FINAL TECHNICAL REPORT

For The

AFE ION MASS SPECTROMETER DESIGN STUDY
LaRC Cooperative Agreement #NCC1–119

Submitted To

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA 23665–5225

From

THE UNIVERSITY OF TEXAS AT DALLAS
CENTER FOR SPACE SCIENCES
P.O. BOX 830688, MS FO.22
RICHARDSON, TEXAS 75083–0688

PERIOD OF PERFORMANCE: JUNE 1, 1987 THROUGH MARCH 31, 1989

Prepared by: _Willie Wright_   Approved by: _John H. Hoffman_
Willie Wright   John H. Hoffman
Program Manager   Principal Investigator
(214) 690–2840   (214) 690–2840

March 14, 1989

ABSTRACT

This final technical report covers the activities engaged in by the University of Texas at Dallas, Center for Space Sciences in conjunction with the NASA Langley Research Center, Systems Engineering Division in design studies directed towards defining a suitable ion mass spectrometer to determine the plasma parameter around the Aeroassisted Flight Experiment vehicle during passage through the earth's upper atmosphere. Additional studies relate to the use of a Langmuir probe to measure windward ion/electron concentrations and temperatures. Selected instrument inlet subsystems were tested in the NASA Ames Arc–Jet Facility.

1.0 SUMMARY

This Final Technical Report covers the research performed by the University of Texas at Dallas, Center for Space Sciences, toward accomplishing the research objectives of NASA Cooperative Agreement No. NCC1–119 entitled "AFE Ion Mass Spectrometer Feasibility Study". The instrumentation investigation performed under this study was for the intended purpose of defining a set of instruments capable of determining the chemical identification and measuring the concentration of the ionized component in the shock layer on the windward side of the Aeroassist Flight Experiment vehicle during flight through the upper atmosphere. A conceptual design is presented for the accomplishment of the measurements listed above. An ion mass spectrometer design has been studied to accomplish the identification of chemical species and the quantization of the positive ions. A Langmuir probe design has been studied to provide electron and ion concentration and temperatures. Laboratory studies were performed simulating the two instruments against the expected flight requirements. The following paragraphs provide details of the research accomplishments.

2.0 COOPERATIVE EFFORT

The research covered by this report was made possible by the direct scientific and technical support of the NASA AFE Team members. Specifically over the course of this investigation the following cooperative support was provided by NASA:

a) A theoretical model of the aerothermodynamic properties on the windward side of the AFE.

b) Thermal, electrical, and physical properties of the surface from which ions are to be measured.

c) The sample tile material for the test and coordination of the testing and data reduction in the NASA Arc–Jet Test Facility.

d) Revised levels of predicted ion concentration and electron temperatures as they were available from the computational fluid dynamics analysis.

e) Coordination of the effort with the AFE Team and the reporting of the feasibility study to the AFE Team.

The expertise of the Systems Engineering Laboratory at LaRC and the Arc–Jet Test Facility at Ames were exceptionally important to this research.

3.0 LANGMUIR PROBE STUDY

The primary objectives of the Langmuir probe Study were accomplished with the completion of the testing of the model probe in the Ames arc–jet chamber.

3.1 Langmuir Probe Description

The probe consisting of a BeO body having iridium tube inserts and vapor deposited iridium reference planes was successfully fabricated and assembled into a test article suitable for arc–jet testing in the Ames 20MW Arc–Jet Facility. Figure 3.1 gives design details on the Langmuir probe. The arc–jet test was conducted with a survey level heat input of 3 BTU in^{-2}sec^{-1}. The probe heated excessively beginning near the pitot tube and extending upwards to the peak area. The probe body fractured laterally beginning at the mouth of the pitot tube. Although the test was terminated after 70 seconds, thermocouple, pyrometer, and video data were obtained. The following list of significant accomplishments resulted from the test program:

a) Fabrication of a BeO probe and demonstration of its "safe" operation in the arc–jet facility at temperatures in excess of the AFE requirements.

b) The development of a process for the deposition of iridium on the BeO surface.

c) The development of a process for attaching thermocouples and wire leads to iridium.

d) Design and fabrication of TPS tiles and their installation around the Langmuir probe in the test article.

e) The installation and calibration of thermocouples in the test article.

f) The fracture and overheating of the Probe offers evidence of deficiencies in design in the area of the pitot tube. The test experience using the 20MW Arc–Jet Facility provided new data on the performance of the plasma as related to this type of test.

g) The development of instrumentation to make a Langmuir probe measurement in a hot plasma.

The list above is not all encompassing but, rather, points out the range of research involved in the Langmuir probe activities. Appendix A is a report on the thermal characteristics of the probe in an arc–jet.
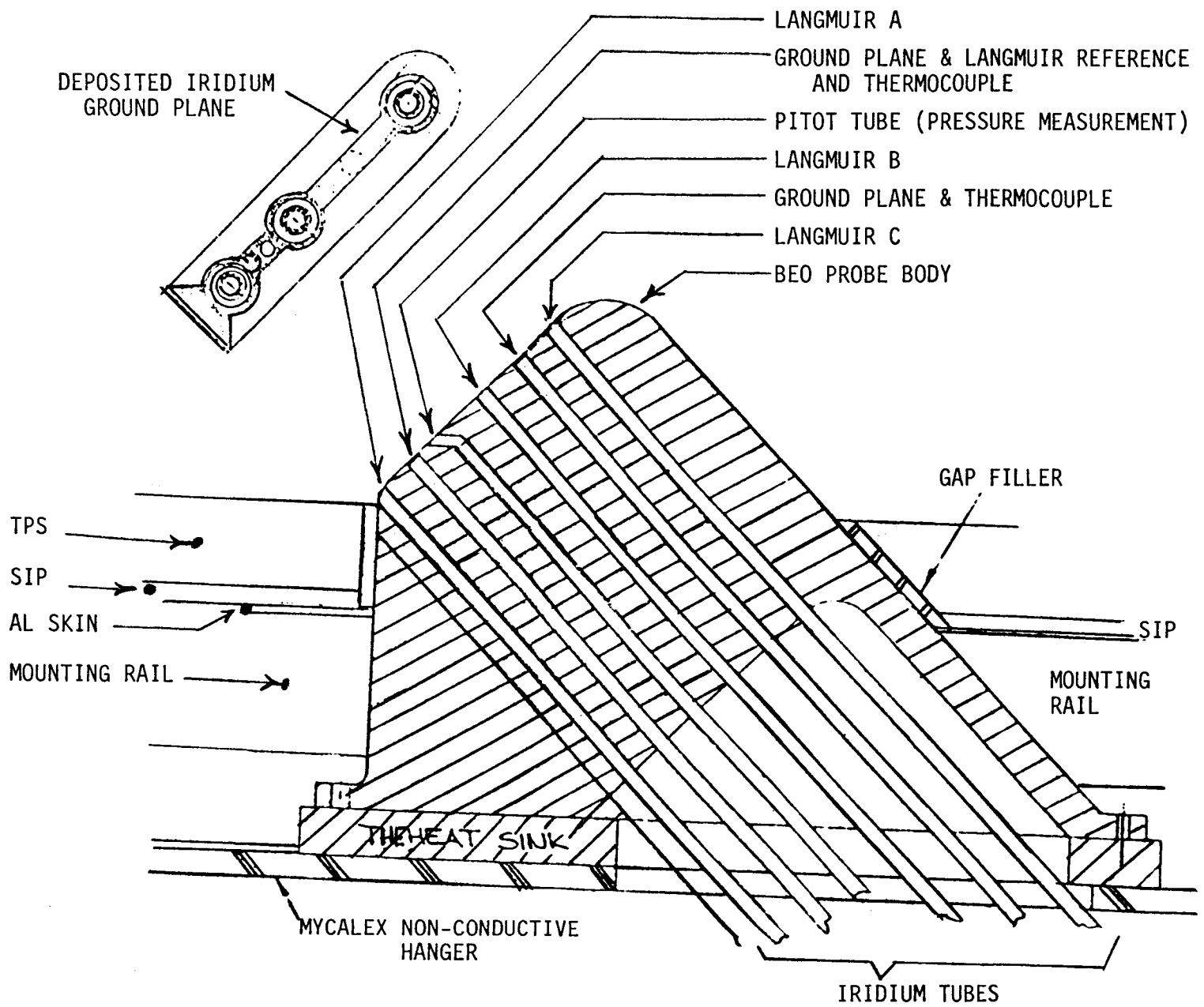
DEPOSITED IRIDIUM
GROUND PLANE

LANGMUIR A

GROUND PLANE & LANGMUIR REFERENCE
AND THERMOCOUPLE

PITOT TUBE (PRESSURE MEASUREMENT)

LANGMUIR B

GROUND PLANE & THERMOCOUPLE

LANGMUIR C

BEO PROBE BODY

GAP FILLER

TPS

SIP

AL SKIN

MOUNTING RAIL

SIP

MOUNTING
RAIL

THE HEAT SINK

MYCALEX NON-CONDUCTIVE
HANGER

IRIDIUM TUBES

FIGURE 3.1   LANGMUIR PROBE DESIGN DETAILS

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4.0   ION MASS SPECTROMETER STUDY

The IMSE study resulted in the selection of an miniature magnetic sector mass analyzer interfaced to the windward AFE surface by an iridium cup mounted into a TPS tile with a .005 inch diameter orifice to serve as a gas inlet to the mass analyzer. An ion pumped differential pumping system was selected to interface the high pressure to low pressure regions. The iridium cup and orifice system was tested in the Ames 20MW Arc–Jet Facility.

The vacuum pumping system was simulated in the UTD laboratory. These test results are summarized as follows:

a) Demonstrated successfully that the iridium cup and orifice will survive the arc–jet plasma environment.

b) Demonstrated successfully that the IMSE configuration can provide the vacuum environment necessary to make ion measurements in the expected AFE entry environment. These results were obtained using vacuum–ion pumps and a wake vent tube.

c) Developed Vendor sources for iridium and iridium fabrication along with welding and brazing of iridium to titanium.

4.1   Ion Mass Spectrometer Instrument Description

To study the plasma parameters around the AFE vehicle during passage through the earth's upper atmosphere, it is proposed to use a miniature magnetic sector–field mass spectrometer mounted behind the aerobrake with inlet oriented to look in the ram direction.   Specific information to be provided by the instrument is the chemical identification and number density of the charged particles in the windward side boundary layer. In addition, a neutral gas composition measurement would be obtained periodically throughout the flight. Flight data would provide a baseline for validating non–equilibrium flow field computer models and for correlating with radiative heat transfer data. Verification of chemistry models, which relate to the heat budget problem, will be possible once the ion species and their concentrations are determined. By having baseline data that will place flow field models on both the windward and leeward sides of the AFE vehicle on a firmly established basis, the design of the future Aeroassist Orbital Transfer Vehicles (AOTV) will be greatly enhanced.

Data from the mass spectrometer can be correlated with the ion and electron

concentration results from the Langmuir probe to provide absolute number densities of the identified ion species. Neutral gas densities can be obtained by correlating the mass peaks with the pressure data from the Langmuir probe to obtain concentrations for each gas species identified in the mass spectra. Neutral gas concentrations are needed to determine the background gas composition — whether it be ambient atmospheric gases or gases contaminated by outgassed species from the surface of the vehicle. Ion species formed in the bow shock that interact with neutral gas molecules close to the IMSE entrance aperture will sustain the possibility of compositional alteration. In order to determine the extent of this process, the neutral gas composition must be known. By sampling the neutral gas molecules and ions through the same port, ion—neutral chemistry processes can be identified. Any significant unexpected neutral or ion species should be added to computational flow field model calculations.

The current models of the composition of both neutral and ion species as a function of distance from the AFE vehicle surface are given in Figures 4.1 and 4.2. The abscissa scales of the two figures are different, but the results show that the ion composition has a significant trough near the vehicle surface, probably due to recombination at the surface. These models are based on ambient gas composition for the atmosphere. Neutral gas pressures ranging from on—orbit at $<10^{-6}$ torr to 15 torr (2000 N/m^2) at 87 km lie within the range of operation of the neutral gas analyzer. Ion concentrations from 10^8 to 10^{16}/cm^3 can be measured with the very wide dynamic range detector that will be used.

