between IES and the outer cathode in 3 spots. resistances are good-no change from previous.
argon bottles are low in pressure and we can not refill them.

reduced the inner cathode resistance to 0.59 ohms and removed the air from the gap upstream of the inner cathode. we were setup to run again when the power station reported a problem. Marcus tells us at 1815 that there is an indication of short circuit between mainlibe and ground. This problem cannot be fixed until Monday(by coincidence the people at the power station had been wanting to go home)

during borescope inspection argon was initiated while I was in the test chamber. I asked DLR to interlock the argon system so that this is not possible.

June 19

was informed by Marcus that AEG has been called to troubleshoot the problem at the power station
we took the electroplated IES to the shop for machining. also asked DLR find the other liner-it arrived today.
I inventoried spare parts for electrode liners and IES

1030 power station problem is solved.
1130 frwd and ctr pressure transducers have been replaced with 25 bar instruments. rear is 40 bar. calibration done.
adjusted the bypass valve opening time to 2 seconds.
ran test 6-18B for 5 seconds. stopped because the cathode was unstable. Voltage across the gap upstream of the inner cathode is fluctuating 20 between 80 volts.

borescoped the cathode region and condition in the IES gaps looks about the same.
the diverger exit flange M13-2 shows some evidence of activity.
I asked DLR to return argon to the u/s gap and to remove air from diverger and to lower resistance on the inner cathode TO 0.0395 minimum setting.

ran test 6-18C for 3 seconds. post test review shows that the cathode region is more stable.
we did not change anything and ran again. Test 6-18D FOR 50 seconds. the current was stable at 600 amps and we increased to 800 amperes after 30 seconds. split between cathodes was 550/200 I/O. reached 8.5 bar but pressure was still increasing.

Since heater is stable at these conditions. we ran again at 50 g/s and increased the current to 1000 amperes for test 6-18E. total test time was 67 seconds. result was a fwd chamber pressure of 8.93+ and voltage of 2630. indicated cathode current split was 630/230. all parameters are stable and we will run again. This completed condition 1 and 2 and we move on now to condition 3 with a mass flow of 75 g/s.

test 6-18F ran for 28 seconds. We stopped the test when the increase in chamber pressure drove all the current to the inner cathode. Manifold pressure had not reached steady condition but we achieved 10.7 bar for an estimated mass flowrate of 60 g/s.
Based on these reults we will increase the inner cathode resistance to 0.06 ohms. also borescoped the anode and cathode regions and they look as expected. The inner cathode has not shed any copper onto the u/s flange at this point. wear is mainly on the u/s face of inner cathode and downstream face of outer cathode. all current is on the inner anode at this point.

ran test 6-18G for 25 seconds. we stopped when the voltage between IES and inner anode went to zero.
resistance measurements of the IES to anodes indicate 0.2 Mega ohms-substantial decrease from previous so we borescope.
Borescope shows damage to IES in 2 locations. cathode looks same as before.
we have decreased the inner anode resistance to 0.040 and increased the inner cathode resistance to 0.073 in preparation for the next test.

ran test 6-18H for 65 seconds. we reached 75 g/s at 1000 amps. The fwd chamber pressure was 12.5 bar. cathode current split was interesting see attached. all current on inner anode. borescope of the heater shows same results as before. resistance between IES and anodes is 0.27 megaohms.

June 20

comparison of previous (phase 2) data with yesterdays run-assumes mass flow was 5% lower than indicated for phase 2 data

test/date	current	mdot	voltage	Fwd Press	comment
4-7B/ 4/94	930	47.5	2650+	8	
6-18E/6/95	1000	50	2630	9	
4-8B 4/94	1000	82	2862	11.4	
6-18H/6/95	1000	75	3215	12.5	
4-9A/4/94	1000	93	3475	14.+	
6-18I 6/95	1000	85	3500	14.3+	

had a meeting with DLR and we discussed the plan for todays tests. inner cathode resistance has been increased to 0.082 ohms. I told them that there was a good chance that we would blow out in the 4S*2P configuration and suggested that we go ahead with a 10kv megger test. they do not want to do this and have a reluctance to go to 8S*1P before the new boots arrive. Marcus is checking their arrival.
We took another electroplated liner to the shop and checked on the IES progress.

1130 AM we ran test 6-18I for 30 seconds. the test was stopped either by the photocell or flowfield observer after bright flashes were seen in the boundary layer. reached 14.3 bar at an effective mass flowrate of 85 g/s(estimated) with a voltage of more than 3500 volts.

inspected the heater and nozzle. pieces of copper can be seen hanging from the throat. cathode and anode region look ok with the borescope. and all data from the heater looks normal.

received the IES back from the DLR shop.

removed the nozzle throat. It has a hole through the water passage approximately .75 inches from the inlet side. We will reinstall the throat that was used in phase 2 tests with 3 additional segments and gas rings that we provided in March of 94 There are two problems:

a) cooling for these segments. They only have available 300 psig water pressure without taking water away from the electrodes.

b) one of the segments M19-4 is not as flat as it should be after rework from 6-1A problem. DLR shop has this segment now and is checking it.

June 21

the modified nozzle isolator package has been built up and passed the vacuum test.
the gas ring between the outer cathode and the noz isol pack was dropped during disassembly and I replaced it from our stock with a -2A.
We took the Mycroy material to the shop and have asked them to build some spare rings(4). also ordered 2 more liners from ESPE. The DLR shop should be finished with the electroplated liners by end of this week.
I reminded DLR that the three additional tapered segments were not part of the heater from the viewpoint of contractural requirements and suggested that they have to find away to get 600psig water to these segmnts. we do not plan to have any air in the nozzle isolator package.Also told them this was DLR delay time(1 day)

increased the cathode resister to 0.098
1600 ran test 6-18K for 67 seconds. we stopped when das operator reported a problem.
the split of current for the cathodes was 600/400 I/O.
reached 15.8 bar on the center pressure xducer at an effective mass flowrate of 93 g/s.
voltage was 3800 volts.
during this test we heard a loud pop that came from the direction of arc heater/test cabin.
somewhat coincident with that the fwd pressure xducer dropped 4 bar and then gradually increases for the remaining 15 seconds
checking the torque on tie rods and some were not at the specified values. retorquing these and checking resistances.
resistance in the gap between IES and anodes is decreased and voltmeters show periods of zero voltage. So we borescoped the heater, but everything looks similar. we installed the shorting lug between the anodes to protedt the IES.

ran test 6-18L for 90 seconds. we reached 16.1 bar on the center pressure transducer at a voltage of 3830 and mass flow of 99.2 g/s.

