ELECTRO-OPTICAL SYSTEMS

A XEROX COMPANY

PASADENA, CALIFORNIA 91107 · 213/351-2351

Second Annual Progress Report

CONTACT ION ENGINE SYSTEM
FOR ATS SATELLITES D AND E
Contract NAS5-10380

Prepared for
National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland 20771

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EOS Report 7202-A-2 1 July 1969

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ABSTRACT

This report covers the second 12-month effort on a program to fabricate and test ion microthruster systems for Applications Technology Satellites D and E, provide appropriate ground support equipment, and provide technical support of spacecraft integration, launch, and operation. During the first year, microthruster system development was completed, a prototype model system was fabricated and successfully tested to design qualification levels, and flight hardware units were fabricated, acceptance tested, and delivered for integration on ATS-D. During the second year, support of ATS-D operations was continued, culminating in the successful operation of both microthruster systems in orbit. Flight hardware units for ATS-E were completed, acceptance tested, and delivered to the spacecraft contractor. Support of ATS-E operations is continuing.

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ILLUSTRATIONS

SECTION 1

INTRODUCTION AND PROGRAM SUMMARY

Microthruster system development was begun in December 1966 under sponsorship of the Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base. Initial design work was carried out and and breadboard and experimental model systems were fabricated and tested. The present program began March 22, 1967. During the first year, microthruster system development was completed, and a prototype model system was fabricated and successfully tested to design qualification levels. For conducting checkout and operational testing of the microthruster systems, test consoles were designed and fabricated. Thruster subsystem simulators were designed and fabricated for testing the electronic portions of the system under circumstances where it would be inconvenient or impossible to operate a thruster. Two flight model microthruster systems (S/N 03 and 05) were fabricated, acceptance tested, and delivered to the spacecraft contractor for integration on the ATS-D satellite. As a result of spacecraft integration tests, microthruster system modifications were made to ensure compatibility with spacecraft equipment. The most important modification consisted of the addition of an external filter box which provided transient filtering on all telemetry, power, and command lines.

During the second year of the program (the period covered by this report), the flight spare system (S/N 06) and the two systems for the ATS-E satellite (S/N 07 and 08) were completed and acceptance tested. ATS-D support operations were carried out. They consisted of microthruster system and spacecraft testing at Hughes Aircraft, microthruster preflight checkout at Eastern Test Range (ETR), and system operation in orbit from the control center at Goddard Space Flight Center (GSFC). ATS-E support operations are currently in progress. To date, systems S/N 07 and 08 have been delivered to Hughes Aircraft, and preliminary spacecraft integration testing has been successfully completed. The prototype microthruster system (qualification model) was refurbished and delivered to GSFC for further testing. A thruster cesium feed system was tested after approximately 11 months storage and found to operate satisfactorily, thus answering some questions about the shelf-life capability of the systems. (Corroborating evidence was later obtained from the successful operation of both units on ATS-D after approximately 9 months in storage since their last operation.)

Because of some anomalies discovered in neutralizer operation during acceptance testing of systems S/N 07 and 08, an investigation into the effects of the environment on neutralizer operation was carried out. It was concluded that neutralizer design was satisfactory but that modifications in testing procedures were required. These modifications were made prior to final testing of systems S/N 07 and 08.

Thus, with the close of the second year, the great majority of the technical effort on the program has been successfully completed. The remaining task is support of ATS-E operations. This and the completed tasks are discussed in more detail in the following sections.

SECTION 2

ATS-D SUPPORT OPERATIONS

2.1 SPACECRAFT SUPPORT AT HUGHES AIRCRAFT

The previous report covered fabrication and acceptance testing of the microthruster systems and filter units. On April 6, 1968, the systems were tested at Hughes using the Experiment Package Console (EPC) and STATS. Each system was tested first with the thruster on the control logic and power conditioning (CLPC), then with the thruster simulator. Measurements were made of telemetry transients associated with sparking. All performance was satisfactory.