The IMS is a miniature magnetic mass spectrometer that is mounted just under the aerobrake surface about midway between the Microwave Reflectrometer Ionization Sensor (MRIS) and the Langmuir probe rake along the same 4° ray. Figure 4.3 shows the configuration of the instrument. It has several major parts that are related to the vacuum pumping system and are designated by A through D in the figure. The entrance aperture consists of a 2.5 cm diameter iridium cup with a flat end that is flush mounted with the thermal tile surface on the forward side of the aeroshell. The cup is heat sinked through a ring of titanium to a mycalex plate that provides electrical isolation for the cup and transfers heat to the structure of the aerobrake vehicle. Iridium was chosen for the cup material because of its very high melting point, 2450° C, extreme inertness and good thermal conductivity. A gold—palladium braze is used to join the iridium to the titanium heatsink. Iridium and a particular alloy of titanium (Ti—6Al—2Sn—4Zr—4Mo) have compatible thermal expansion coefficients so the vacuum integrity of the system can be maintained during the rapid heating cycle of entry into the atmosphere. Ambient gases
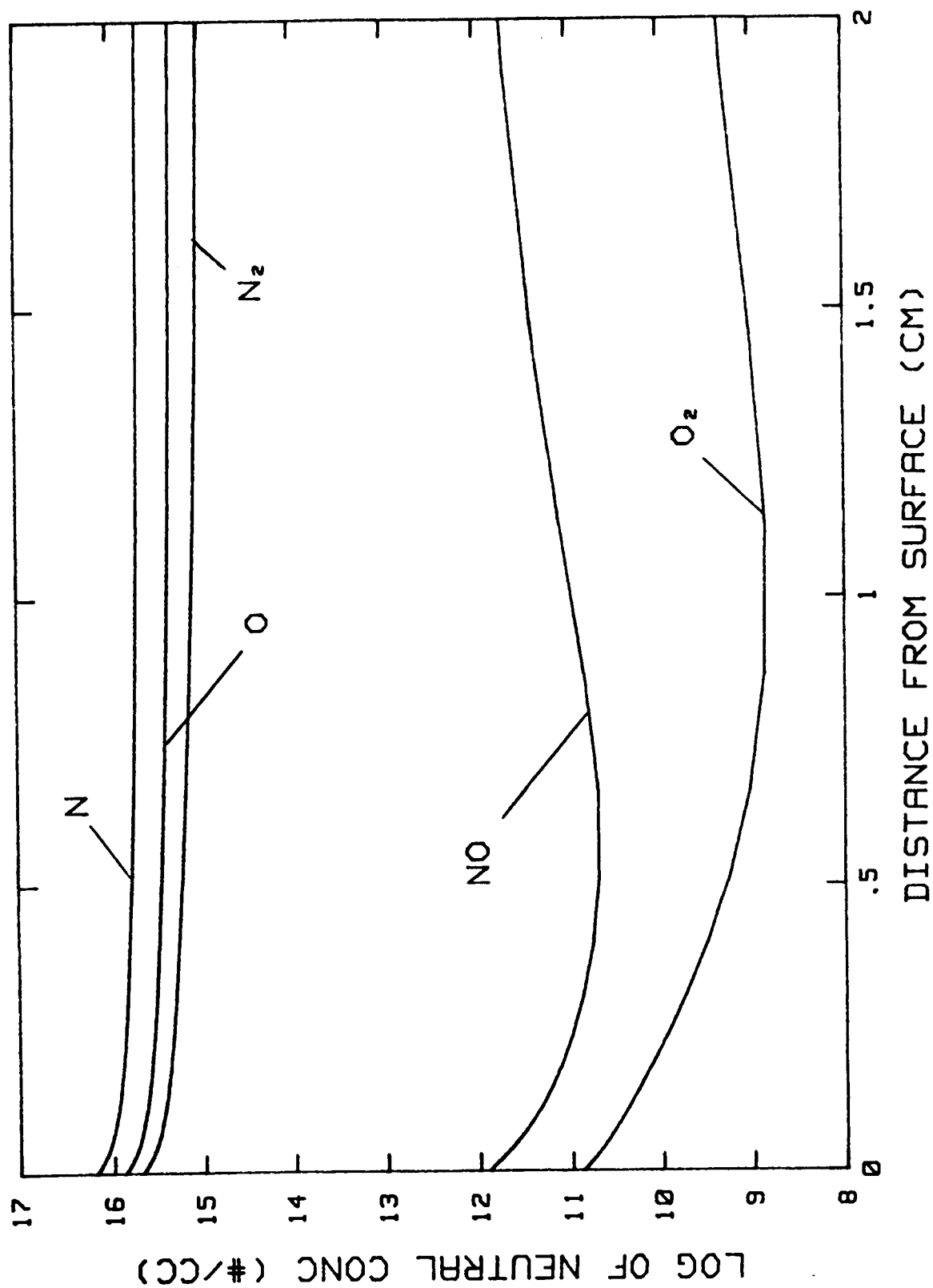
Figure 4.1. Neutral gas species concentrations as a function of distance from aeroshell surface.
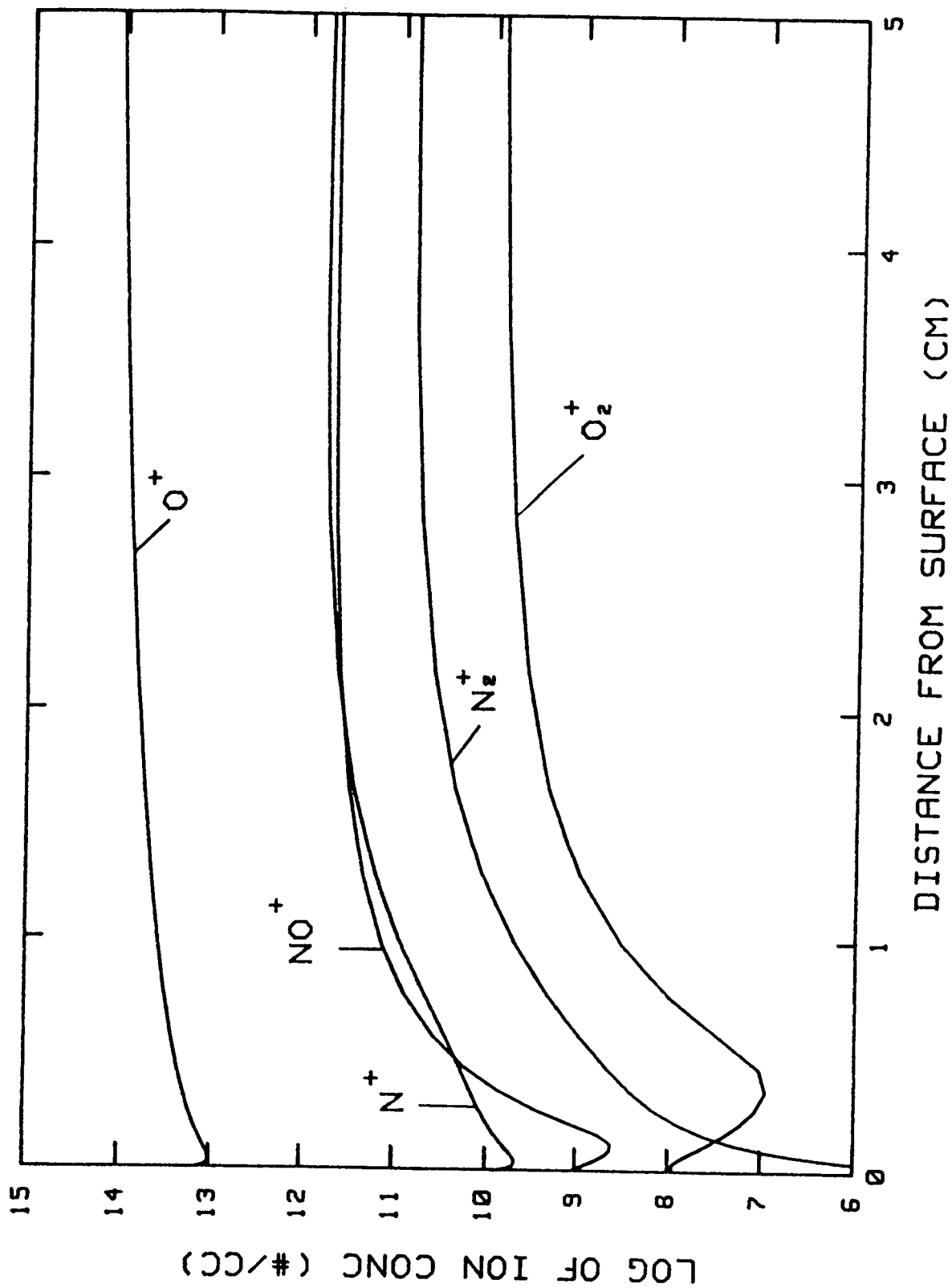
Figure 4.2.   Ion species concentrations as a function of distance from aeroshell surface.
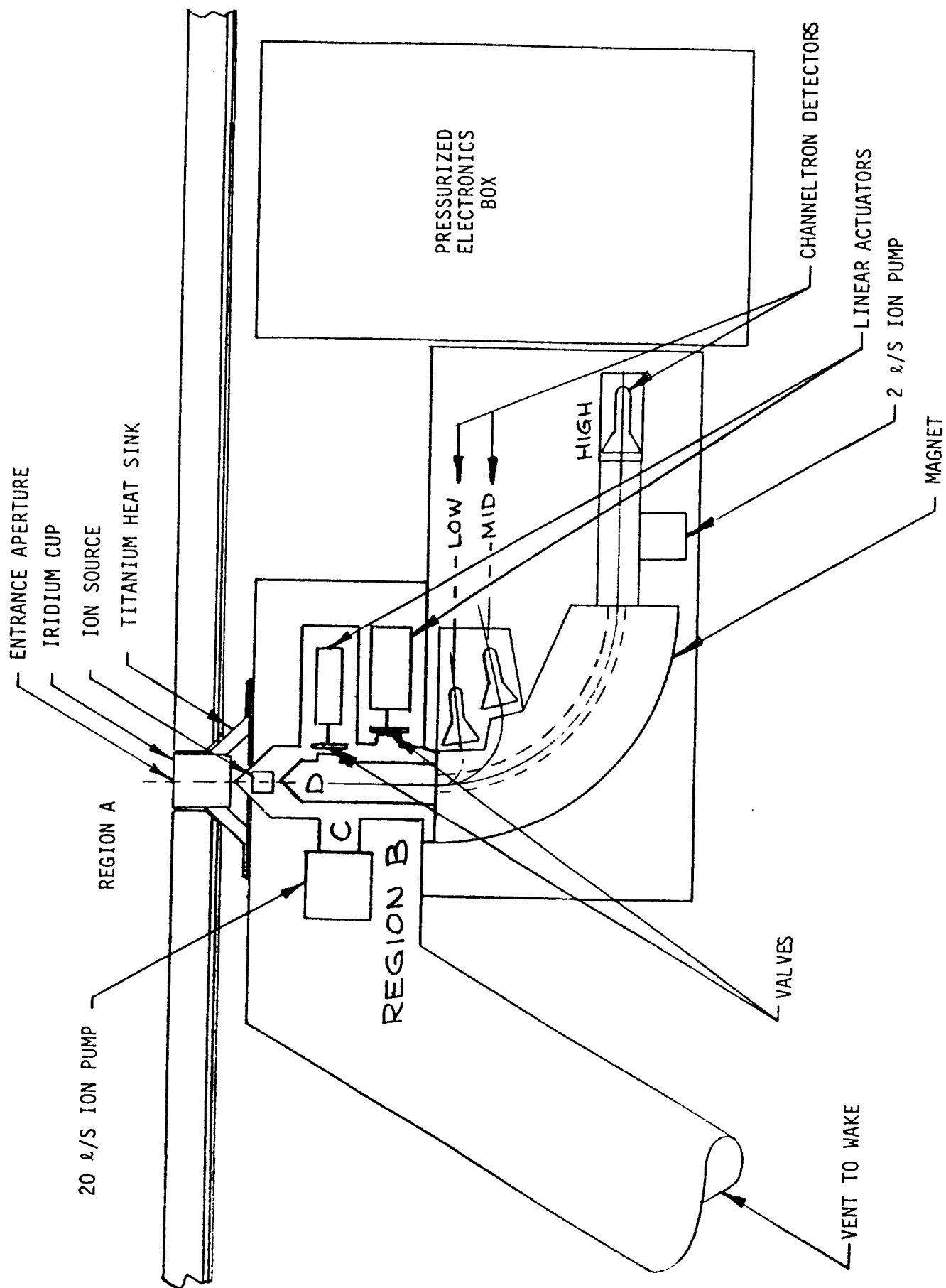
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ENTRANCE APERTURE
IRIDIUM CUP
ION SOURCE
TITANIUM HEAT SINK

REGION A

20 ℓ/S ION PUMP

REGION B

VENT TO WAKE

VALVES

MAGNET

2 ℓ/S ION PUMP

LINEAR ACTUATORS

CHANNELTRON DETECTORS

PRESSURIZED ELECTRONICS BOX

LOW
MID
HIGH

C
D

Figure 4.3. IMSE Sensor configuration showing entrance aperture, differentially pumped vacuum regions, vent tube valves, and mass analyzer.

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with a mixture of plasma particles (positive ions) from the region within a few mean free paths of cup's outer surface (Region A in Figure 4.3) flow through the cup's orifice and are allowed to expand freely into Region B. Cone B–C acts as a skimmer that allows only a small fraction of the gas to flow into Region C. The remaining gases are vented to the wake side of the AFE vehicle through a large tube. The maximum pressure in Region B is 10^{-3} torr when the ram pressure is 20 torr. Region C is pumped by a 20 ℓ/sec ion pump that maintains in it a pressure of less than 2×10^{-5} torr. The two aligned orifices (B and C) form a molecular beam of the incoming gases that impinges on a slit that is the input aperture to Region D. This slit is the object slit to the mass analyzer. The latter is pumped by a 2 ℓ ion pump that maintains its pressure in the 10^{-7} torr range, which is more than adequate for operation of the mass spectrometer. This pump was developed at UTD for the Pioneer Venus mass spectrometer (*Hoffman, et al.*, 1979b). In order to evacuate the instrument on–orbit and for functional and calibration tests, a valve operated by a linear actuator is installed between Regions B and C, and another is installed between Regions C and D. These valves are opened during initial evacuation through the vent tube until the pressure reaches a range where the ion pumps may be started (10^{-4} torr range). After the ion pumps are operating, as determined by monitoring the pump currents, both these valves are closed by a command from the microprocessor. The mass analyzer can be safely operated when the Regions C and D pressures are less than 2×10^{-5} torr.

The positive ions that accompany the gas flowing into the entrance aperture impinge on the cone B–C. Collisional losses in Region B after expansion are small. Assuming no focusing of the ion flux in Region B, approximately .01% of the flux into Region B will pass through the cone B–C. In Region C the flux will have been collimated into a beam that impinges on the entrance (object) slit to the mass analyzer (Region D). The positive ions are accelerated to the object slit by the mass analyzer high voltage (300 to 1200V). Of the order of 1% will enter the analyzer, and with a transmission factor of 10%, ambient plasma densities in the range of 10^8 to 10^{16} are measurable.