DLR wanted to run gain setting of 47 on the photocell so we did. previous test was 33.
this may be too sensitive for the 7 minute test. fwd pressure transducer continues to indicate low by approx 2 bar. Don/Jim, please analyze and respond real phenomena or instrumentation. we checked calibration and it reads 20 bar with 20 bar. CENTER XDUCER IS LOCATED ADJACENT TO OUTER CATHODE/FWD XDUCER AT GAP 2 segments d/s.
borescope results inner cathode has localized wear at 0700 area. we will try to balance the currents more evenly 500/500 tommorrow
constrictor bore looks clean a couple of segments are rougher now. how much increase in orifice dia required to pri 1/2 to achieve 18 bar?-currently we have 0.5mm in each

June 22

had a meeting with DLR(it took more than 1 hr) and at this meeting they agreed to run single anode configuration for the acceptance point 2. wrote a memo of record to document.
changes for the next test are increase pri 1 flow with 2 each orifices of 0.8 mm and pri 2 with 2 each orifices of 1 mm
changed the orifices.
1300 Although post test yesterday we had a good vacuum, the system vacuum today is too high 2.6 torr. DLR will install the blanking plate and check for arc heater leaks with helium. they are also investigating a problem with the gate valve d/s of the HEX.
Yesterdays problem with the forward press indication was a leaking(failed)hose connection. we replaced it

1630 we pressurized the heater and found a leak at the o-ring d/s of the outer cathode. this joint was disturbed to replace the nozzle. the o-ring is charred and the gas ring shows signs of overheating. it was also cracked. rework is underway. they checked the repaired joint with a pressure decay test

We began test 6-18M at 1923. During the startup procedure we got a water system fault. this was corrected by switching on the pump-overlooked in the procedure.
Application of current resulted in an external arc which damaged the ballast resistor. Damage is to one tube only and the anode 100 ohm resistors. This problem resulted as follows:
During yesterdays work we shorted the anodes together to avoid additional damage to the IES. The 100 ohm resistor connection to the anode IES was disconnected today and grounded since we are running single anode configuration. This created a circuit.
Are there other failure scenarios that could cause a problem like this with the cathode 100 ohm resistors or in the anode region? If so. the advantages of having that connection should be re-evaluated and the connection removed.
borescoped the heater-looks ok.

June 23

ballast resistor tube was replaced with a spare tube that we provided. we leak checked the assembly and inspected for other problems. looks ok. DLR replaced the 100 ohm resistors but they are not connected.
spare electroplated IES shipped from Tullahoma on 6/22
DLR notified me that they were ready to test at 1100. at 1113 we cannot activate power due to a problem in the SPS or related systems. at 1130 I recommended they ground before continuing troubleshooting.
continued spares inventory
at 1300 I am notified that the problem is apparently on the facility power side and power

substation people are now troubleshooting
1430 the problem on the facility power side seems to be a coil that has been damaged by continuous voltage application. they have replaced it and are retesting
1600 there is still a problem apparently with the LBK system the coil is energized all the time even without the contact of the control room switch.
1700 DLR reports that they have solved the problem. the interface contactor in the control desk was frozen in the on position. they have replaced that now and the system works they burned up another facility coil before finding this.

1730 we began test 6-18N. The test ran normally until approx 50 seconds into the run the center pressure transducer showed a slight decrease in pressure from the frwrd transducer. approximately 6 seconds later there was an arc that ocurred in the gap between the outer cathode and the downstream flange M17-1. this arc damaged the spin coil-it leaks and also the M17-1 segment. the test was terminated by operators as soon as possible.
The heater was operating at 15.6 bar and 3900 volts when this problem ocurred.
There are spares for the damaged parts and reassembly will begin on Monday.

June 26

regarding the problem that ocurred on 6-18N, after looking at the parts more closely, the damage was most probably due to plasma leakage through this joint rather than an arc. The gas ring,insulator and o-ring were burned through. There is erosion of the spin coil and electrode housing assemblies. The spin coil itself and the electrode liner appear to be undamaged. The segment M17-1 has a spot of damage on the tapered spoolpiece and the gas tube has been burned through. These parts are in transit to Tullahoma for disposition. prior to dissasembly we checked the torque on the bolts. looking downstream:

2 oclock 6-7 n-m
4 oclock 7-8 n-m
8 oclock >11 n-m
10 oclock>11 n-m

original torque was 12 n-m for all bolts.
the location of the leakage was 12 to 1 oclock.
the top gas line was blanked off. The bottom line was connected to the center pressure transducer. prior to the test the joint had passed a pressure decay test at 19 bar and we had good vacuum <1 torr.

1100 The nozzle isolator package has been rebuilt and vacuum test is underway. after 2 tries DLR reports the -6 insulator is too thick(2.4 mm) I gave them a spare of 2.3 mm thickness and vacuum is good. DLR shop to return the insulator to print dimensions.

electrode has been built up with the existing liner. liner weight loss for 14 starts and 8.2 minutes of run time was 0.41 grams. no signs of localized erosion on either electrode.

drying of the heater is in progress.resistance in the heater are not good at this point we will leave it under vacuum tonight

we checked on progress of the gas rings. the 16 and 10A will be ready at 1500.

changes prior to the next test include:

1)add 1 % air to the gap downstream of the outer cathode

2)relocote the end of constrictor voltmeter to this gap

3)changed the gas ring u/s of the inner cathode to a -10A was a -10

cathode assembly complete at 1530/assembly in work at 1615
center pressure transducer has water intrusion-we will dry it
and the hose.

June 27

gave DLR the Sverdrup spares and inventory list and asked for there review and signature 1105 heater vacuum is not very good 8 torr. We had a meeting with DLR and the following actions will be taken.

*The heater vacuum will be measured independent of the facility.

*ice will be removed from the tests cabin

*the leak at the gate valve will be investigated-it is worse than last week

we received the electroplated IES and I gave it to DLR to machine. The inlet water tube is crimped and will require evaluation. received the remachined part at 1550 and it is on the shelf again.
DLR reprted vacuum is good on the heater at 1300, main problem was the gate valve. resistance in the diverger are low-we asked DLR to blow air through these slots and then to check again.
talked to customs in Frankfurt to clear the shipment of 2 new liners these will be at the hotel tommorrow noon.

1715 We were notified that they were ready for next test at approx 1630 but the vacuum level of the heater is too high 1.7 torr. We changed the o-rings in all disconnected joints and are waiting for good vacuum.
at 1815 DLR reported that the vacuum level was down in the heater to 1.45,there were no leaks in the cathode region using the helium leak detector and recomended that we fire the heater. I checked the cathode region with the helium leak detector and found that the joint downstream of the cathode leaked. also checked the bolt at 10 oclock and found that it was loose with my hand. I ask them again about the results of the pressure decay test and discovered this had not been done. We will pressurize the heater to 25 bar for a pressure decay test-in progress at 1900. hot test tommorrow.