The filter-CLPC-thruster simulator assemblies (S/N 03 and 05) were then installed on the spacecraft in preparation for spacecraft solar-vacuum testing. On April 9 both systems were pretested as a preliminary to solar-vacuum testing. On April 13 and 18 the systems were tested as part of the spacecraft solar-vacuum test. The procedures followed were Tests 4 and 5, Volume V, ATS-D and ATS-E Acceptance Test Plan, Hughes No. SSD 80094R. Test results were normal.

On May 4 the tests above were repeated in air, following solar-vacuum testing. On May 6 the simulators were removed and the flight thrusters were installed on the CLPC's. The completed flight units were reinstalled on the spacecraft, and air checkout was conducted successfully (tests 1, 2, and 3 of the acceptance test plan). Flight plugs were returned to the custody of EOS for final installation at ETR. On May 15 a final air check was conducted and preparations were made for shipping ground support equipment to ETR. On May 16 alignment measurements were made on the ion engine systems.

Because of the rework performed on the spacecraft, it was later decided that single-axis random vibration testing should be performed. Following this test, an additional air checkout was conducted on the microthruster systems June 2. On June 3 the spacecraft was shipped from Hughes to GSFC.

2.2 SPACECRAFT SUPPORT AT ETR

On June 24 air checkout was performed on both microthruster systems at Cape Kennedy. All data was normal.

Late in the prelaunch sequence, after the flight plugs were installed, the microthruster systems were to be given a final check consisting of commanding on the regulators and verifying normal readings from the temperature telemetry channel. To verify that no problems would be encountered in conducting this test at the scheduled time, the test was conducted in late June by EOS and GSFC personnel. As anticipated, no problems were encountered.

In early July a new voltage monitor unit was installed on the F-4 spacecraft. Since this unit shares voltage regulators with the two ion microthruster units, it was decided that the air checkout procedure should be repeated for each microthruster unit. The tests were conducted by Mr. Robert Bartlett of GSFC, and they confirmed that no problems had been caused by the substitution of the new voltage monitor unit.

Later in July the air checkout test was conducted on both microthrusters, following which the flight plugs were installed. The final check described above was made and the spacecraft shroud was installed. From this time on, the only microthruster testing consisted of periodic repetition of the temperature telemetry check. After approximately a 3-week delay, spacecraft launch took place on August 10.

2.3 ORBITAL OPERATION SUPPORT

The ion microthrusters aboard ATS IV were operated successfully during five test periods, the first test occurring on August 15, 1968 and the last on October 9, 1968. EOS personnel participated in the first test; the remainder were conducted by GSFC personnel.

In general, the results of the tests were highly satisfactory. Both systems operated as anticipated. No high voltage sparking was detected, and accelerator electrode drain currents were negligible. There was no evidence of electromagnetic interference caused by system operation. Because of the size of the still-attached Centaur stage and the low-altitude orbit, appreciable neutralizer emission current was observed only during a few brief periods. This effect had been predicted. Results of the tests are reported in detail in a paper entitled "Cesium Contact Ion Microthruster Experiment Aboard Applications Technology Satellite (ATS) IV," by Robert E. Hunter and Robert O. Bartlett of NASA/GSFC and Robert M. Worlock and Edmund L. James of EOS. The paper (AIAA No. 69-297) was presented by Dr. Hunter at the AIAA 7th Electric Propulsion Conference, March 1969.

On September 4 a series of measurements was made on a voltage regulator identified as P/N 475308-102, S/N Y1, rated load 1.46A. The purpose of the measurements was to determine the undervoltage dropout point under typical ion engine load conditions. With a load resistor corresponding to 1.25 amperes at 24.0 volts, the dropout point was 17.1 volts output (19.3 volts input). For heavier loading the dropout voltage was slightly higher; for lighter loading, slightly lower. Since the ion engine CLPC undervoltage dropout point is approximately 19 volts, it can be expected to turn off before the regulator as spacecraft battery bus voltage drops. This is consistent with data obtained during operation of ion engine No. 2 during test No. 2.

In the course of studying the neutralizer data received from ion engine test No. 5, a number of tests were conducted on laboratory microthruster hardware. In one test, the effect of reduced neutralizer emission requirements (such as produced by ram ion current in orbit) on microthruster floating potential was measured. The experimental setup and data obtained are shown in Fig. 1 and Table I.