A laboratory test version of the above vacuum maintenance system has been constructed. Figure 4.4 shows two photographs of it connected to a large turbo molecular pumped vacuum chamber. Figure 4.5 is a diagram of the test configuration. The long pipe leading to the chamber has the same pumping characteristics as the vent tube in the flight configuration. The large vacuum chamber simulates the wake region that is at a pressure of less than 10^{-4} torr. The system was evacuated with all pumps operating. Residual
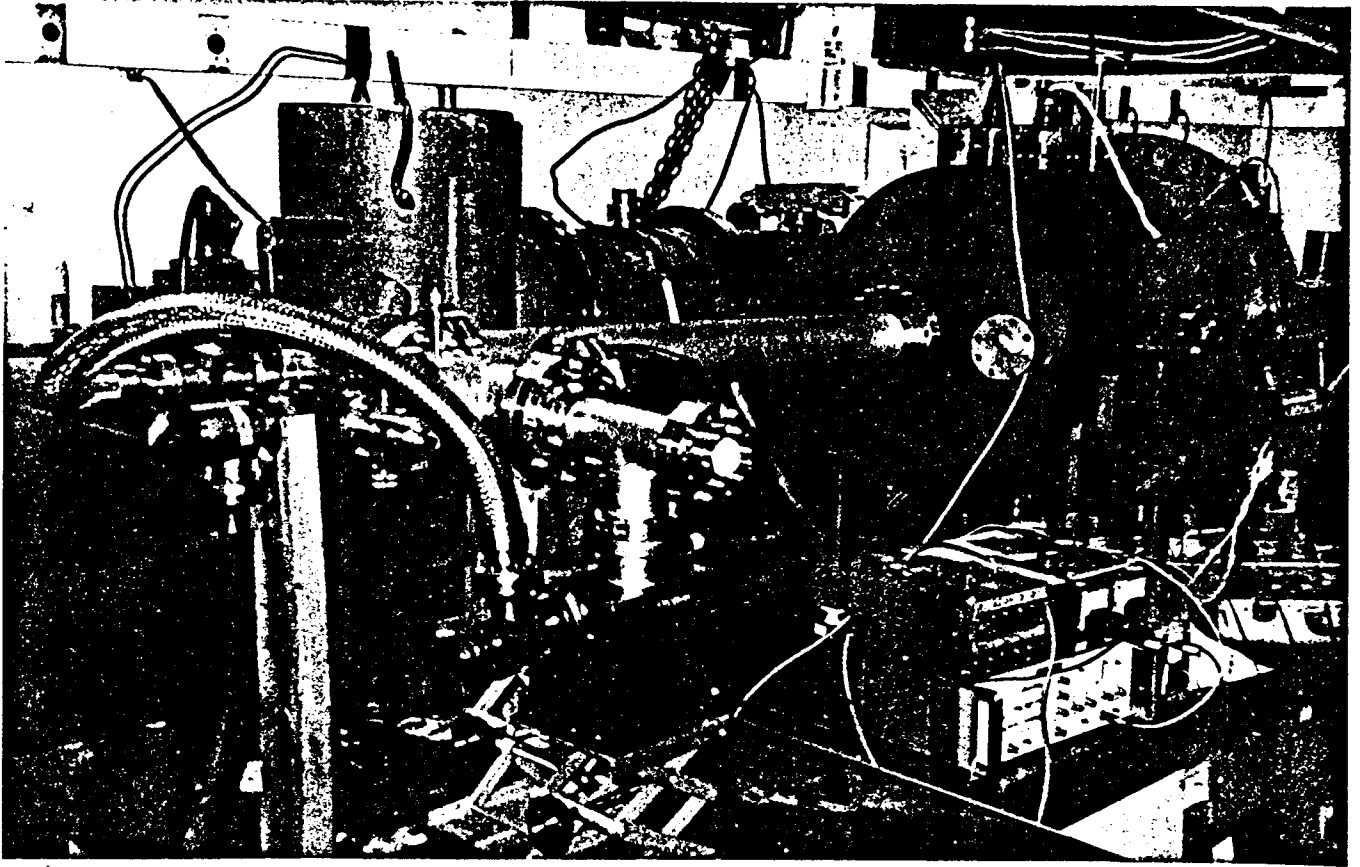
Figure 4.4a.   Photograph of IMSE vacuum test configuration showing vent tube to large vacuum chamber.
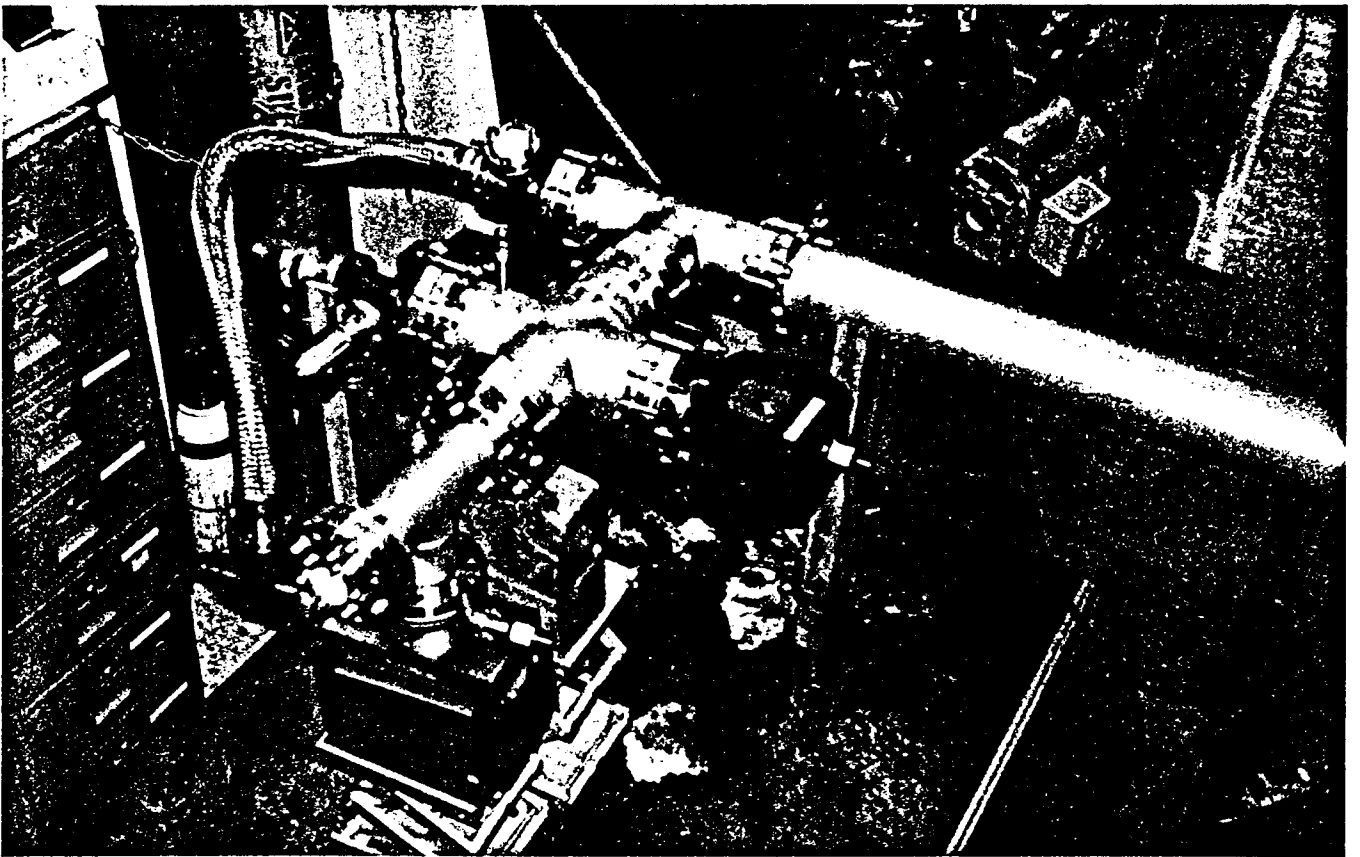

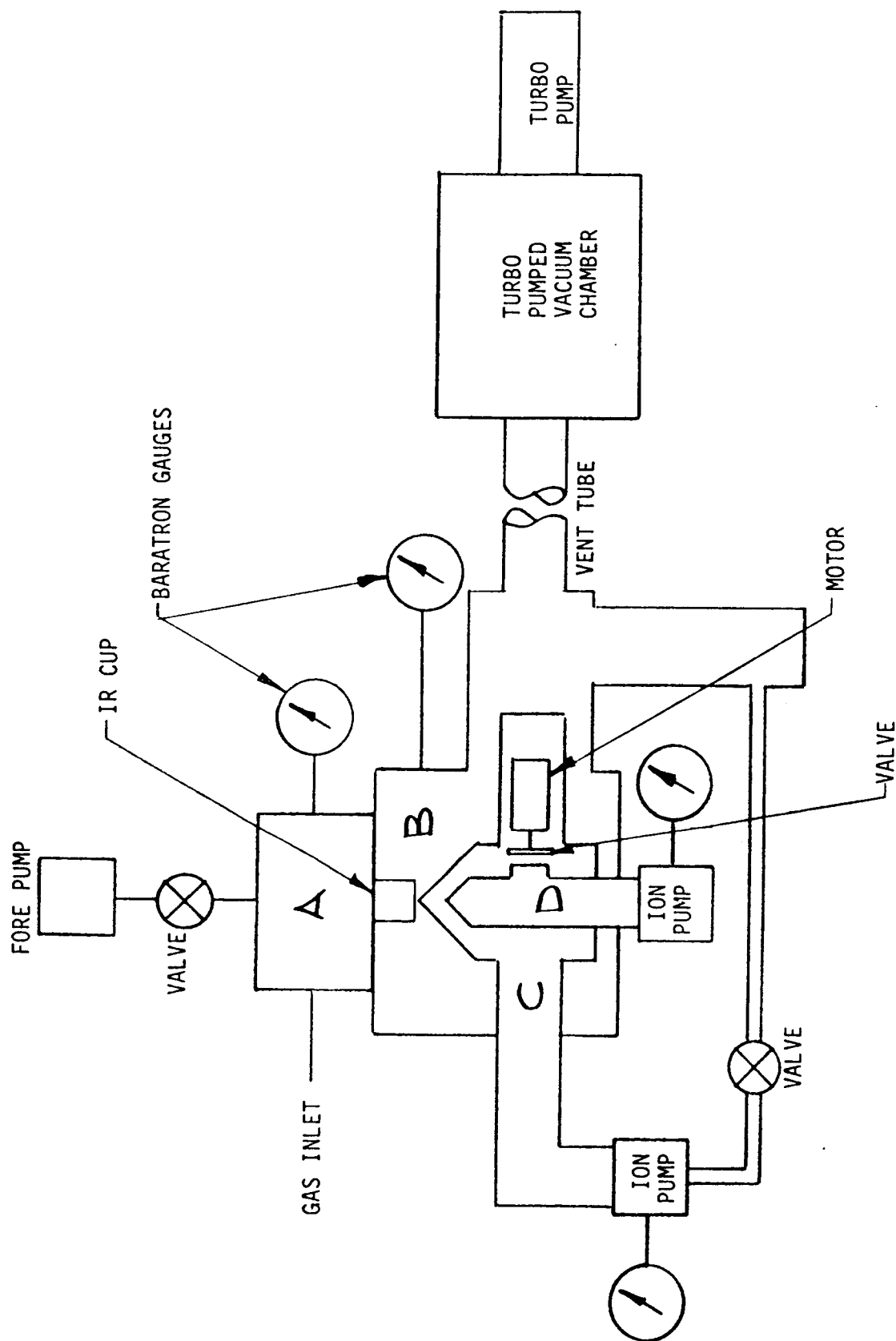Figure 4.4b.   Close-up photograph of test configuration showing ion pumps.

Figure 4.5.   Schematic of mass spectrometer test configuration.

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TABLE 4-I

Region	A	B	C	D
Pressure (torr)	0	1.0×10^{-6}	1.4×10^{-6}	4.0×10^{-7}
	1	2.4×10^{-6}	1.8×10^{-6}	5.0×10^{-7}
	2.5	6.6×10^{-6}	2.4×10^{-6}	6.0×10^{-7}
	5.8	2.2×10^{-4}	3.8×10^{-6}	7.0×10^{-7}
	10.0	4.1×10^{-4}	6.0×10^{-6}	8.5×10^{-7}
	15	6.7×10^{-4}	9.0×10^{-6}	9.5×10^{-7}
	20	9.6×10^{-4}	1.4×10^{-5}	1.0×10^{-6}
after 30 minutes	20	9.8×10^{-11}	1.3×10^{-5}	9.8×10^{-7}

<u>Pressure Sensor</u>

Region A   Baratron Gauge
Region B   Baratron Gauge
Region C   Ion Pump Current
Region D   Ion Pump Current

Orifice Size in Entrance cup (Region A to B) 0.18 mm

pressure readings are given in the first row of Table 4–I (0 torr in Region A). Air was then admitted to Region A which simulates the ambient atmosphere outside the aeroshell. The pressure was increased stepwise to 20 torr where it was stabilized. Pressures measured in each region are listed in table versus the readings in Region A. After 30 minutes, while maintaining 20 torr in Region A, pressure readings were again taken (last line in the table). Figure 4.6 is a plot of the pressure data in each region as a function of the ambient pressure (Region A). All pumps were able to maintain their respective pressures even though air (with 1% argon) was used as the test gas. The ion pumps were able to handle the argon content with ease. Based on this test, pumping system parameters for a flight model of IMSE are given in Table 4–II.