June 28

0915 the leakage of the heater at 25 bar was .o17 atm/min. DLR disconnected the vacuum gage from the heater and measured the vacuum level with a different gage. Indicated vacuum was <.5 torr. they are troubleshooting now to resolve the difference.
1010 we checked the joints between the cathode and M17-1 and the nozzle throat connection with helium leak detector and got no indication of leakage. The old vacuum gage still reads high 1.6. even though the connections have been checked with helium detector. we will proceed.
ran test 6-18O FOR 70 seconds. reached almost 4000 volts in the 4S*2P configuration. heater pressure indicated is 16.3 bar at 1000 amps and 100 g/s. all data indicates stable operation. there was discussion about water in the flow field but we borescoped the heater with water up and saw no indication heater looks ok with the borescope
changes for the next test are as follows:

a)incr pri 1 to 6% flow 2 each 1.2 diam orifices
b)incr pri 2 to 8% flow removal of all orifices
c)rear retard flow 3%
d)increase current to 1200 amps
e)increase inner cathode resistor to 0.105
f)increase water flow to the inner anode from the outer anode

Test 6-18P ran for 4 seconds. cutoff because of the photocell-we had a bright flash that tripped us off line. compared the data with previous run and decided to a)remove the air from rear retard and b)orifice pri 2 with 2 1.4 mm orifices. resistances look ok
test 6-18Q ran for 95 seconds. cutoff ocurred because of the high current interlock(1200) amps. we will reset this interlock to 1400 amps. reached 16.7 bar and was still increasing with the mass flow down to 99.3. we will change the pri 1 orifices to 2 each 1.6 mm orifices and run again.
we checked the resistances and the torque on the attachment bolts. the long tie rods had relaxed to 8.5 to 10 n-m. These were retorqued to 12 n-m. resistances are good.
DLR informed us this afternoon that they would work on Friday. this is a change from previous plans and we are trying to rebook our flights home to accomadate an additional day.
ran test 6-18R for 4 seconds. arc blewout due to instabilities in the anode region. we will reduce the pri 1 flow to 2 each 1.4 mm orifices and try again.
ran test 6-18S for 100 seconds. shutdown after steady-state conditions were reached. These were indicated pressure=16.91 bar

voltage= 4000 volts
current=1200 amp
mass flow=99.7 g/s

we adjusted the pressure for area effects and calculated the enthalpy. the enthalpy is 19.6 MJ/kg. Based on these conditions I recommended to DLR that we remove the electrodes and weigh them and perform the acceptance test. but I am sure this will take some discussion.

borescoped the heater the converger has some copper flow probably caused by the unstable runs. will necessitate its removal for cleaning. the electrode assemblies look as expected. the end of constrictor is very clean. we will borescope it more carefully after electrode removal.

we received the new electrode liners from Espe.

June 29

removed the electrode assemblies and inspected them. the anodes look as expected. the arc attachment point is on the crown as a result of the higher primary air flow, no erosion on the outer anode. the inner anode has lost 7.02 grams for I**2*t=23*10**8 some of this loss was due to the arcing damage to the IES that occurred on test 6-18G. material recovered from the heater amounts to xx grams. IES can be cleaned up and used again.

converger and first 2 1/2 packs have arc tracks on the edges of segments. this is a new condition. It is most probable that this anomaly occurred as a result of test 6-18P. In this test we increased the air flow to the converger and anode assembly by removing the orifices from prim 2 and adding air behind the outer anode. The requested gas ring for the prim 2 was not installed(a larger ring was). The converger has been removed and will be cleaned up by hand. The two 1/2 packs have been removed and will be cleaned up with sandpaper.

the pri 1 gas ring has failed. we do not know the reason why. there is some heating that has ocurred in the failure

the inner cathode liner has even distribution of wear by visual inspection. we have requested profile measurements on all liners. the copper loss for I**2*t= 2.7*10**8 is 3.55 grams. the outer cathode also has even wear and has a copper loss of 2.49 grams for I**2*t= 1.2 *10**8. diverger can be cleaned and used again.

we had a meeting with DLR to discuss the next step and the results were:1)DLR does not want to run the heater at currents higher than 1000 amperes under high pressure conditions. they would prefer to stay at 1000 amps and accept the decrease in pressure to 16 bar. they would agree to run the next test for 7 minutes at these conditions to "see where we are on contamination"
3)DLR will not commit to this test as an acceptance test as of 1430-I have asked for clarification of this point

gave DLR 3 new liners for the inner anode and cathodes. we will use the same outer anode(no current)
updated the spares inventory and gave it to DLR for review

June 30

DLR had a meeting and decided that the 16 bar condition was not high enough for acceptance.
We have asked for a recalibration of the air system using the sharp-edged orifice and also pressure transducer calibration.
we will run the same pri 1 and pri 2 flow as test 6-18S-this means 45%.
shipped the hi-pot tester. I signed off on the spares list and gave it DLR. They signed it and returned. received DLR's version of the time allocation for June. I gave them my input and am waiting for revisions.
1415 DLR setting up for calibration test-heater is ready.
1530 We were informed that the amplifier for the mass flowmeter is not functioning properly and we will not perform the calibration as requested. they will do it after we leave.
1630 we had another meeting with DLR. They are concerned about the 1200 amps on the single anode for long duration. We agreed to run a long test to see where we are. the first 5 minutes will be at 1000 amps and the final 2 at 1200 amps.
the bolts on the cathode were rechecked prior to the test

we ran test 6-19 for 6 minutes. we shutdown because of roughness in the flowstream and other parameters. The pressure at 1000 amperes is 16.5 bar for 4100 volts. This voltage is 200 volts above the promised power supply envelope.
borescope results:

anode and cathode regions look fine the cathode has shed copper on adjacent flanges and anode also has lost some copper to adjacent parts. the constrictor bore has more copper in it than normal, but looks ok. there are some segments that need closer attention, i.e. flange segment for pack 1. these are probably not getting the cooling required because of the DLR manifold weld problem.