As a possible explanation for the low neutralizer electron emission currents observed, the effect of repetitive neutralizer switching was investigated in laboratory tests. Microthruster system S/N 10 was operated and neutralizer emission was observed to be normal. Then the neutralizer heater current telemetry channel was shorted to ground, causing the neutralizer select circuit to switch repetitively between the two neutralizers. A complete cycle (neutralizer A to B, then back to A) took 310 milliseconds. Since the time for a cold neutralizer to reach full emission after application of heater power is approximately 500 milliseconds, emission attained during the 155 milliseconds each neutralizer was on was only a small fraction of full emission. Average emission during this operation was approximately 1% of beam current. Neutralizer response was further investigated by ungrounding the telemetry output and issuing periodic neutralizer select commands with a pulse generator. Command rate was varied between one and 16 commands per second and heater current and emission were recorded. The results were consistent with the self-cycling data. The conclusion is that failure of the neutralizer select circuitry could not account for the apparent reduced emission capability observed during orbital test No. 5.

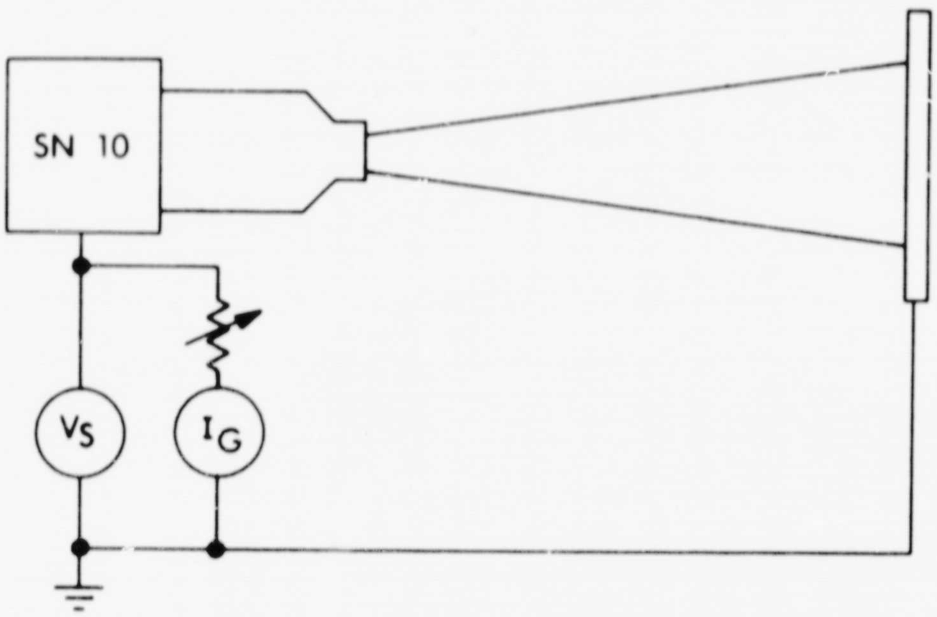

Figure 1. Experimental Setup

TABLE I

EMISSION DATA PARTIALLY NEUTRALIZED BEAM

Beam Current (μA)	Emission Current (μA)	Ground Current (μA)	System Potential (V)
660	670	0	68
660	575	100	60
660	340	300	43
660	90	600	14
660	0	680	0

SECTION 3

FLIGHT ACCEPTANCE TESTING

3.1 FLIGHT SPARE SYSTEM S/N 06

System S/N 06-11 was started through flight spare acceptance testing in late April. Thermal-vacuum testing was conducted April 24 and 25. The test was successful except that during the hot portion of the test the X-deflection circuitry was inoperative. After completion of the acceptance test, investigation revealed that module A6 did not operate properly at the high end of its required temperature range. The module was replaced with another A6 module and the CLPC was found to operate satisfactorily over the full temperature range.

Since this unit had to serve as flight spare for both flight systems (S/N 03 and 05 on ATS-D), it was decided that the maximum thrust level should be reduced from 20 to 16 micropounds. The necessary resistor was installed on the circuit board.