TABLE 4–II
PUMPING SYSTEMS

ENTRANCE APERTURE
   Diameter: .007"
   Length: .015"
   Pumping Speed: 3×10^{-3} ℓ/s

PUMP TUBE
   Diameter: 3"
   Length: 48"
   Pumping Speed: 50 ℓ/s

ORIFICE INTO REGION C
   Diameter: .035"
   Length: .035"
   Pumping Speed: .05 ℓ/s
   Main Sputter Ion Pump: 20 ℓ/s

MASS ANALYZER ENTRANCE SLIT
   A = .012" x .200"
   Pumping Speed: .4 ℓ/s
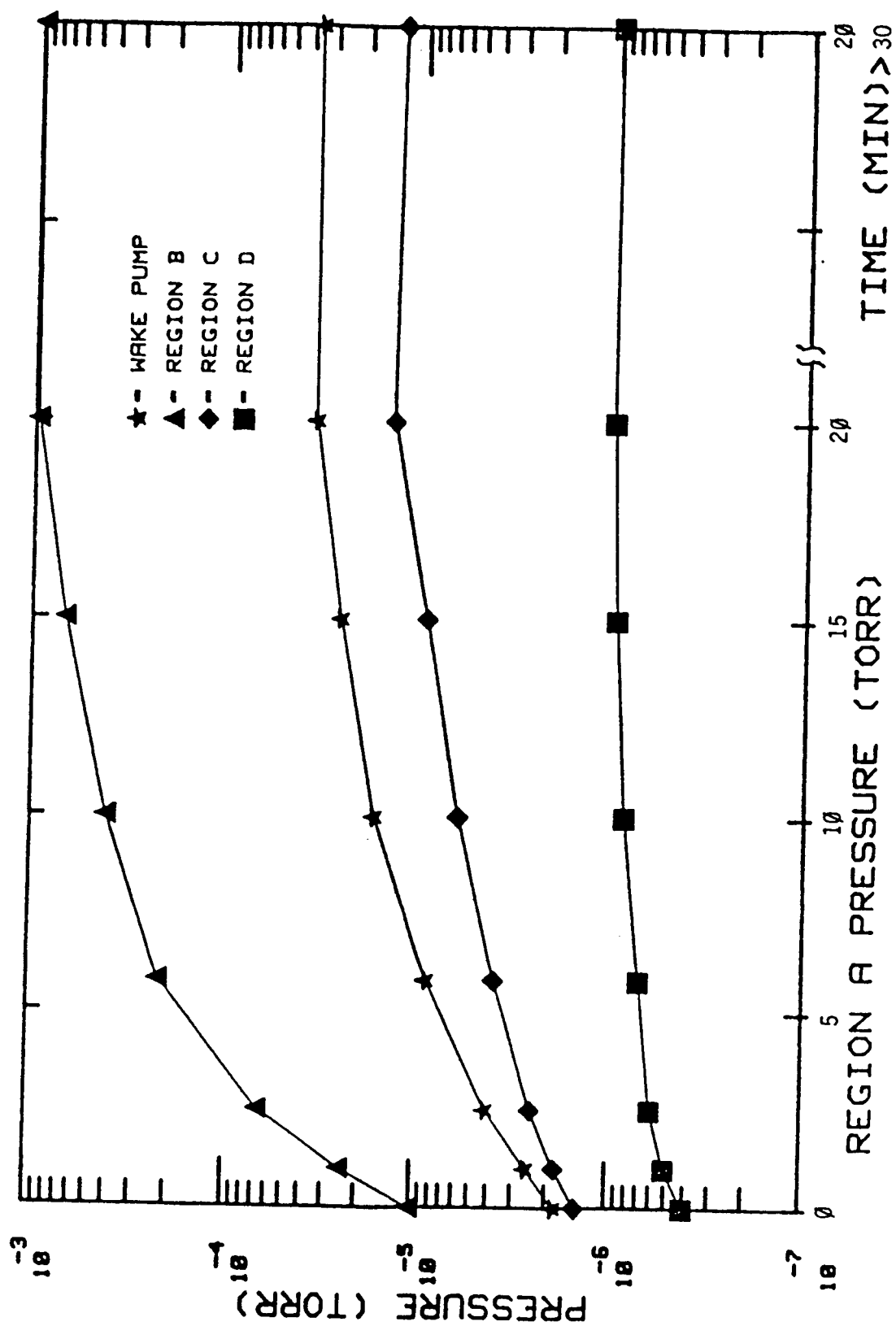   Analyzer Sputter Ion Pump: 2 ℓ/s

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Figure 4.6. Plot of pressure data taken during IMSE vacuum test.

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Positive ions that flow into the entrance orifice into Region C have been formed into a beam that is accelerated to the object slit (D) of the mass analyzer by the negative high voltage applied to the slit and following drift tubes. The ion beam then enters the magnetic field where the radius of curvature of the ion beam trajectory is proportional to $\sqrt{m}$ as given by

$$\frac{m}{e} = kR^2B/V$$

here m/e is the mass to charge ratio of the ion, R is the radius of curvature in the magnetic field of strength B, V is the ion accelerating voltage applied to the object slit drift tubes, magnet and collector slits, and k is a constant. The magnet is made of Nd–Fe–B and has a field strength in its gap of 3300 gauss. This value is typical for an ion mass spectrometer. Three paths, differing in radius of curvature by a 1:2:4 ratio, lead to three collector slits which are placed at the image points for each ion beam (See Figure 4.3). By varying the ion accelerating potential, V, over a factor of 4, from 1200 to 300 V, ions in the mass ranges 1 to 4, 4 to 16, and 16 to 64 amu are successively focused on the collector slits. The high mass channel range may easily be extended to 100 amu, or higher, simply by lowering the ion accelerating voltage. This may be necessary if there is significant outgassing from the hot aeroshell surface because NO⁺ charge exchanges readily with other molecules and to see the complete ion population an extended mass range will be necessary. The mass scan is under the control of the microprocessor so the extensions are easily implemented. The low mass channel which covers H^+, H_2^+, and He^+ is optional depending on the model predictions as to the expected density of hydrogen ions. The presence or absence of this channel does not affect the design of the rest of the instrument.

Mass resolution is defined herein as the interference or overlap between peaks in the spectrum. Interference from a given peak at mass M to a peak at M ± 1 amu shall be less than 1% of the given peak; and at M ± 2 amu it shall be less than 0.05% of the given peak. The mass spectrum of SO_2 shown in Figure 4.7 clearly shows that these conditions exist for the SO peak, 48 amu, vs 47 and 46 and would also hold for the high mass side of the 48 amu peak if it were not for the sulfuric isotopes, ³³S(0.75%) and ³⁴S(4%) which produce the peaks at 49 and 50 amu. For the low and mid mass channels, the resolution will also meet the above criteria. Mass resolution (M/ΔM) of each of the three channels is set by the slit widths and can be adjusted by simply changing the collector slits.

The relative sensitivity of the instrument will be demonstrated in the calibration
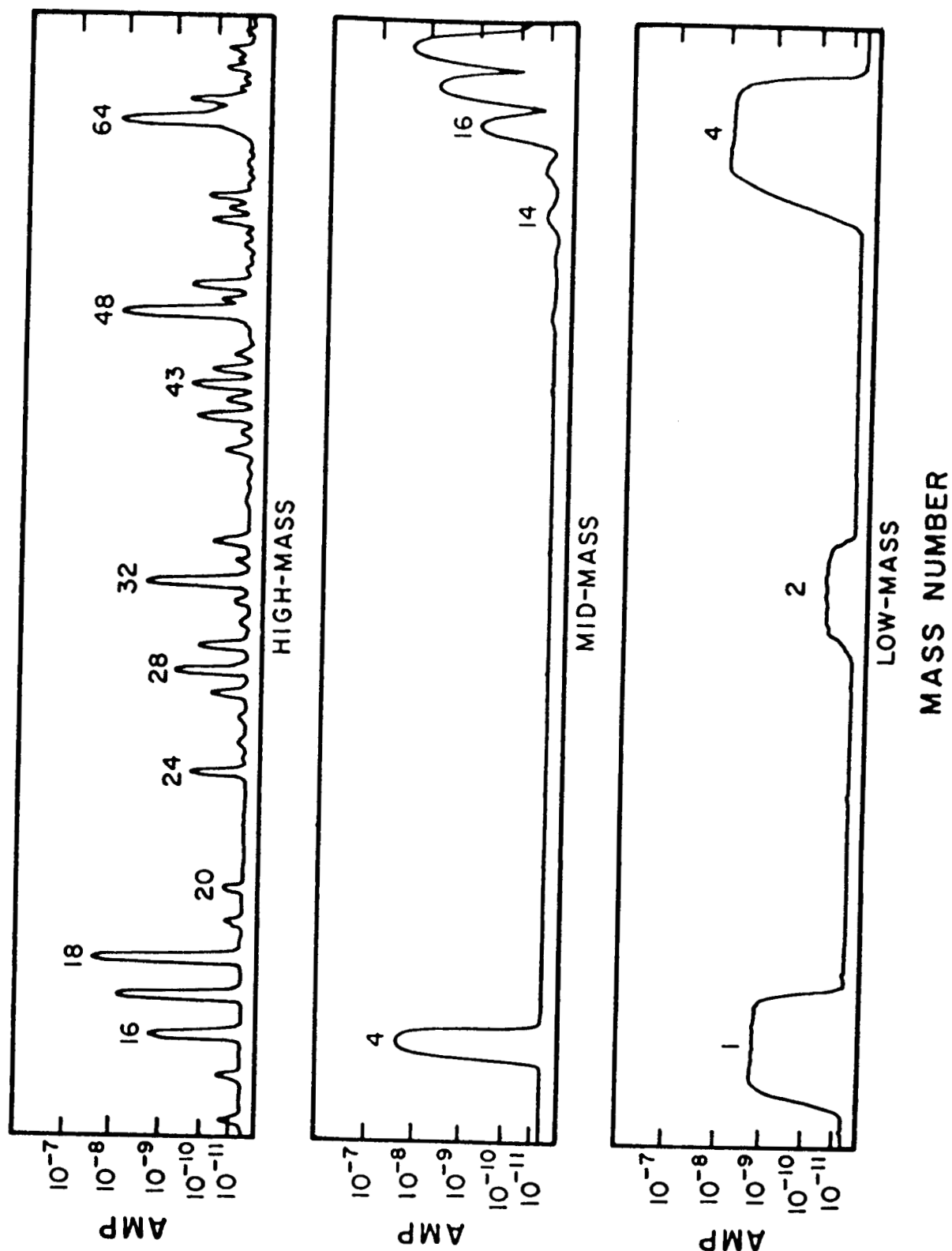
Figure 4.7. Mass spectrum of SO_2 taken from a 3 channel mass analyzer similar to that proposed for IMSE.

tests according to the following criteria. From the ratios of peaks in the 14 to 32 amu range, the ratio of the parent gases will be determined to an accuracy of 5% for pressures greater than 1 torr (5% of the total) outside the instrument entrance aperture (Region A). It is planned to use air for this test since the O_2/N_2 ratio is accurately known. A normal mass spectrum shows this ratio to be near 0.1 instead of 0.27, but taking into account ionization cross sections an accurate ratio can be determined. Mixtures of methane in nitrogen will also be used in this test.

During the tests the mass discrimination of the instrument will be determined. Relative to the nitrogen peak, the instrument response at both CO_2 and H_2 mass positions will be at least 50%.

Linearity of response will be tested over a 1000:1 range of input fluxes. The beam flux will be varied over that range by adjusting the gas pressures and gas mixtures in Region A during calibration tests. In addition, isotopic ratios of hydrogen (H_2/HD) and carbon (CO_2; 44:45 ratio) will be used to verify linearity of response.

The mass scan (ion accelerating voltage) will be under the control of a microprocessor (*Hoffman, et al.*, 1979b). It may be continuous, or selected mass numbers may be monitored in any order (peak stepping mode) although the scan is usually done in a monotonic sequence. There are no gaps in the mass range from 1 to 64 amu or higher if necessary. It is planned to cover the entire mass spectrum in 4 seconds, but this time and the sequence of mass peaks monitored can be adjusted by a command. Since the instrument must be operated during reentry without ground control, the microprocessor will be programmed to do a survey scan (peak stepping) periodically to determine the overall composition of the plasma and then concentrate on several major peaks. By using three preidentified peaks as standards (such as N_2^+, Ar^+, and H_2O^+), the microprocessor will be able to tune the peak positions to the correct locations for each ion to be measured and continue to readjust the tuning between each scan of the spectrum, thereby improving the accuracy with which each peak amplitude is measured. Also by this process, the mass number of each peak will be accurately known.

The data are accumulated as counts or currents from channeltron electron multipliers, one for each collector slit, that can be operated in either the pulse counting or current amplification mode. Bandwidth of the counting system is 10 MHz. Normal accumulation time is 80 msec but this time is controllable by the microprocessor. If the counting rate on any channel exceeds a few MHz, the microprocessor automatically switches into a current mode by reducing the electron multiplier gain. The output current

is measured with a log electrometer amplifier. This method was used on the Dynamics Explorer RIMS ion mass spectrometer (*Chappell, et al.*, 1981) to extend its dynamic range and to protect the channeltrons from excessive counting rates. Use of this combination of pulse counting and ion current measurements provides a dynamic range of at least 9 orders of magnitude.