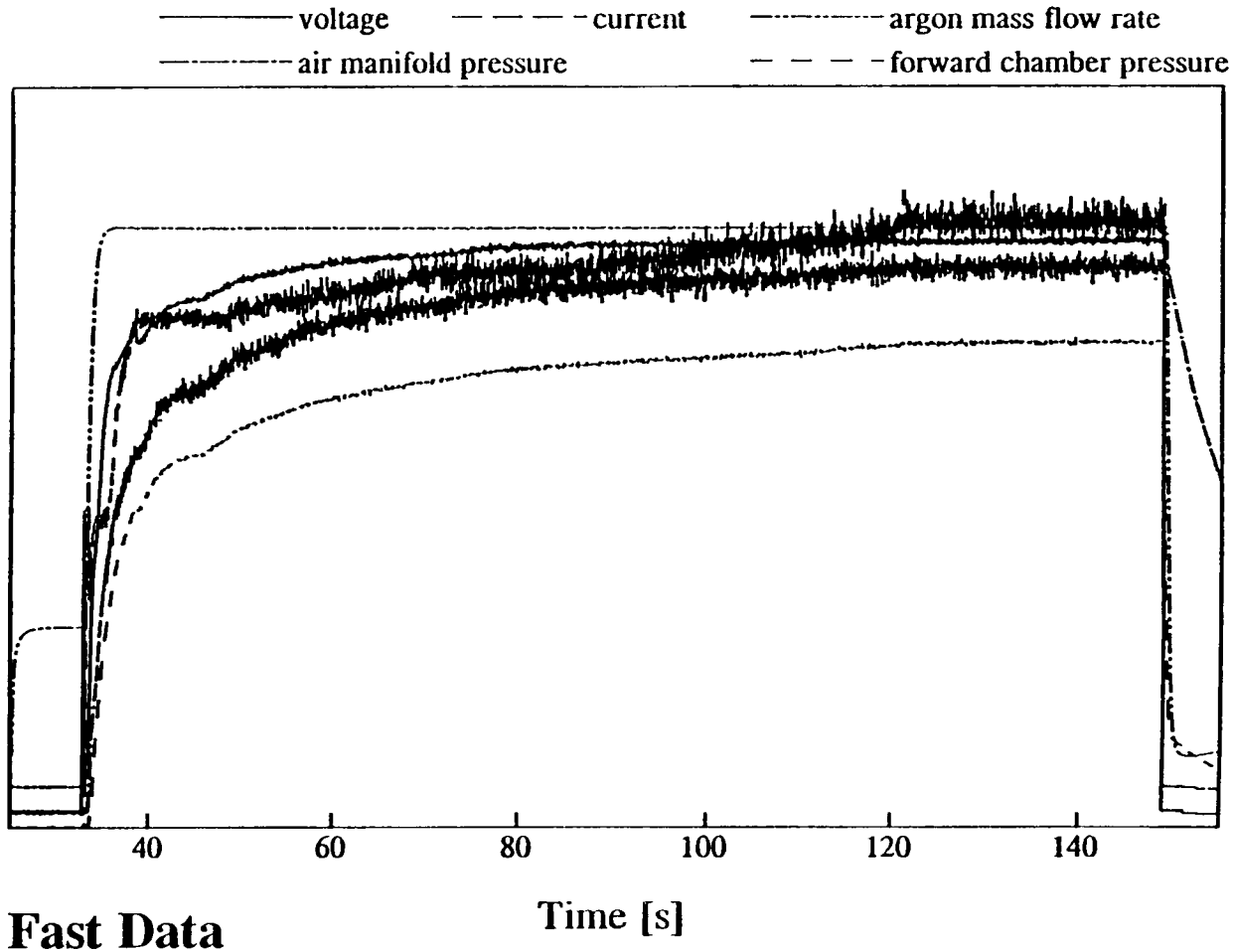
October 1995

sucessfully completed revised DLR acceptance conditions at 1000 amperes.