On May 6, CLPC S/N 06 was subjected to the postfabrication acceptance test, using the laboratory model thruster simulator. Operation was satisfactory except that automatic transfer of the neutralizer select relay was marginal, due to the short duration of the transfer pulse. The best available solution was to lengthen the pulse by adding a capacitor to slow down the signal which terminates the transfer pulse. This modification was incorporated. The CLPC was subjected to single-axis flight acceptance random vibration, assembled with an air/vacuum thruster simulator, and then subjected to the flight spare thermal-vacuum test. This test was completed on May 10 and acceptance testing of the flight spare system S/N 06-11 was considered complete.

The malfunctioning A6 welded module was returned to WEMS, Inc. (the welded module manufacturer) for failure analysis. At EOS direction, the epoxy encapsulation around the terminals of the transistors in the malfunctioning flip-flop was removed, and it was discovered that an interconnecting ribbon was out of position and causing a short circuit. The ribbon was moved and the encapsulation repaired. Retesting showed the module to be operating satisfactorily.

As a check on the probability of other ribbons being out of position, module sets 02, 07, and 08 were returned to WEMS for X-ray photography. Analysis of the photographs showed no ribbon mislocations.

3.2 FLIGHT SYSTEMS S/N 07 and 08

During May, fabrication of CLPC S/N 07 and 08 was completed and the units were subjected to the postfabrication acceptance test. S/N 07 passed without incident; S/N 08 required only adjustment of the negative high-voltage overload trip point. Final assembly of the corresponding thruster subsystems was started.

On June 18 final assembly of microthruster system S/N-07-12 was completed and flight acceptance testing was started. Vibration test (with filter unit S/N 04) was uneventful. The remainder of the filter unit acceptance test (electrical checkout and thermal cycling) was then completed. The microthruster system was next subjected to the flight acceptance thermal vacuum test. This test was completed satisfactorily with the exception of an anomaly in the behavior of one neutralizer filament. When the No. 2 filament was turned on, the filament heater current telemetry indicated a normal value. During the course of a few hours, however, the indicated current decreased from 2.43 to 2.21 amperes. Lower than normal heater current was corroborated by inadequate electron emission. When the filament was turned off and turned on again some time later, the anomalous behavior was repeated. The thermal vacuum test was completed and an investigation of the neutralizer malfunction was begun. Because of their scope and application to other systems, the neutralizer investigations and results are discussed separately in Section 5 of this report.

On July 1 microthruster system S/N 08-13 was subjected to the air checkout test as the first step in the flight acceptance test sequence. During this test, a number of telemetry indications were abnormally low. The acceptance test sequence was interrupted, the system disassembled, and the apparent CLPC malfunction investigated. It was found that wiring on the welded module circuit board has been damaged by improper technique in installing and removing the magnetic shield which encloses several of the welded modules. Wiring with damaged strands was cut and spliced. Wiring with damaged insulation only was sleeved. After repairs were completed, bench testing showed the unit to be operating normally.

Other CLPC units were inspected for indications of similar wiring damage. CLPC S/N 07 was found to have one wire with damaged insulation and CLPC S/N 01 was found to have one wire with damaged strands. Repairs were made by the techniques described above and bench tests were conducted to confirm normal operation.

In early August, neutralizers for flight systems S/N 07 and 08 were assembled and conditioned using the revised procedures and specifications arrived at during the previous month's investigation into unstable filament operation, described in Section 5. Operation of all neutralizers was normal.

On August 6, 7, and 8, flight system S/N 08 was subjected to flight acceptance testing. Operation of the system (including neutralizers) was normal with the exception of one anomaly. During the thermal vacuum test, two instances were observed in which the beam control feedback loop underwent an apparent discontinuous shift in operating level. Vaporizer heater power changed discontinuously and stabilized at a slightly different value. The beam current responded to the change in vaporizer power and stabilized at a new value approximately 10% off from the original value. In one case the beam current increased; in the other it decreased.