In the pulse counting mode, counts are accumulated in a 20–bit shift register and outputed directly to the data handling system maintaining the 20–bit format. At the rate of 12 words per second from 3 channels plus housekeeping and status flags, a data rate of 800 bps is adequate to retain all of the data. Alternatively, a data compression algorithm could be introduced to compress the data words in the range of 10 to 16 bits if the data rate needs to be increased. Accumulation times and scan rate are under the control of the microprocessor and can be optimized during the test phase of the flight hardware. The data words are time tagged by the instrument's microprocessor and by the spacecraft computer when transferred to the mass storage. At a data ratio of 800 bps for a flight time of 600 sec, plus pre– and post– entry calibrations, the data storage requirement is 62 kbytes.

In the neutral gas measurement mode of the instrument, an electron beam ion source mounted in Region C produces an electron beam that ionizes the ambient gas beam that has passed through the aperture in cone C. An iridium filament (2 for redundancy) produces the electron beam, nominally having 70eV energy, but which may be switched to 20eV in order to change the fractionation or cracking pattern of the molecular gas species to aid in the identification of parent molecules. Ions are formed by electron impact at the potential of cone C, which is now biased about 10V positive to exclude all ambient ions from entering the mass analyzer. The ion beam is then accelerated through the slit in D which is at its normal potential, V, and through the magnetic analyzer. The neutral mode operation will be under the control of the microprocessor so the duty cycle and sequencing of operational modes can be optimized at a rather late date in the test phase of the program. At the moment, it is envisioned that two neutral spectrum scans will be interspersed between every 8 ion mode scans. The filament will not be turned off during the ion mode, but will be biased about 6 volts positive preventing electrons from gaining the energy necessary to produce ions. This method was successfully used on the GIOTTO neutral mass spectrometer when operated in its ion mode (*Krankowsky, et al.*, 1986). Operation of the mass analyzer for the neutral mode will be the same as for the ion mode.
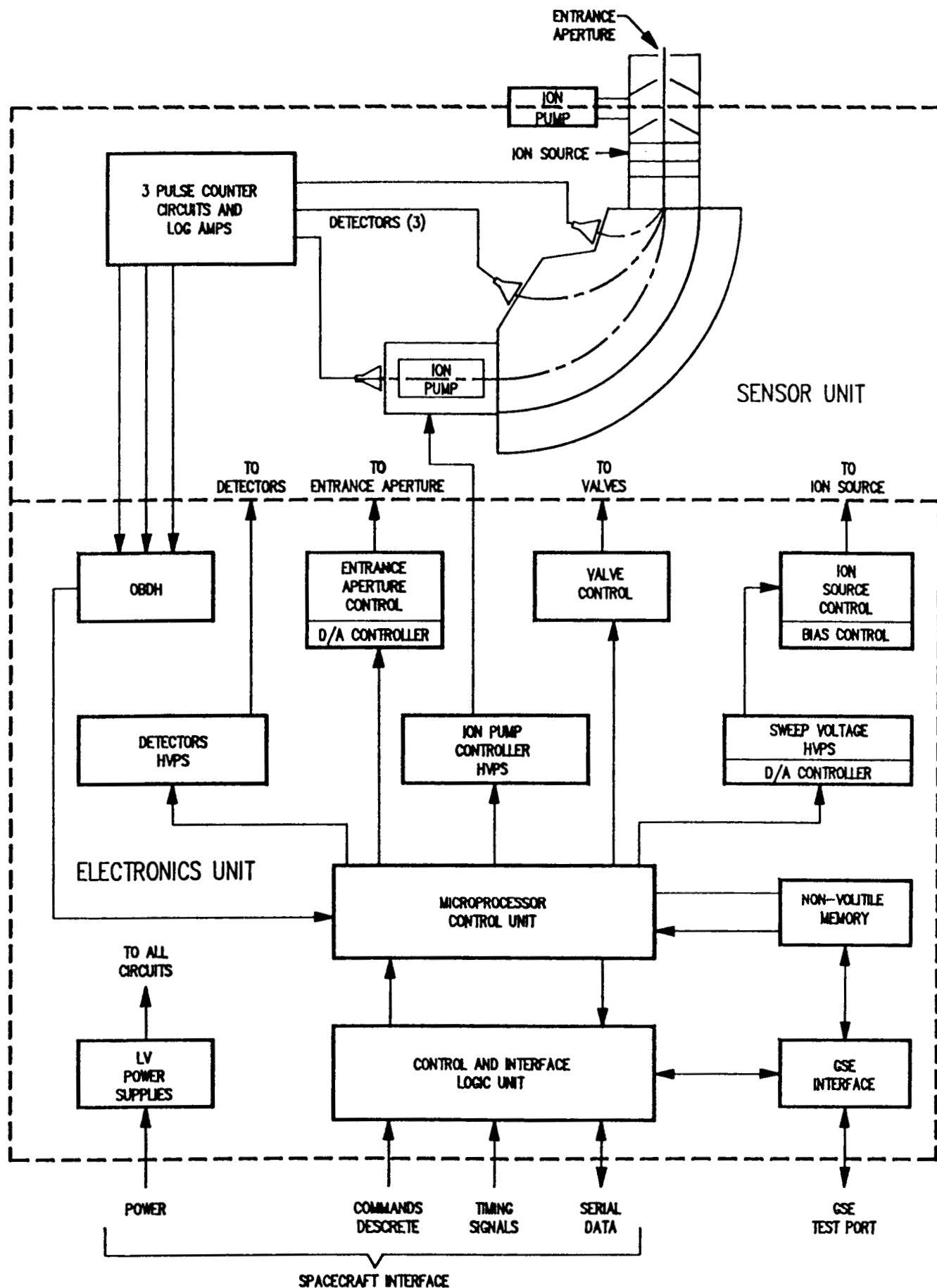
Mass ranges, accumulation times, and data processing will likely be identical, but would be optimized for this mode after the test program has been completed.

The electronics of the IMS will provide the necessary voltages and currents to operate the mass spectrometer and receive and process the signals from the detectors. It will provide timing and sequence signals and be capable of accepting modifications of the operating sequences and parameters by software (memory load) and discrete commands. Specifically, the electronics consists of the microprocessor, low voltage power supplies, electron multiplier power supplies, ion accelerating power supply, ion pump supplies and controls, valve controls, ion counting circuits, log amplifiers, and data handling circuits. All power supplies are to be digitally controlled by the microprocessor. In addition, housekeeping and status flag circuits are provided as feedback to the microprocessor and to aid in interpreting the data. Figure 4.8 is a block diagram of the electronics.

A list of instrument parameters is given in Table 4–III.

The ground support equipment (GSE) will consist of a PC–AT compatible computer with hard disk and floppy disk drives, 24–32V power source, command generator, and data buffers that will be used to operate the instrument during tests and calibration as well as for pre–integration tests with the AFE spacecraft. It will provide power and commands, including clock and enable pulses, to the instrument, monitor the status of engineering functions, provide electrical signals to stimulate collector currents for non–vacuum tests, accept and store output data from the instrument and provide a means for modifying the IMSE internal software which controls the instrument's sequence of operations. A serial word or memory load command capability is required for this purpose. An EPROM programming computer system exists in the laboratory which will be used to reprogram PROMS as necessary. Commands required to operate the instrument are Power ON/OFF, and mode select discrete commands for the Primary Mode (alternate ion and neutral mass sweeps including peak position locking), on orbit check out, ground operation (non–vacuum), stand–by, pump out in orbit and reset.

Testing of the instrument will be done in several configurations. In laboratory non–vacuum conditions, the GSE will supply signals to stimulate the counter circuits for a functional check of the instrument. High voltages to the channeltrons, the ion pump, and the high voltage sweep (V) and the ion source filament circuit will be inhibited to prevent damage to the channeltrons and the filament wires. In–vacuum and on–orbit the high voltages and filaments will be operational after the mass spectrometer analyzer has been evacuated to a pressure of less than 3×10^{-6} torr. In–vacuum testing will be done by

ENTRANCE
APERTURE

ION
PUMP

ION SOURCE

3 PULSE COUNTER
CIRCUITS AND
LOG AMPS

DETECTORS (3)

ION
PUMP

SENSOR UNIT

TO
DETECTORS

TO
ENTRANCE APERTURE

TO
VALVES

TO
ION SOURCE

OBDH

ENTRANCE
APERTURE
CONTROL

D/A CONTROLLER

VALVE
CONTROL

ION
SOURCE
CONTROL

BIAS CONTROL

DETECTORS
HVPS

ION PUMP
CONTROLLER
HVPS

SWEEP VOLTAGE
HVPS

D/A CONTROLLER

ELECTRONICS UNIT

MICROPROCESSOR
CONTROL UNIT

NON-VOLITILE
MEMORY

TO ALL
CIRCUITS

LV
POWER
SUPPLIES

CONTROL AND INTERFACE
LOGIC UNIT

GSE
INTERFACE

POWER

COMMANDS
DISCRETE

TIMING
SIGNALS

SERIAL
DATA

GSE
TEST PORT

SPACECRAFT INTERFACE

IMSE BLOCK DIAGRAM
Figure 4.8

introducing various gases generally mixed with air into a vacuum chamber (Region A, Figure 2.3) to simulate the atmospheric in–flight conditions. A plasma discharge source will produce an adequate positive ion population to test the instrument operational modes and characteristics. On–orbit check–out will involve using the neutral mode to look at background gases to test the operation of the instrument prior to reentry.

It is planned to perform instrument calibrations in the plasma chamber at SAIC (see Section 1) in conjunction with the Langmuir probes (assuming they are calibrated there) in order to obtain a cross calibration of the two sensors. The plasma formed in the chamber will replace Region A (Figure 4.3) and both sensors will sample the same source plasma. Plasma densities and composition will be adjusted to simulate the best predictions of the in–flight conditions.

The instrument will be mounted just aft of the aeroshell from two longitudinal stringers of the AFE spacecraft. It will be located halfway between the MRIS and one of the Langmuir probe rakes on the long side of the forebody. The mass analyzer is located in a differentially pumped chamber and is maintained at a pressure of less than 10^{-6} torr during on–orbit and reentry phases of the mission. The electronics are all located in a pressurized box (1 atmosphere of N_2) adjacent to the mass analyzer. Thus, the electronics may be operated by itself anytime, but when connected to the mass analyzer, the high voltage and filament power supplies can be operated only when the analyzer is under good vacuum conditions. In this manner there will be no corona or arcing problems since high voltages are not exposed to the ambient vacuum, but only see a pressure of 1 atmosphere or good vacuum conditions. As a further precaution, the IMSE interface circuits will provide protection to the AFE circuits and instruments in case the IMSE should experience any corona or arcing.

The instrument parameters of power, weight, volume, data storage requirements, commands, and temperature ranges are given in Table 4–III. Environmental specifications (random & sinusoidal vibration, EMI) pose no problems since many instruments have been produced by UTD that have met or surpassed such requirements and all have flown successfully on various spacecraft. Vibration tests, EMI tests and instrument verification tests will be performed according to procedures that are consistent with applicable specifications and guidelines imposed by the AFE program.

TABLE 4-III
IMSE INSTRUMENT PARAMETERS

INSTRUMENT: Magnetic Sector-Field Mass Spectromter

MEASUREMENTS: Ion and Neutral Gas Composition

MASS RANGE: Low Channel: 1-4 amu
                           Mid Channel: 4-16 amu
                           High Channel: 16-64 amu (can be extended to 100 amu
                                                      or higher)

MASS RESOLUTION: At mass 48 (M48)
                                Peak interference at $\pm$ 1 amu <1% of M48 peak
                                Peak interference at $\pm$ 2 amu <0.05% of M48 peak

SENSITIVITY: Ion Concentration: 10^8 to 10^{16}/cm^3
                           Neutral Gas Concentration: 10^{-6} to 15 torr (2000N/m^2)

RELATIVE SENSITIVITY: In mass 14 to 32 range, parent species to be derived to
                                accuracy of 5% when parent species partial
                                pressure is greater than 1 torr.

DYNAMIC RANGE: Pulse counting and log amplifier: up to 10^9

OPERATIONAL MODES: Ground Checkout
                           Ground Test and Calibrate
                           On-orbit Checkout/Calibration
                           Pumpout in Orbit
                           Standby
                           In-flight Data Collection (Reentry)

COMMANDS: Power ON/OFF
                           Serial Word
                           Discrete Commands

WEIGHT: 26 lbs

POWER: 12 watts at 24-32 volts

BIT RATE: 800 bps

DATA STORAGE: 62 Kbytes

TEMPERATURE: Inlet: -40° to +2000°C
                           Electronics Operating: -20° to +50°C
                           Electronics Storage: -50° to +125°C

PRESSURE: Atmospheric (760 torr) to $\leq 10^{-6}$ torr

5.0 TEST REPORTS

A thermal analysis and test summary of the arc–jet test of the Langmuir probe is provided in Appendix A.

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Krankowsky, D., J. H. Hoffman, P. Lammerzahl, D. Dorflinger, U. Woweries, U. Dolder W. Shulte, J. J. Berthelier, J. M. Illiano, G. Gogly, P. Thevenet, R. R. Hodges, and W. W. Wright, "The GIOTTO Mass Spectrometer," ESA, SP–1077, 109.

APPENDIX A
LANGMUIR PROBE THERMAL ANALYSIS

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia
23665-5225

NASA

December 9, 1988

University of Texas at Dallas
Center for Space Sciences
Attn: Mr. Willie Wright
Founders Hall
P. O. Box 830688
Richardson, TX   75083-0688

Subject: Cooperative Agreement NCC1-119, Failure Analysis on PIECE Rake

Enclosed is a copy of the analysis report from the Systems Engineering Division,
Engineering Analysis Branch, which determines a potential heating rate on the
PIECE rake leading edge during the arc jet test in May of 1988. The analysis
determines the heating rate based on the following:

-    Matching only the temperature response of thermocouple TC-15.