APPENDIX D

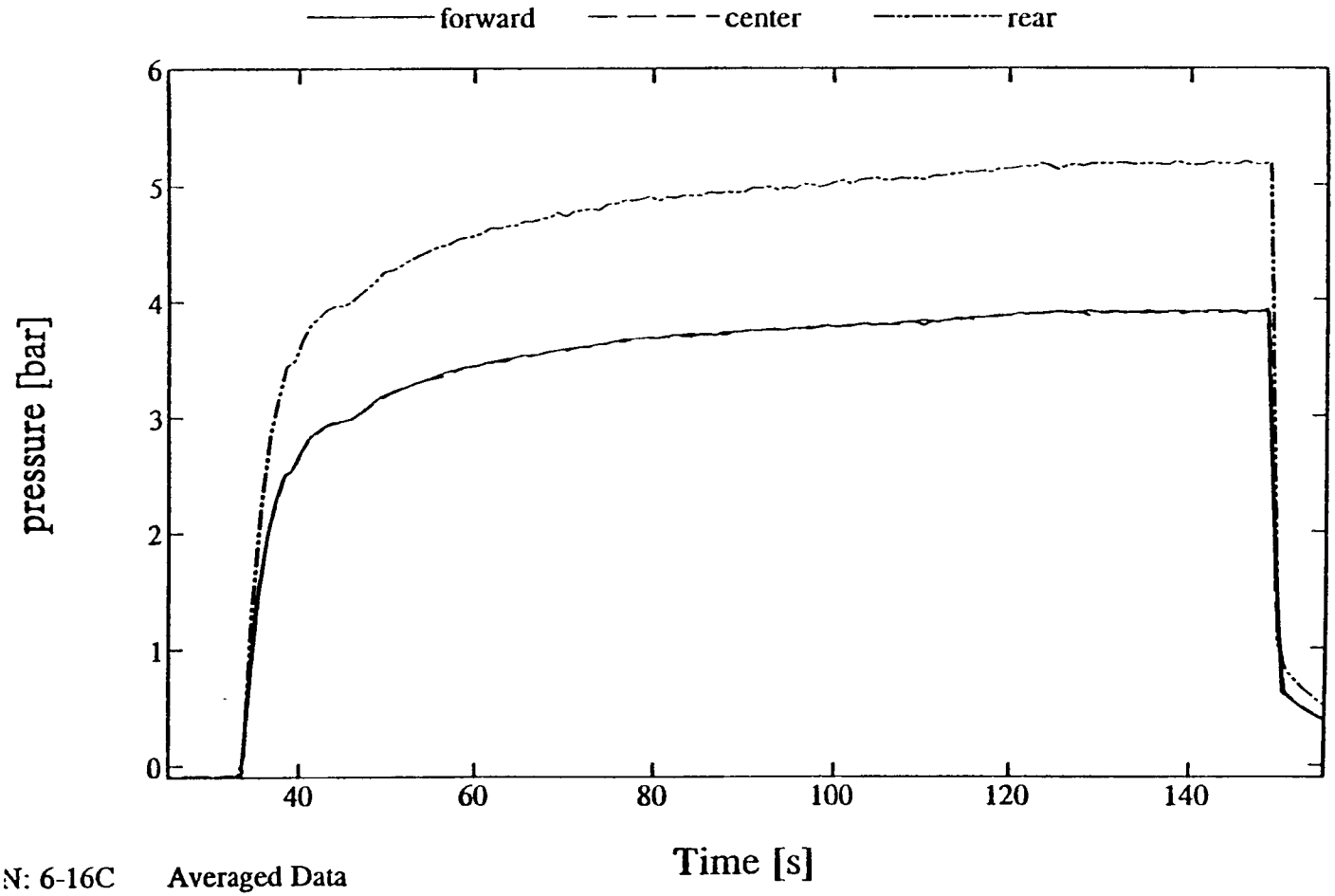
SAMPLE DLR DATA PACKAGE RUN 6-16C

Run 6-16C



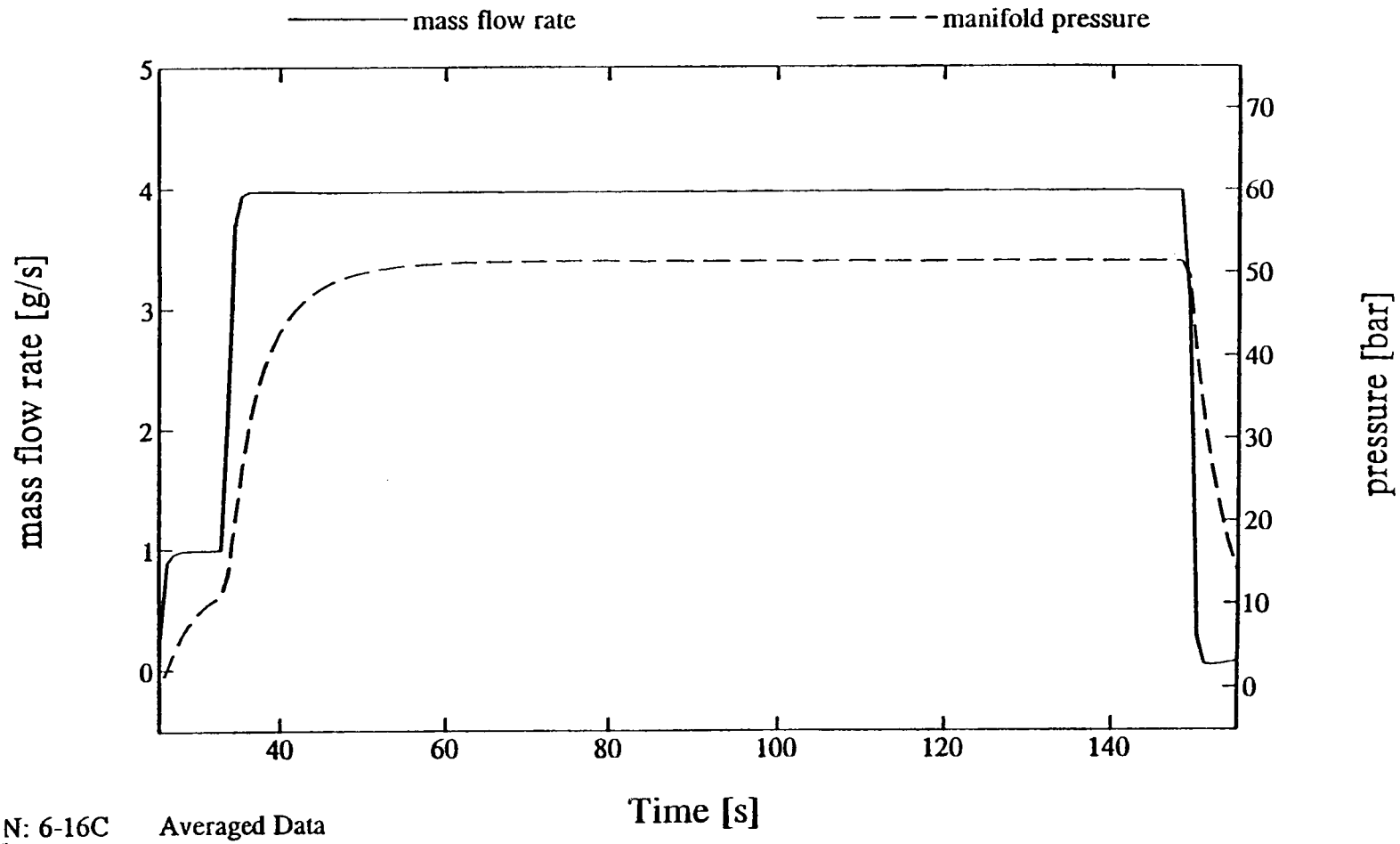
Fast Data

Arc heater chamber pressures