After the acceptance test the CLPC was tested with an air/vacuum thruster simulator to determine the cause of the beam current shift. At first it was suspected that the shifts were connected with temperature changes. However, no shifts were produced by changing the CLPC environment temperature. A reexamination of the acceptance test strip chart records suggested that the shifts were correlated with thruster sparking. This lead proved more fruitful. On several occasions when sparks were deliberately produced, shifts in simulated beam current were produced.

The only difference in beam control feedback loop circuitry between the first few CLPC and S/N 07 and 08 is that in the later models a zener diode was incorporated in module A14 to limit the input signal at the operational amplifier AR1. Although there was no obvious way in which the zener diode could cause the observed effect, it was nevertheless suspect. A qualification model module, S/N 128 was substituted in CLPC S/N 08 and sparks were produced. No shifts in simulated beam current were observed, reinforcing the hypothesis that the shifts were related to the presence of the zener diode. The A14 module removed from CLPC S/N 08 (S/N 007) was returned to its manufacturer (WEMS, Inc.) and the zener was disconnected. When this module was replaced in CLPC S/N 08, shifts in simulated beam current could no longer be produced. It was concluded that the presence of the zener was in some way responsible for the level shifts.

On August 21 and 22 flight system S/N 07 was retested to flight acceptance levels as directed by the Technical Officer. This test was intended to demonstrate that in full system operation the neutralizer operated as intended and that the CLPC was not degraded in the process of making minor wiring repairs. The test was successful except for an occurrence of the anomalous behavior described above. When the system was turned on, beam current levels were observed to be approximately 10% lower than normal. During the course of the test, one additional small shift was observed. (Like S/N 08, S/N 07 incorporates the zener diode in module A14.)

To return S/N 07 and 08 to flight status, it was decided that new A14 modules should be built and installed. By September 27, fabrication and testing of three modules at WEMS was complete, and the units were delivered to EOS.

On October 3 reacceptance testing of CLPC S/N 07 and 08, consisting of single-axis random vibration and thermal vacuum testing with thruster simulator, was successfully completed. On October 4 the two microthruster systems and test console S/N 2 were delivered to Hughes Aircraft. On October 7, EPC tests of the systems (including filter box) were conducted. In the course of this testing, two anomalies were uncovered. The first was that on both systems 07 and 08 the Y deflection telemetry data was substantially different from that obtained before; data corresponding to small deflections was approximately 0.5 volt higher than normal while data corresponding to large deflections was approximately 0.5 volt lower than normal. The second anomaly was that on system 08 the deflection potential appearing between CLPC terminals 9 and 11 was approximately half the normal value for deflection in the "up" direction.

Both systems (and the test console) were returned to EOS for investigation. The first anomaly was traced to the effect of the filter box on the Y deflection telemetry signal. With the filter box removed, the data were the same as observed during acceptance testing; with the filter box in place, the data were the same as observed in EPC testing at Hughes. The shifts produced by the filter box appeared to be related to the effect of the filter box input capacitance and the telemetry channel output zener diode on transients appearing on the telemetry lines. Since no unexplained changes had taken place and no serious loss of performance was involved, the problem was resolved by recalibrating the telemetry channels with the filter box in place. Tests with three different filter boxes on one CLPC verified that the effect was associated with the filter design rather than an anomaly in a particular unit.

The abnormally low deflection potential appearing between terminals 9 and 11 on CLPC 08 was traced to a failure of resistor R29, an 18.2K resistor in series with one of the secondaries on the Y deflection converter transformer. Failures of this type had been observed before (on CLPC 04) and were attributed to electrical breakdown associated with high-voltage sparking. CLPC 08 had been subjected to high-voltage sparking (direct shorting of positive and negative high-voltage supplies not involving the 300K current limiting resistor present during normal thruster sparking) during the investigation of beam control loop anomalies. The malfunction was resolved by replacing the failed R29 and taking steps to eliminate direct positive-to-negative shorting from any future testing. Following resistor replacement, CLPC 08 was subjected to single-axis acceptance level random vibration and thermal-vacuum testing with a thruster simulator.