-    No attempt was made to determine at what point the rake failure occurred.
     It was assumed that the crack existed at the "arc on" point time t=0 second.

-    It was assumed that the heating rate was constant along the length of the
     leading edge and varied by a sine relationship around the leading edge
     radius to a constant value along the flat sides of the rake.

Also enclosed are several curves which compare the test data and the computed
heating rates.

Figure 1 is a comparison of the arc jet cathode voltage and the temperature at
thermocouple TC-15. The ordinate scales of the two curves have been matched to
give a roughly equivalent curve height and to clarify the relationships between
the curves. The significant relationship here is the apparent sensitivity of
the slope of the TC-15 curve to changes in the cathode voltage level during the
run. The change in the slope of the temperature curve was used as the basis to
determine the periods of constant heating rate in the analysis.

Figure 2 compares TC-14 with the cathode voltage. As in figure 1 the ordinate
scales are matched to show relationships. While TC-14 was the lower of the two
leading edge thermocouples and never reached the same temperatures as TC-15 the
general trend of response to the changes in cathode voltage are evident.

Figure 3 compares the calculated heating rate profile with the cathode voltage. While the cathode voltage data was not utilized in the development of the heating rate profile, the match in time phasing is evident and would be expected based on the analysis approach. There is less correlation in the magnitude of the heating rate levels to the cathode voltage other than to note that the signs of the curve slopes match. The swings in the analytically determined heating rate values are probably due to forcing the analysis to match the temperature data of TC-15 without consideration of a measurement error band and not attempting to match the response of more than one thermocouple.
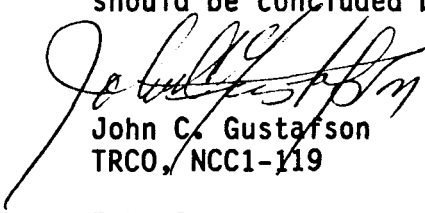
A comparison was made of the TC-14 data to computed values (figure 4). Here data varied from the calculated value by <100 °F. A variation between measured and calculated temperatures at TC-14 would be expected since the analysis allowed this node to float. The comparison of the two curves would indicate that the heating rate applied to the base of the rake was too high.

Assuming the proportionality of the heating rate to the cathode voltage then it seems reasonable to average the peak heating rates to some level between 180 and 160 BTU/ft^2-sec. This would degrade the match between calculated and actual data at TC-15 at peak temperature. It would also reduce the difference between the peak temperature calculated at TC-14 and the measured temperature.

The conclusion that can be drawn from this analysis is that the heating rate at the rake leading edge was significantly higher than the 20 BTU/ft^2-sec that had been anticipated for the test.

At what point in the test the rake cracked is not resolved nor can it be without a much more detailed analysis effort and the results would be debatable based on the information we have in hand. Under the heating conditions experienced it would not be unexpected for the rake to fail due to a thermal stress build-up. Most probably the crack initiated in the thin cross section at the pressure port entrance and progressed backward across the rake. With the loss of conduction to the main body of the rake, the front to back thermal gradient became too large and the vertical crack formed.

Since the PIECE rakes, and the IMSE have been removed from the AFE Spacecraft experiment complement, it is not planned to perform any further analysis at LaRC. This completes the study effort on NCC1-119 and the cooperative agreement should be concluded by the computation and submission of the final report.

John C. Gustafson
TRCO,/NCC1-119

5 Enclosures

cc:
JSC--D. Tillian
UTD--Dr. Hoffman, UTD
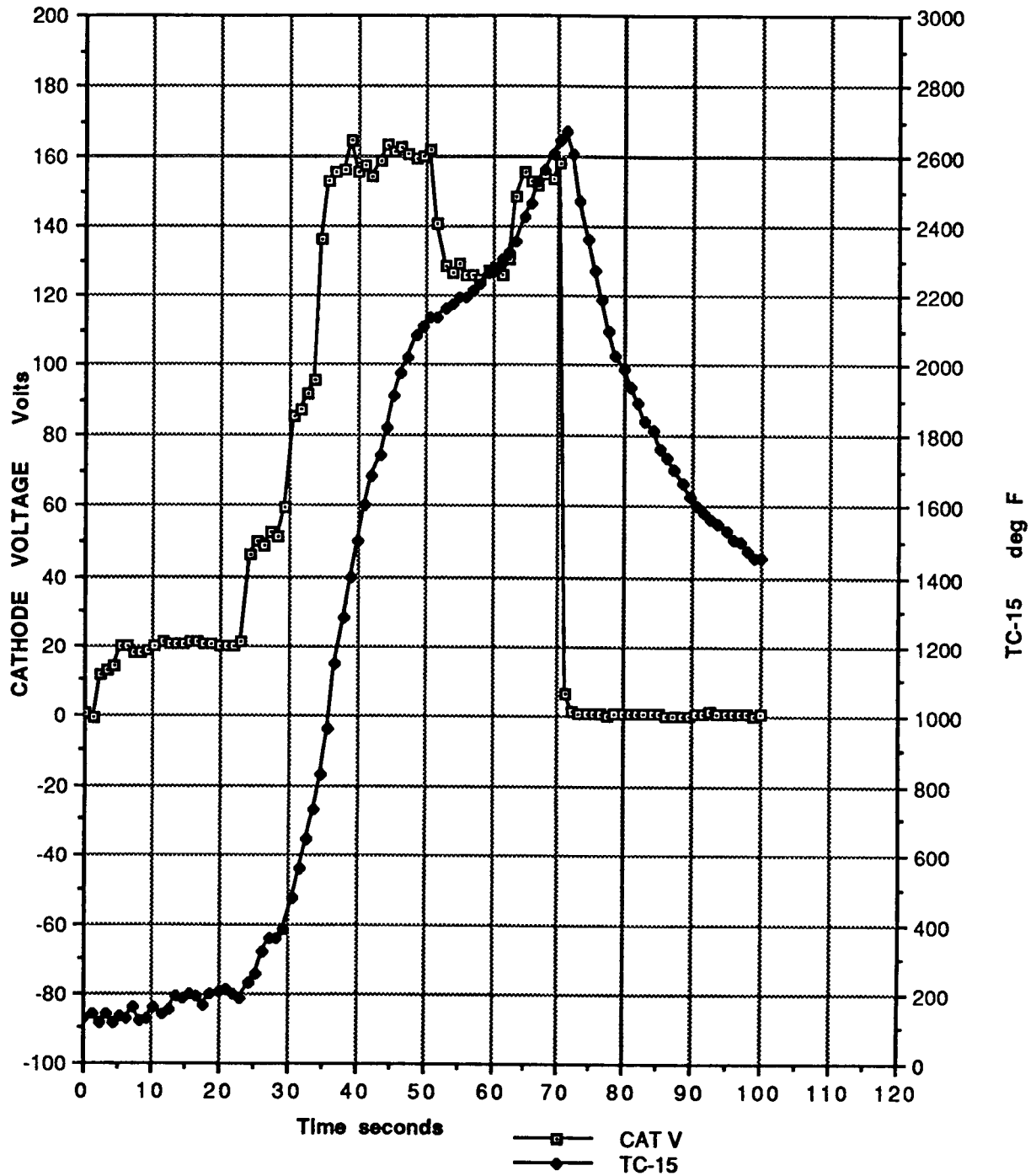
COMPARISON CATHODE VOLTAGE & TC-15 vs RUN TIME

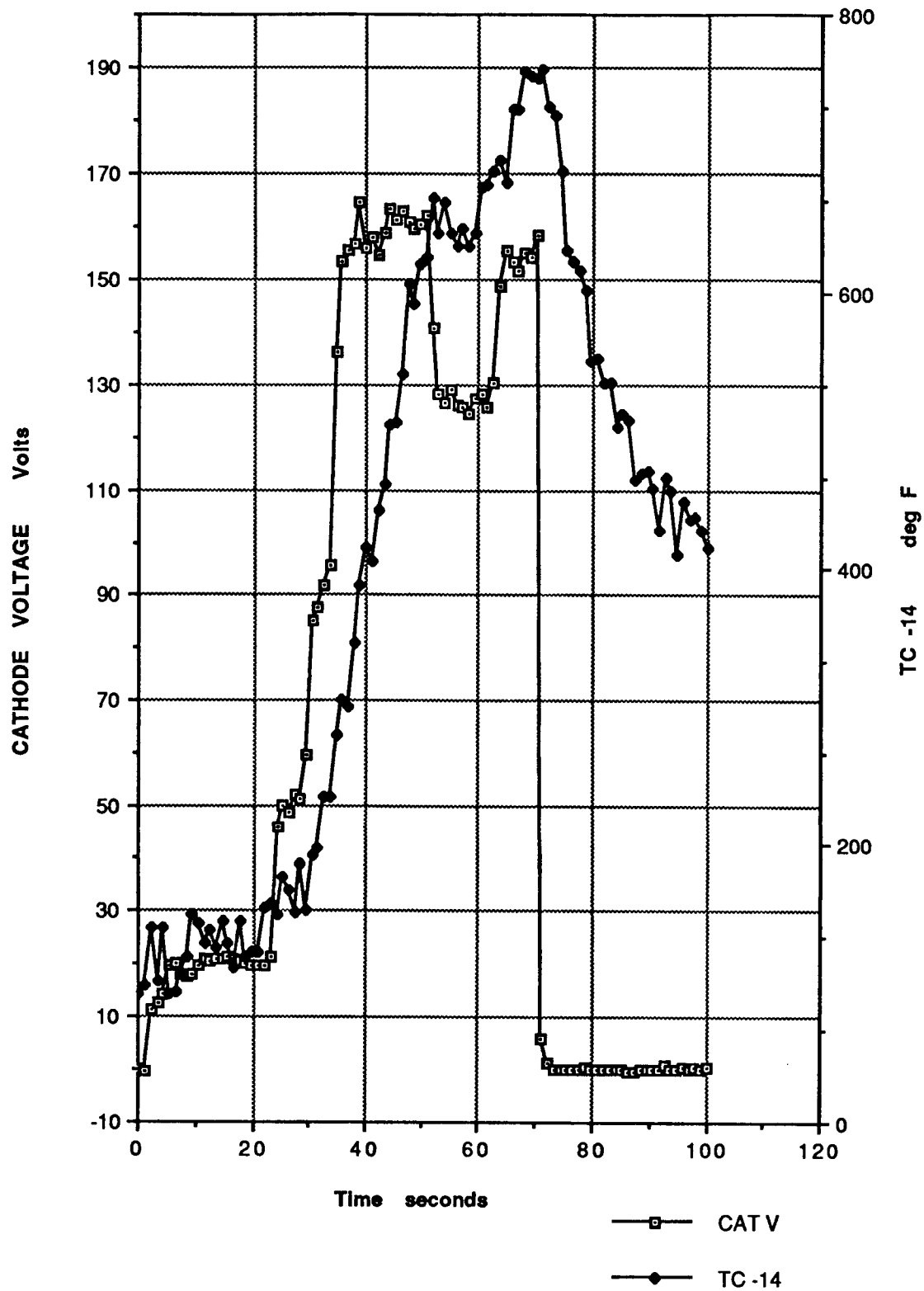Figure 1.

COMPARISON CATHODE VOLTAGE & TC 14 vs RUN TIME

Figure 2.

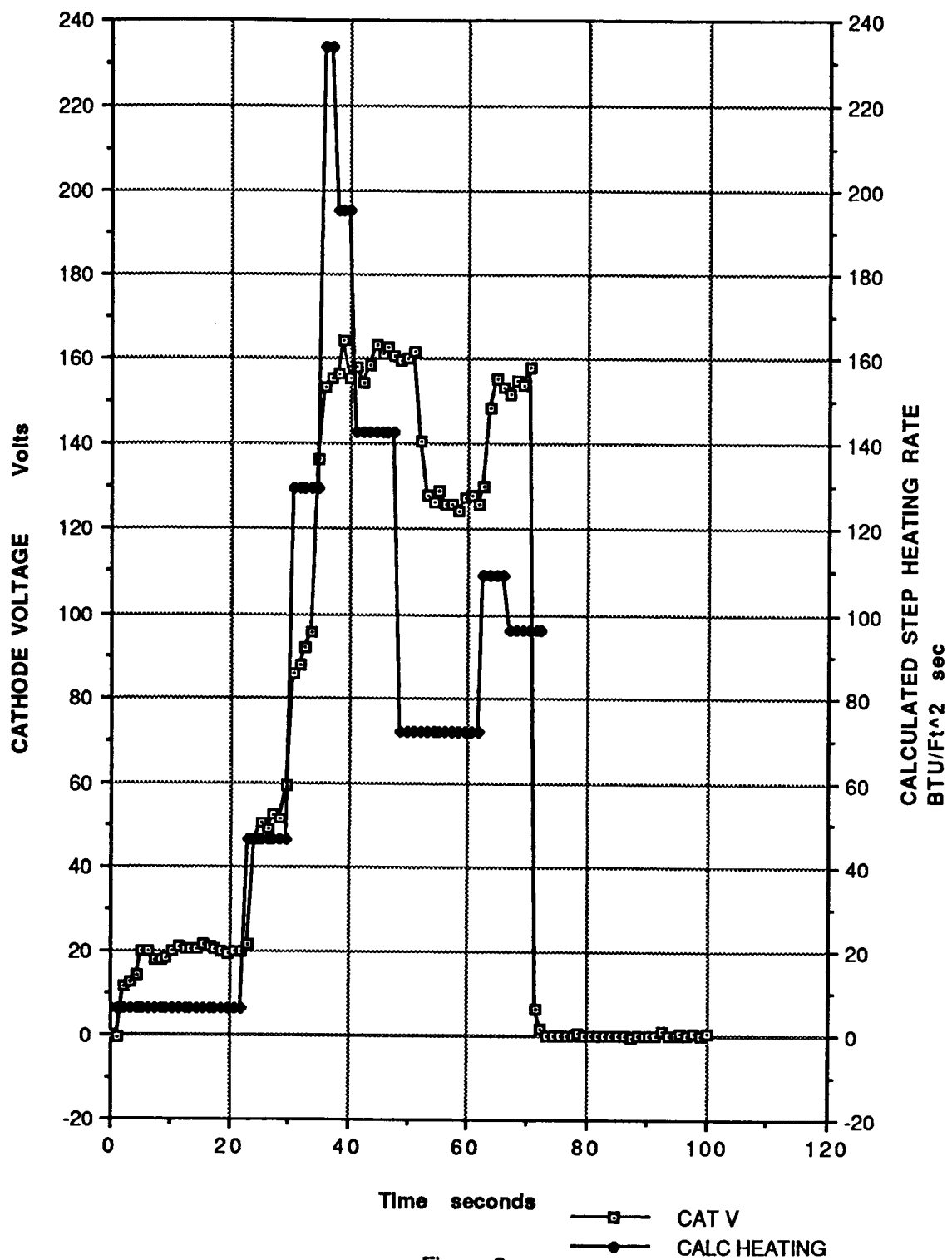**CALCULATED STEP HEATING RATE & CATHODE VOLTAGE vs RUN TIME**

Figure 3.