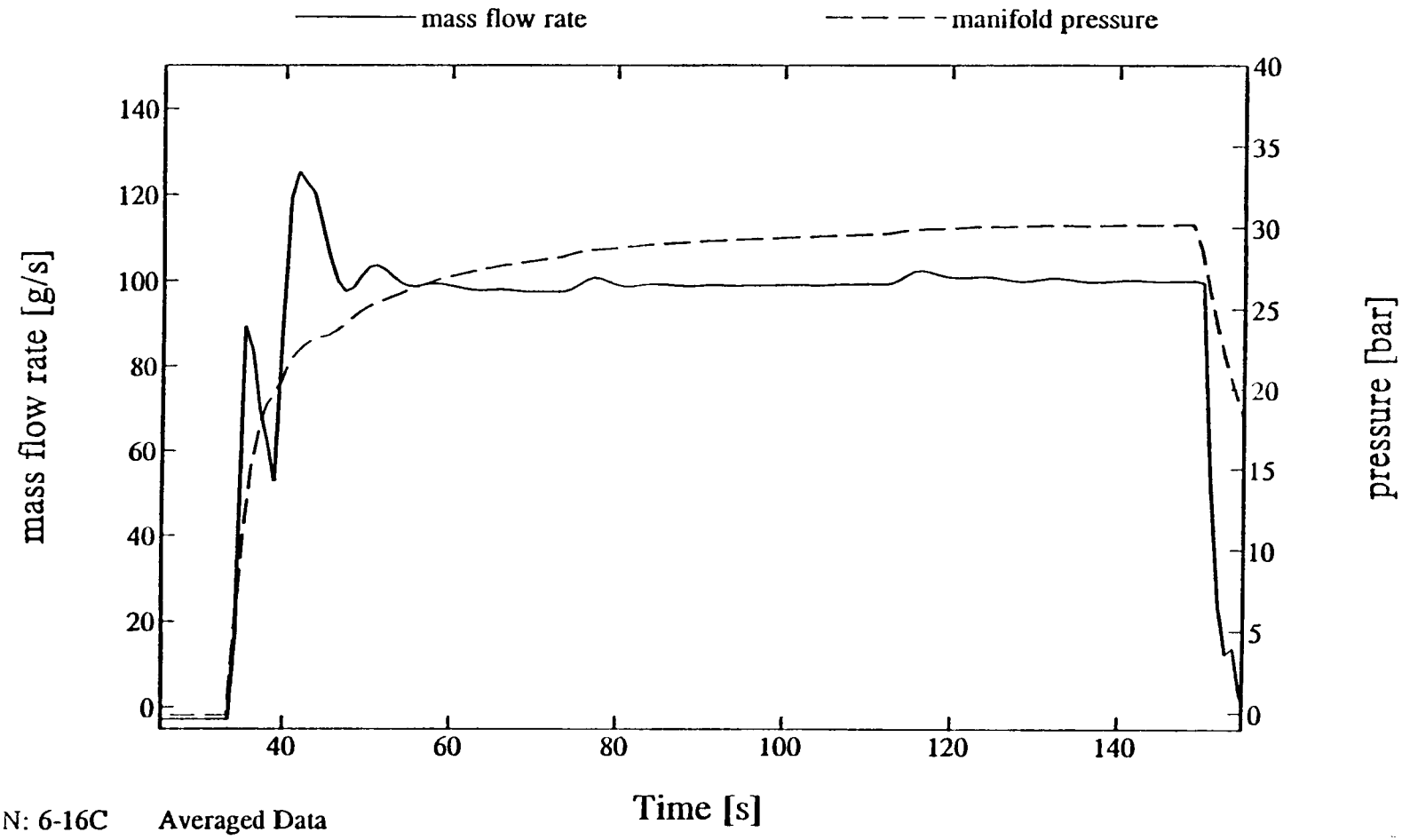
N: 6-16C Averaged Data

Argon supply system

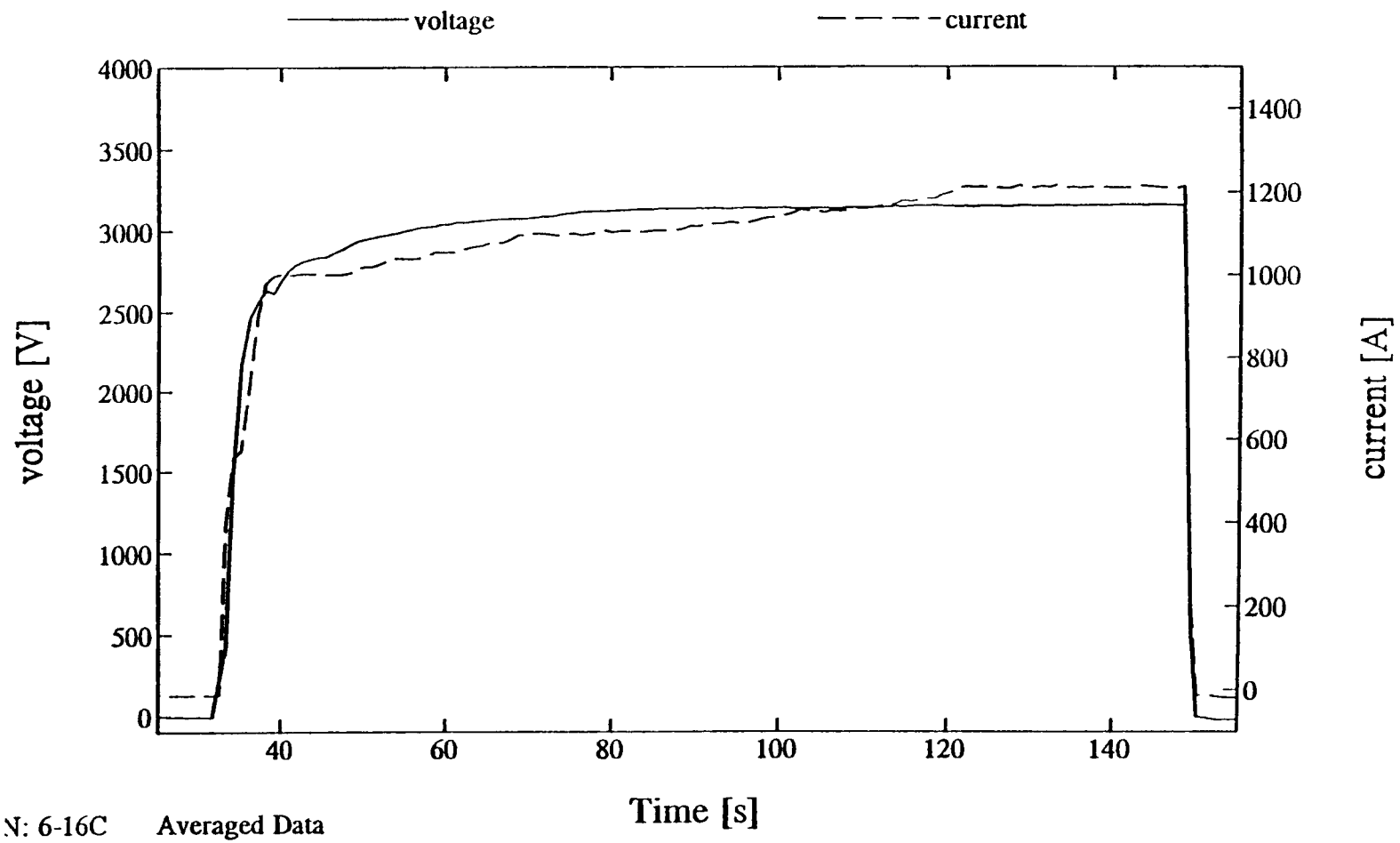


N: 6-16C Averaged Data

Air supply system

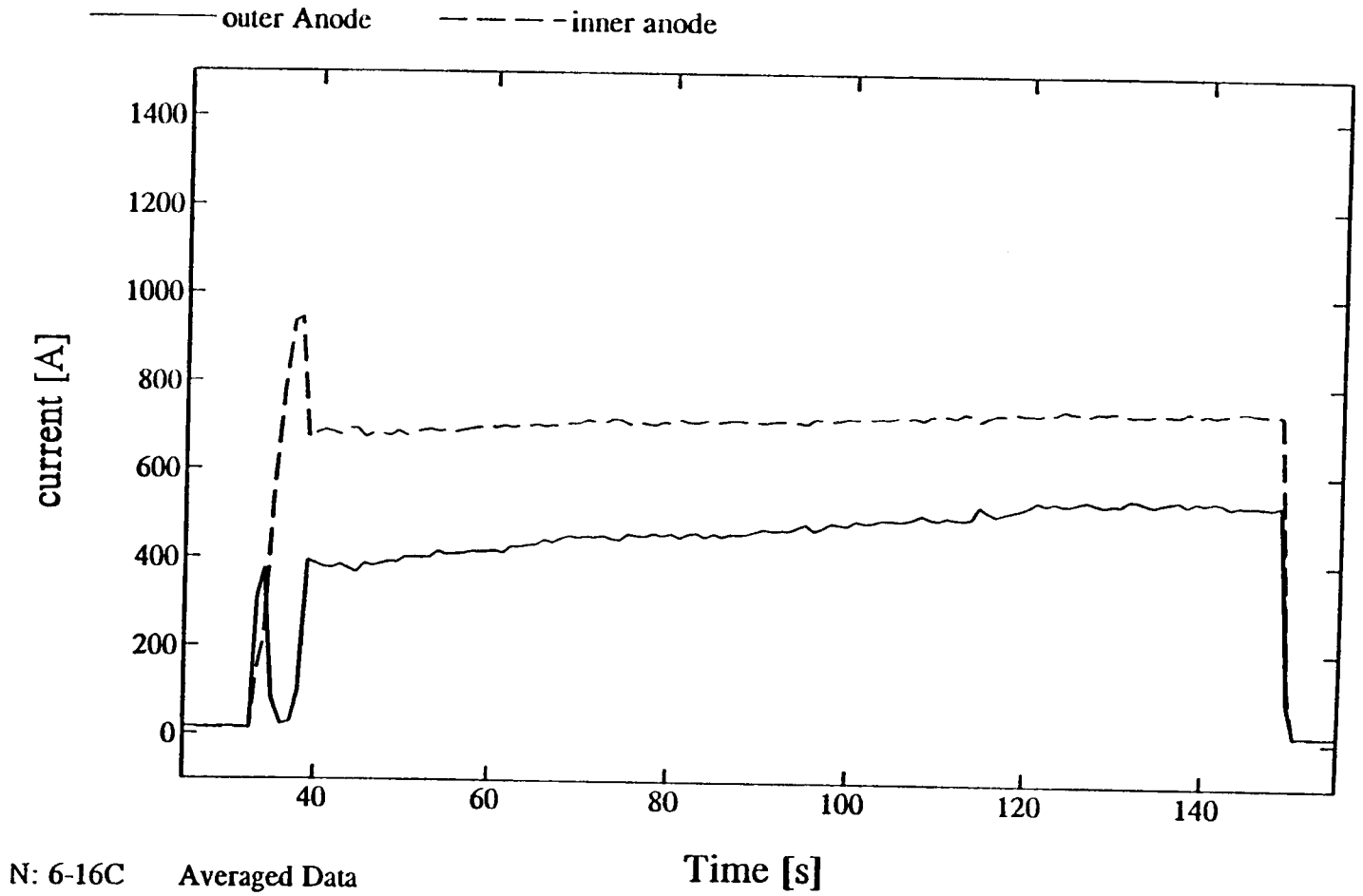