On October 22 systems 07 and 08 and the test console were redelivered to Hughes. On October 22 and 23, EPC testing of both systems was successfully completed. First the systems were tested with the thrusters in place on the CLPCs (Tests 1, 2, and 3 of Volume V, ATS-E Acceptance

Test Plan, Hughes No. SSD 80377R). The thrusters were then removed, the thruster simulators were installed, and tests 4, 5, and 6 were completed. The systems were then placed in Government Bonded Stores pending spacecraft integration tests.

SECTION 4

ATS-E SUPPORT OPERATIONS

On October 29 systems 07 and 08 (CLPCs and air/vacuum simulators) were installed on the F-5 spacecraft and checked out by performing Tests 4 and 5 of Volume V, ATS-E Acceptance Test Plan. All operation was normal. The systems were then removed from the spacecraft and returned to stores.

On January 28 Pirani gauge measurements (Test 1, Volume V, ATS-E Acceptance Test Plan) were made on systems 07 and 08. Both measurements indicated that pressure was satisfactory and had not changed since the previous measurement.

On March 13 both systems (CLPCs and air/vacuum simulators) were installed on the F-5 spacecraft in preparation for spacecraft long-form testing scheduled for April.

SECTION 5

NEUTRALIZER INVESTIGATION

5.1 INTRODUCTION

Because of questions regarding neutralizer performance raised during acceptance testing of microthrusters for ATS-E and during orbital testing of ATS-4, two separate investigations were undertaken to examine neutralizer behavior. The results of the two efforts complement one another, indicating that the quantity of residual oxygen present affects neutralizer emission and filament resistance. Neutralizer operation in partial pressures of oxygen above 10^{-6} torr leads to reduced emission and increased filament resistance. Operation at lower partial pressures, such as in cryopumped vacuum facilities or as would be experienced at synchronous altitude, produces adequate emission and stability.

During flight acceptance testing of microthruster system S/N 07-12 in June 1968, an anomaly was noted in the behavior of one neutralizer filament. After 3 hours of normal operation, the filament heater current decreased from 2.43 to 2.21 amperes (telemetry readings 3.69 to 3.35 volts). Lower-than-normal heater current was accompanied by inadequate electron emission. In the subsequent investigation neutralizer behavior was observed in 22 separate vacuum tests, which showed that electron emission and filament heater current were more sensitive to vacuum chamber pressure than had been previously appreciated. Specifications were therefore revised to limit filament operation to pressures below 10^{-6} torr. By-products of this investigation included data on telemetry drift as a function of temperature and improved fabrication techniques for the decel-neutralizer assembly.

During microthruster tests aboard ATS IV, neutralizer emission in Test 5 was only 300 μA when the ion beam was 756 μA and the spacecraft potential was -140V. Proper neutralizer emission should have maintained the spacecraft at -40V. Since emission-limited behavior of the neutralizer could explain this result, an investigation was undertaken to examine the effects on neutralizer behavior caused by the time history of electric field and by various residual gasses.

5.2 NEUTRALIZER FILAMENT CURRENT INVESTIGATION

The neutralizer filaments for system S/N 07-12 were fabricated from GE sample tantalum-yttrium and conditioned per Procedure 7202-137B in a 1' x 3' vacuum system. Approximately six feet of 0.007-inch-diameter tantalum wire doped with 50 ppm yttrium was received from GE as a sample. This wire was operationally tested at EOS by demonstrating 12,000 hours of operation. Filaments constructed from the sample were used on the ATS Qualification Unit and ATS Flight Units 03, 05, and 06. During processing, vacuum chamber pressure remained below 3×10^{-7} torr and emission of 1000 μA per filament was observed.

Postconditioning filament resistance indicated a 4% increase in room-temperature resistance in filament No. 1 and a 6% increase in No. 2. Nominal change during conditioning is 2%, but changes of 6% had been previously observed. This assembly was incorporated in thruster subsystem S/N 12 and underwent thruster conditioning per Procedure 7202-120C in the same 1' x 3' vacuum system. During the operation filament No. 1 was operated for 2 hours in vacuum between 5×10^{-6} and 9×10^{-6} torr; filament No. 2 was operated for 2 minutes at 5×10^{-6} torr. Subsequently, filament No. 1 operated for 10 hours at a nominal pressure of 10^{-6} torr. Electron emission was normal, i.e., in close agreement with ion beam current.