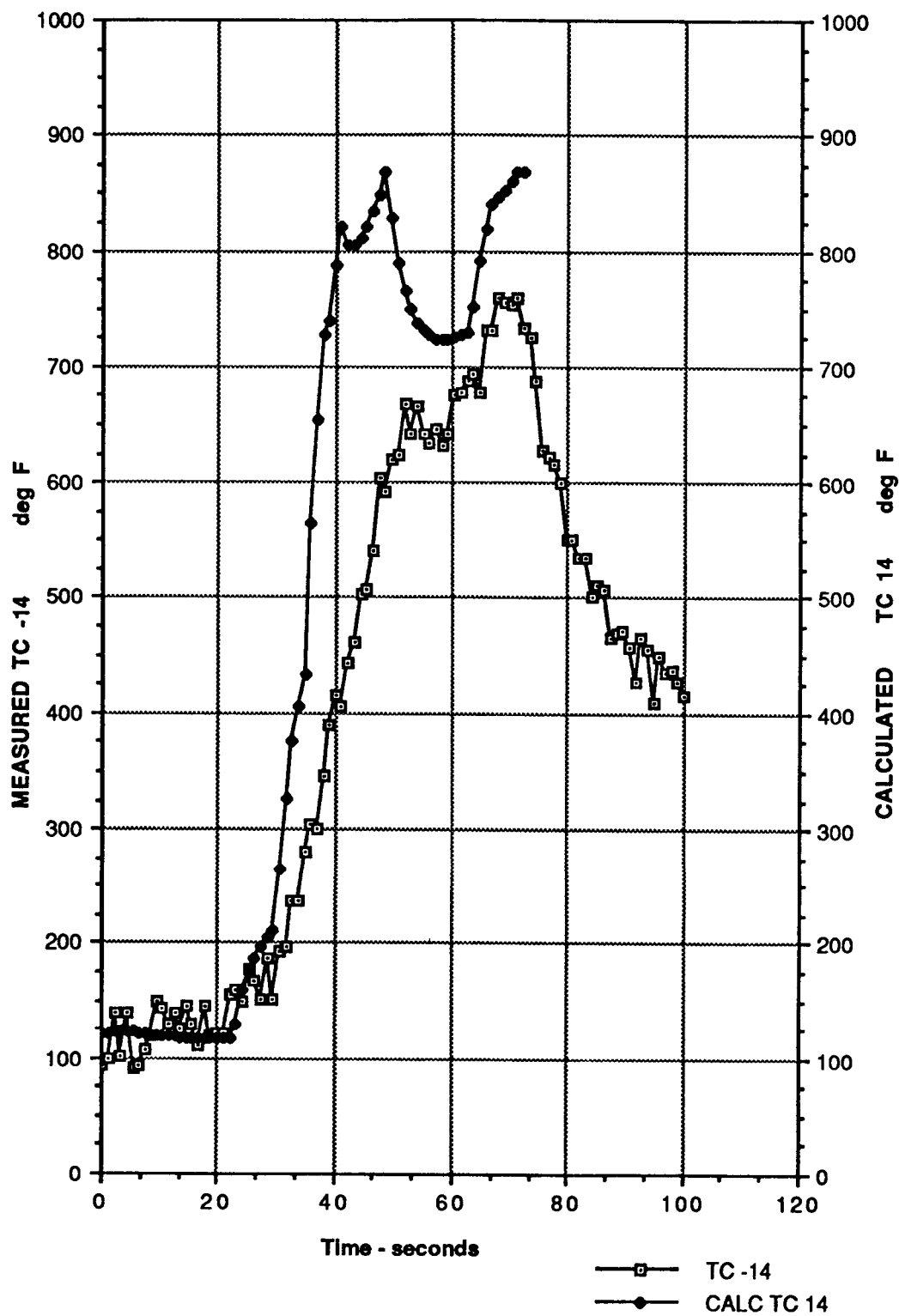## MEASURED AND CALCULATED TEMPERATURES AT THERMOCOUPLE 14 vs TIME

Figure 4.

A-6

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia
23665

NASA

TO: 434/John C. Gustafson, Experiments Systems Section, SSEB, SED

FROM: 431/Aerospace Engineer, Fluid Analysis Section, EAB, SED

SUBJECT: Analysis of AFE PIECE Temperature Data from Arc-Jet Tunnel Test

REF: (a) University of Texas at Dallas Drawing Number 157-501,
               titled "Rake, Probe, PIECE/AFE"

          (b) Printout of temperatures of thermocouples on PIECE test
               article during test of 4 May 1988, at Ames Research Center

          (c) LaRC Drawing No. SK 110287, titled "PIECE T/C LOCATION",
               Sheet 2

          (d) Thermophysical Properties of High Temperature Solid Materials;
               Volume 4: Oxides and their Solutions and Mixtures; Part I:
               Simple Oxygen Compounds and their Mixtures. Thermophysical
               Properties Research Center, Purdue University,
               Y. S. Touloukian, Editor

A test was conducted on an instrumented probe for the Plasma Ion and Electron
Concentration Experiment (PIECE) in an arc-jet tunnel at the Ames Research
Center on May 4, 1988. An attempt has been made to correlate the temperature
data from the test with the results from a thermal model of the probe. The
results indicate that the heating rate on the leading edge of the probe was
much higher than had been expected prior to the test. The higher heating
rates were probably a factor in the failure of the probe by what appears to
be thermal stress cracking.

The PIECE probe test article was fabricated from a block of beryllium oxide,
a material well suited to high temperature environments. The article is
shown in reference (a); attachment 1 shows an outline sketch of the probe.
Rough dimensions were about 7" length by about 4" height. The thickness was
0.6". The leading edge, where sensors were located, was at a 45° angle to
the horizontal and about 3" long. It was semi-circular in cross-section.
Five holes for sensors were drilled into the leading edge and passed
entirely through. Iridium tubes, insulators, and sensor leads were installed
in four of the holes. The test article was bolted to a block of titanium
which served as a heat sink.

Only the upper 2" or so of the article was exposed to flow in the test. The
probe protruded from a layer of Shuttle-type thermal protection tiles.

A-7

A thermal model of the PIECE probe was assembled, prior to the test, with the aim of eventually using it to predict temperatures during actual AFE flights. The baseline version was to be modified to match results from a planned series of tests in the arc-jet tunnel. Thermal model development was stopped with cancellation of the PIECE experiment. The model has only been modified to account for temperatures recorded during the single, shortened test.

Modifications consisted of: (1) Dividing elements where cracks occurred during the test; (2) varying heat loads on element surfaces in order to match temperatures from the test.

The thermal model of the PIECE test article is a lumped-parameter model and uses the MITAS thermal analyzer. The model physically represents half the actual body, taking advantage of symmetry about the mid-plane. Attachment 1 shows the body divided into 68 elements. Some of the irregular shapes were necessary to represent the cracks which developed during the arc-jet heating test.

Most of the flat surface is divided by a 1" x 3/4" grid with the 1" side parallel to the leading edge. The 1/4-cylinder of the leading edge is divided into 1" lengths and each of these is divided into three 30° sectors (to more accurately show the effect of the large variation of the convection coefficient from front to side of the cylinder). The trailing edge is treated the same, except that the lengths are just a little over 3/4".

There are two other elements (or "nodes" in MITAS terminology) in addition to those of the beryllium oxide body. One is the titanium heat sink to which the probe was bolted; the other being the ambient air present in the test facility.

Heat exchange modes are as follows:

(a) Absorption of applied heat loads on element surfaces

(b) Internal conduction

(c) Radiation to surroundings

(d) Radiation across cracks

(e) Conduction to heat sink

Heat exchange with the tiles was neglected. Also, no convection or conduction was accounted for between surfaces formed by the cracks.

The goal of the thermal modeling was to find the heating loads which would result in model temperatures matching test data from startup to shutdown. To make the problem tractable, a set of ten time points was picked, at each of which the temperature match was to be forced. Due to noisy data and non-uniform time increments, it was decided to fit the test data, by least squares, to a straight line segment in each of the 9 time intervals. The temperatures to be matched by the thermal model were determined by the straight line fit at the ten points chosen.

In order to match the test temperatures with the thermal model, applied heat loads on exposed element surfaces were varied stepwise over the chosen time intervals. The rate of change of the test temperature at the hottest location was fairly constant within each of the time intervals. The applied heat load on a given surface element, at any time, was a fixed ratio of the highest heat load, which occurred along the leading edge. Attachment 2 gives the value of this ratio for each location.

The thermal model-predicted temperatures were constrained to match the test temperatures only at the location of Test Thermocouple No. 15, which recorded the highest temperature throughout the test [See Reference (b)]. This location was on the leading edge at the entrance to the second hole from the tip of the probe [See Reference (c)]. The heat loads, during each given time interval, were adjusted until the temperature given by the thermal model at that location matched the test data (as fitted by least squares) at the end point of the time interval. Attachment 3 gives comparisons of the fitted test data and model prediction at the selected times, and the maximum applied heat load during each interval which produced the desired model result. Note that the highest value of the inferred heat load (between 35 and 38 seconds) is over 230 Btu/ft^2-sec. The pre-test analysis, using laminar correlations, had predicted a maximum heating rate of about 27 Btu/ft^2-sec.

Attachment 4 is a plot comparing the model prediction to the original unfitted test temperature. Agreement is generally good, especially where the slope is largest.

In conclusion, the thermal model of the PIECE probe was able to reproduce the test temperature at the hottest recorded location, with an RMS deviation of 16 °F, from startup to shutdown. A maximum heat load of approximately 230 Btu/ft^2-sec was required, during the time interval between 35 and 38 seconds, to match the temperature rate of change of approximately 155 °F per second.