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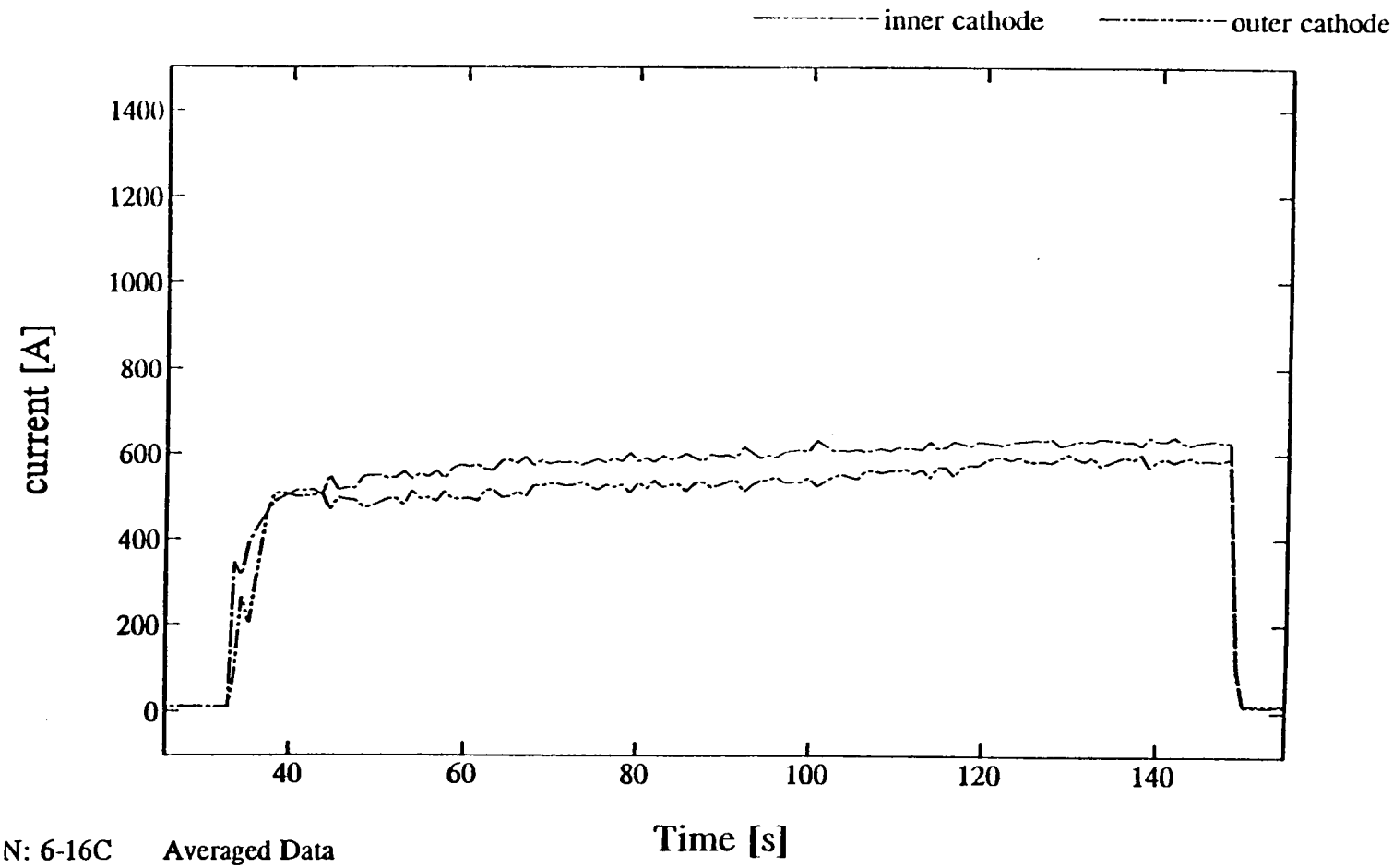
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Electrode currents



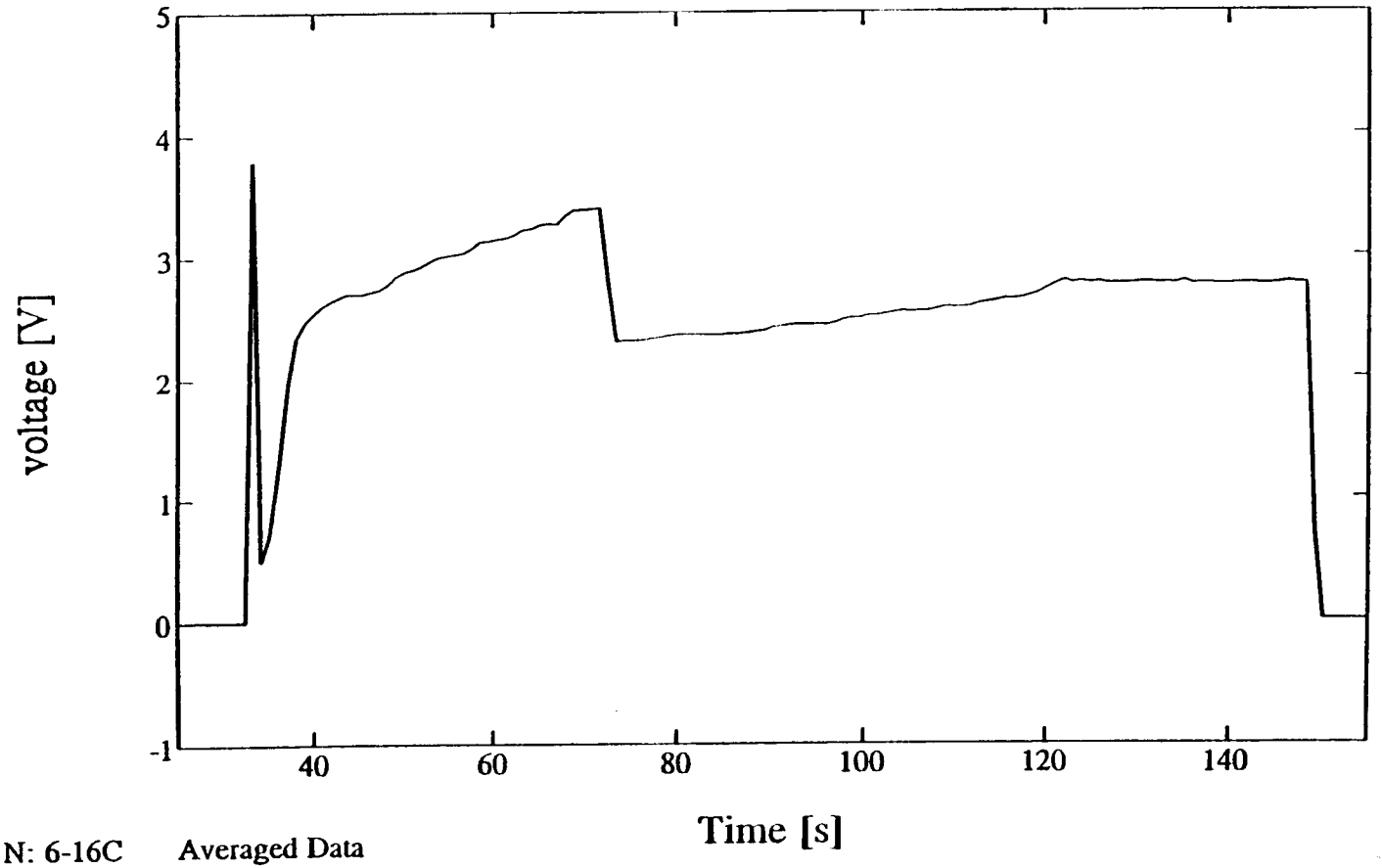
N: 6-16C Averaged Data

Electrode currents



N: 6-16C Averaged Data

Photocell



N: 6-16C Averaged Data

VITA

Robert Kenneth Smith was born in Bedford County, Tennessee on July 26, 1954. He attended public schools in Shelbyville. Tennessee and graduated as salutatorian of his high school class in 1972. After graduation he attended the University of Tennessee at Knoxville as a mechanical engineering major. As a recipient of the L.J.Sverdrup scholarship, he worked as a cooperative engineer at Arnold Engineering Development Center(AEDC)in the von Karman Facility. At UTK Mr. Smith was chosen as a member of the Pi Tau Sigma honorary fraternity and graduated in 1977 with Honors. He accepted a position as project engineer at the John C Stennis Space Center with Rockwell International on the Space Shuttle Main Propulsion Test Article.

After supporting full duration test firings of the Space Shuttle Main Engines for three years, Mr. Smith moved to the Kennedy Space Center and became Rockwell Space Shuttle main propulsion system specialist for launch operations. In this position he was responsible for coordinating design changes, pre and post flight Orbitor vehicle inspections, cryogenic loading support, test procedures, data review and other tasks required to support the ground checkout and launch of the Space Shuttle Orbitor main propulsion system. He maintained this position from the first launch of Columbia in 1981 through the Challenger disaster and the 'return to flight' mission of Discovery in 1988. In parallel with his work at KSC, Mr. Smith earned a Masters of Science Engineering (MSE) degree from the University of Central Florida in 1987.

In 1989 Mr. Smith returned to Tennessee as a project manager for Sverdrup Technology. He also enrolled at the University of Tennessee Space Institute (UTSI) to pursue a doctoral degree in mechanical engineering. He returned briefly to America's space program as a member of the data analysis review team at the Johnson Space Center when the Space Shuttle fleet was grounded in 1990 because of unexplained hydrogen leaks.

As a Sverdrup project manager, he has specialized in the design of high temperature and rocket test facilities. This work includes conceptual, preliminary and final designs of plasma arc heated test facilities in the US, Japan and Europe and modifications to the large liquid propulsion test facilities at NASA Stennis Space Center in Bay St. Louis, Mississippi.