Doyle P. Swofford

Doyle P. Swofford
4508

3 Enclosures

cc:
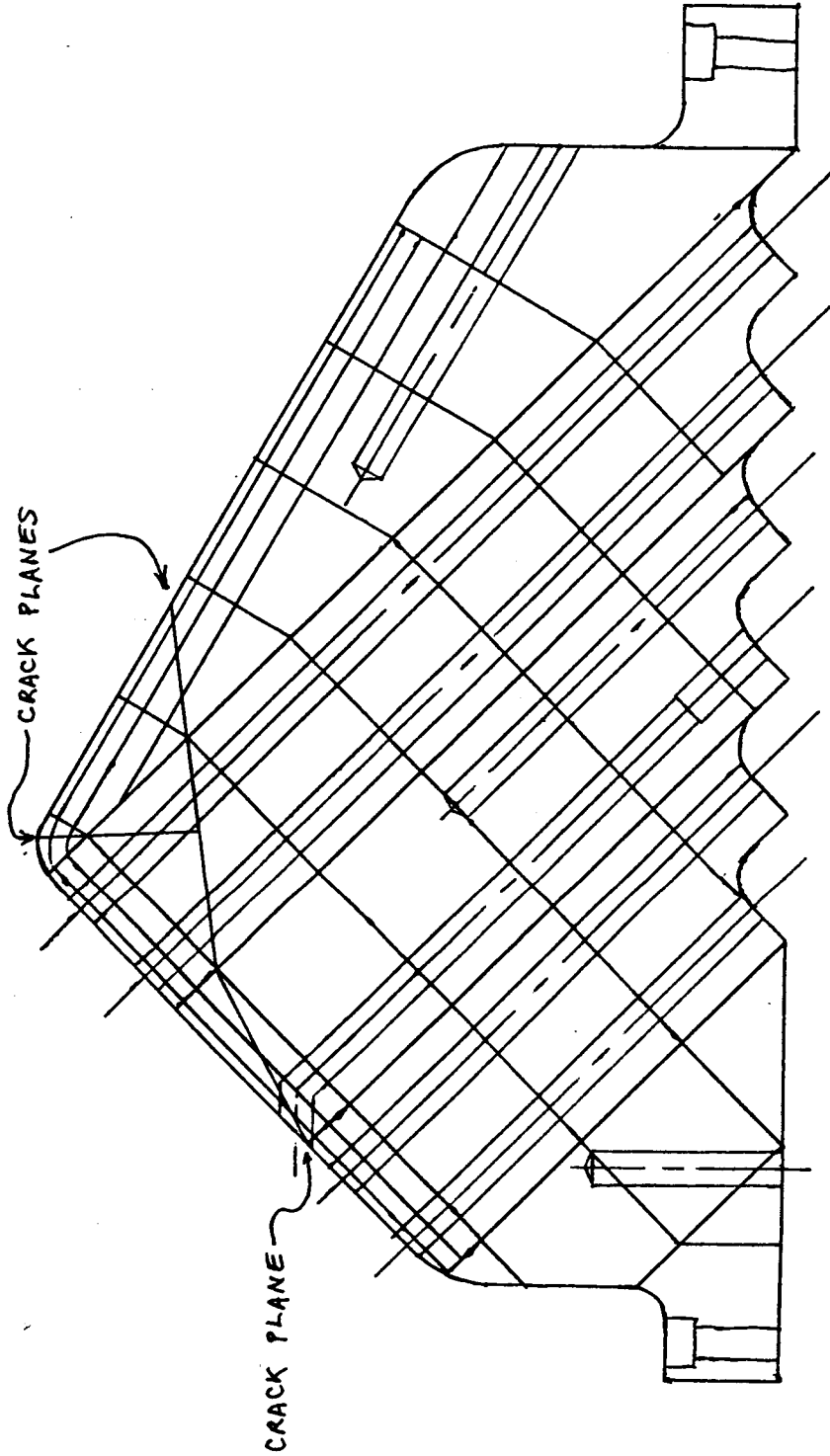431/Doyle P. Swofford
431/EAB Files

431/DPSwofford:ldb   10-24-88   (4508)
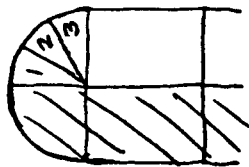
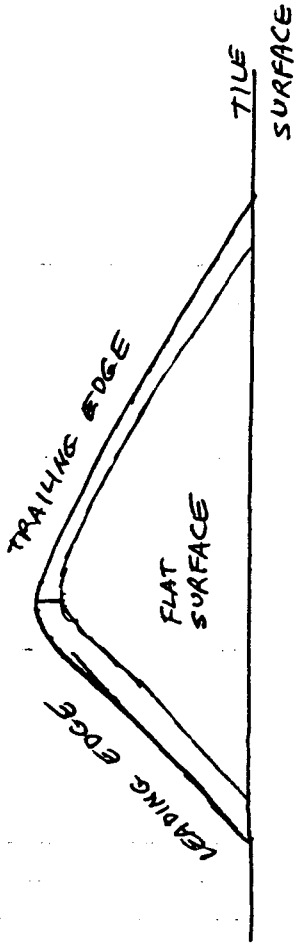431/OHB   *ohs*   *10-25-88*

431/WSL   *wlk*

DIRECTION OF FLOW

CRACK PLANES

CRACK PLANE

ARRANGEMENT OF THERMAL MODEL ELEMENTS (BLUE GRID).

ATTACHMENT 1

A-10

CROSS SECTION OF LEADING OR TRAILING EDGE ELEMENTS

LEADING EDGE		
①	②	③
1.0	.903	.524

FLAT SURFACE
0.3

TRAILING EDGE		
①	②	③
0.6	.542	.314

RATIO OF LOCAL APPLIED HEAT LOAD TO THAT ALONG THE LEADING EDGE

ATTACHMENT 2

22-141   50 SHEETS
22-142   100 SHEETS
22-144   200 SHEETS

TIME, SECONDS	0	23	30	35	38	41	49	63	67	71
T_{FITTED}, °F	115.35	207.35	425.71	838.62	1295.88	1596.49	2094.07	2325.83	2533.88	2669.98
T_{MODEL}, °F	115.35	207.36	425.61	838.43	1295.69	1596.33	2093.79	2325.44	2533.46	2669.54
$Q_{LEADING\ EDGE}$, BTU/FT²·SEC	6.03	46.18	129.75	233.75	195.33	142.60	72.02	109.10	96.17	96.17
SLOPE OF FITTED LINE SEGMENT, °F/SEC	4.00	30.3	82.6	155.2	100.2	64.2	16.1	52.0	33.6	—

ATTACHMENT 3.   COMPARISON OF FITTED TEST TEMPERATURE WITH MODEL RESULTS AT PRESCRIBED TIME POINTS, AND CORRESPONDING HEAT LOAD AT THE LEADING EDGE WHICH RESULTED IN THE MODEL TEMPERATURES SHOWN.

COMPARISON OF TITLE E TEST TEMPERATURE, AT THERMOCOUPLE NO. 15, TO ANALYTICAL MODEL

DEE W/M

○ T.C. #15

◻ THERMAL MODEL
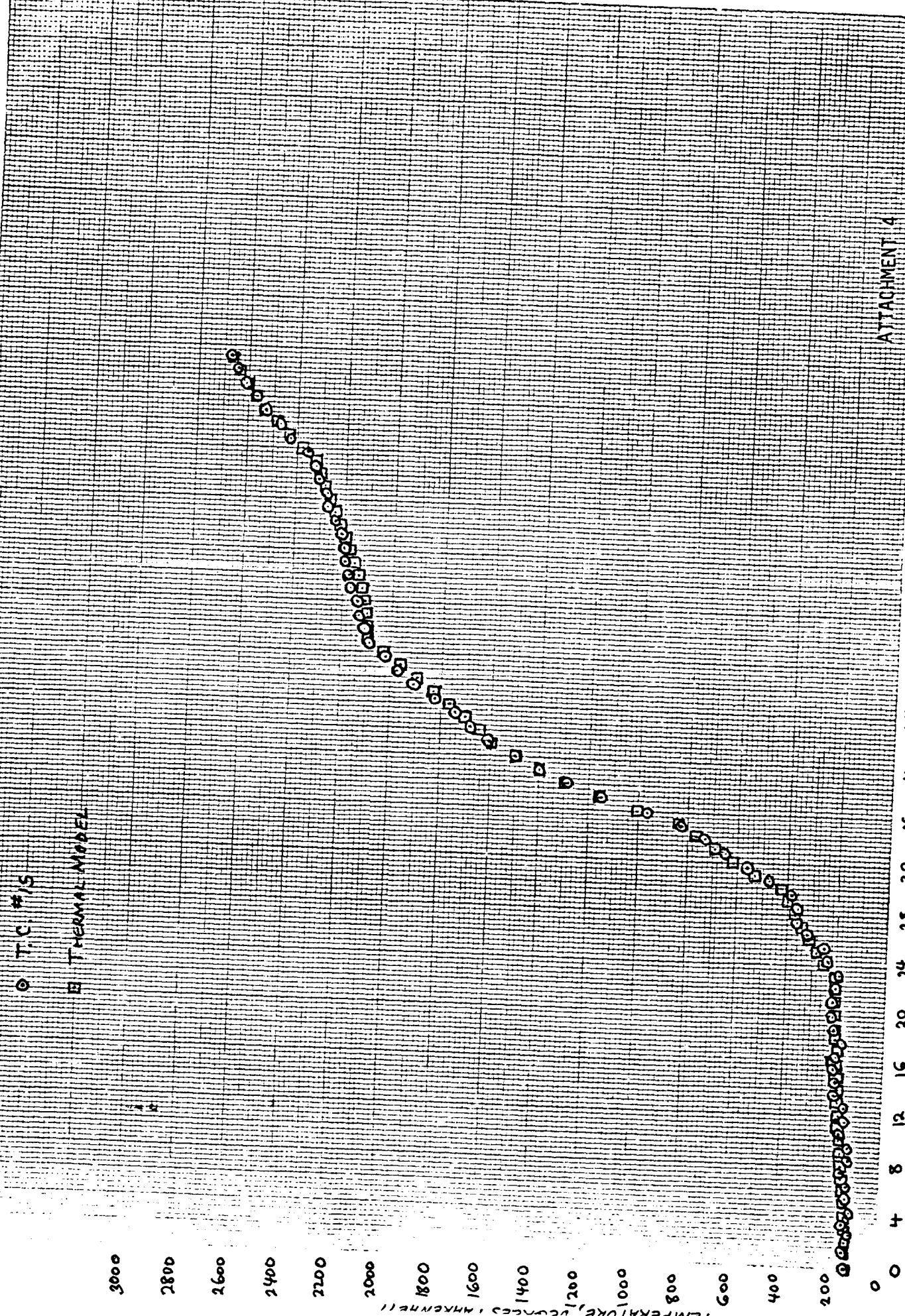
ATTACHMENT 4

TIME, SECONDS

TEMPERATURE, DEGREES, FAHRENHEIT

3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0

0   4   8   12   16   20   24   28   32   36   40   44   48   52   56   60   64   68   72

APPENDIX B
CURRICULUM VITAE
DR. JOHN H. HOFFMAN

THE UNIVERSITY OF TEXAS AT DALLAS
CENTER FOR SPACE SCIENCES

HOFFMAN, John H.
Professor and Head, Physics Program

DEGREES

B. S., Physics, Chemistry, St. Mary's College, Winona, Minnesota, 1951
M. S., Physics, University of Minnesota, 1954
Ph.D., Physics, University of Minnesota, 1958

FIELDS OF RESEARCH SPECIALIZATION

Ionospheric Composition
Planetary Atmospheres
Mass Spectrometry
Stratospheric Cluster Ion Composition
Hyper—velocity Reentry Vehicle Studies

EXPERIENCE

1953–1958	University of Minnesota, Department of Physics, Research Assistant
1958–1959	University of Minnesota, Department of Physics, and Department of Geology, Research Associate
1959–1966	U. S. Naval Research Laboratory, Washington, D. C.
1966–1978	The University of Texas at Dallas, formerly Southwest Center for Advanced Studies, Associate Professor.
1978–	The University of Texas at Dallas, Professor
Present	The University of Texas at Dallas, Head, Physics Program

SPECIAL ACTIVITIES

Member of ISIS Working Group
Member of ISIS Experimenters' Team
Member of Atmospheric Explorer Experimenters' Team
Member of Pioneer Venus Science Steering Group
Chairman of Pioneer Venus Atmospheric Composition Working Group
Member of GIOTTO Neutral Mass Spectrometer Experimenters' Team
Member of NASA Aeroassist Flight Experiment Team

SOCIETIES

American Geophysical Union
Sigma Pi Sigma
Sigma Xi

UTD COMMITTEES

Chairman, Physics Seminar Committee (1970–1972)
Member, Physics Qualifying Exam Committee (1974–1984)
Member, Clark Committee (1978–1979)
Member, NS&M School Council (1978–1989)
Member, Committee on Academic Facilities (1980–1982)
Chairman, Applied Physics Task Force (1980–1981)
Member, Library Committee (1985–1986)
Member, Student Fellowships/Scholarships (1986–1989)
Member, Ad hoc Review Committee (1986–1987)
Member, Academic Council (1987–1989)
Member, Academic Senate (1987–1989)
Advisor for Undergraduate Physics Students (1981–1989)
Chairman, Faculty Search Committee (1989)

PRESENT RESEARCH ACTIVITIES

Analysis of flight data from our experiment on European Space Agency's GIOTTO
mission to Halley's Comet.
Conduct balloon flights at NSFB, Palestine, Texas
Design rotating mirror head for retarding ion mass spectrometer for NASA GGS
mission.
Design instrument for NASA AFE mission.
Design and development of flight instrumentation for the Recoverable Plasma
Diagnostics to be flown on a number of the Space Shuttle missions.
Design and development of laboratory and balloon flight instrumentation to study
the ion composition of the stratosphere. This includes laboratory studies of
sampling techniques of large cluster ions.

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"Neutral Thermospheric Temperatures from Ionospheric Concentration Measurements," with E. Breig, J. S. Donaldson, and W. B. Hanson, AGU Fall Meeting, 1980.

"Composition of the Venus Lower Atmosphere from the Pioneer Venus Mass Spectrometer," with R. Richard Hodges, Jr., R. Donahue, and M. McElroy, AGU Spring Meeting, 1980.

"High Latitude Ionospheric Dynamics," Invited paper given at the John H. Chapman Symposium on Accomplishments of the Alouette—ISIS Program, EOS, 61, No. 17, 318, 1980.

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"Mass Spectrometer Development," Presentation at PAPI Meeting, Goddard Space Flight Center, February 1981.

"Sulfur and Chlorine in the Venus Atmosphere," with R. Richard Hodges, Jr., International Conference on the Venus Experiment, November 1981.

"The Role of Charge Exchange Reactions in Producing the Hot Exospheric Hydrogen on Venus," with R. Richard Hodges, Jr. and B. A. Tinsley, International Conference on the Venus Environment, November 1981.

"Use of a Magnetic Sector Mass Spectrometer for In Situ Stratospheric Ion Composition Measurements," with A. J. Cunningham, EGS Symposium on Ions in the Middle Atmosphere, Leeds, England, August 27, 1982.

"Planetary Atmospheres," Colloquium at UT–Arlington, November 28, 1982. Composition of the Lower Atmosphere of Venus," paper presented with R. Richard Hodges, Jr., at 1983 Workshop on the Venus International Reference Atmosphere (VIRA) during the XVIII General Assembly of IUGG in Hamburg, FRG, August 14, 1983.

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"Demonstrations for Conceptual Physics," Joint Fall Meeting of the Texas Section of the American Physical Society, Stephen F. Austin State University, November 8, 1986.

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