The conditioned thruster was assembled on CLPC S/N 07, and the unit was subjected to flight acceptance vibration, Procedure 7202-411C. The unit was installed in a 2' x 6' vacuum system for flight acceptance thermal-vacuum testing, Procedure 7202-412A. The test chamber is equipped with a cryowall which is flooded with liquid nitrogen during full-scale acceptance testing. Three hours after the start of the test the heater current telemetry for filament No. 1 decreased from 3.71V to 3.35V (telemetry values are reported to minimize errors in data conversion). Emission was less than 50 μA. The change in current took place gradually over a period of 3 minutes; chamber pressure at the time was 5×10^{-7} torr.

The filament was commanded off and allowed to cool. When it was commanded on again, the initial value was 3.59V. In 5 minutes the current telemetry had decreased to 3.35V. During the cold portion of thermal-vacuum, filament No. 1 was again commanded on. The initial value was 3.73V, decaying to 3.65V in 5 minutes. The acceptance test was completed by operating filament No. 2, which behaved normally throughout the test.

Visual inspection after the test revealed no clue to the behavior of the filament. During the posttest evaluation, the filament clamping mechanism was examined. A torque wrench was used to determine if the clamping nuts were torqued to specification. Clamps were found to be undertorqued by 0.3 in-lb, and both filaments were retorqued to spec. The entire operation was conducted prior to a filament resistance measurement. Verifying torque after neutralizer operation is not standard procedure and proved unwise in this case. Filament resistances were 0.15 and 0.17 ohm respectively. The specification requires 0.128 to 0.132 ohm. Subsequent retest in the 1' x 3' chamber verified that both filaments operated at temperatures too low for adequate emission.

Since both filaments were unusable and no clue to the problem was available, decel-neutralizer assembly S/N 07 was refurbished with replacement filaments from GE sample wire. Conditioning was done in the 1' x 3' chamber at a maximum pressure of 2 x 10^{-6} torr. The decel-neutralizer assembly underwent single-axis random vibration at flight acceptance levels and was installed on CLPC S/N 07. A resistor was used to simulate the ionizer heater, and a metallic rod was used to simulate the ion beam. Bias voltage on the rod was adjustable externally. This configuration was used to avoid multiple cycles of the cesium valve in the flight thruster.

Reacceptance testing was attempted with this configuration in the same 2' x 6' vacuum system. Pressure was as high as 2 x 10^{-5} torr briefly and remained above 3 x 10^{-6} torr throughout the test. Liquid nitrogen was not used in the cryowalls during this test, since there was no cesium to condense and no ionizer to protect from contamination, and because the sensitivity of filaments to pressures above 10^{-6} torr was not yet recognized. During the test both filaments degraded. Emission from filament No. 1 dropped from 680 to 150 μA, and filament No. 2 from 125 to 72 μA. Posttest resistance measurements indicated increases to unacceptable levels.

Meanwhile decel-neutralizer assembly S/N 08 was completed using GE sample wire and conditioned in the 1' x 3' chamber at a pressure ranging from 4 x 10^{-6} down to 2 x 10^{-7} torr. Resistance change during neutralizer conditioning was 1% for filament No. 1 and 2% for filament No. 2. This assembly was operated again during conditioning of thruster subsystem S/N 13 at an average pressure of 2 x 10^{-6} and a maximum of 5 x 10^{-6} torr.

Since the neutralizer transformer load lines for CLPC S/N 07 and CLPC S/N 08 were very similar, decel-neutralizer assembly S/N 08 was subjected to single-axis vibration and was installed on the CLPC S/N 07 in the test configuration described above. The unit was installed in the 2 x 6 vacuum system for reacceptance thermal-vacuum testing. Operating pressure was between 6 x 10^{-6} and 3 x 10^{-6} torr throughout the test. Again, no LN_2 was used in the cryowall. Electron emission began at 750 μA per filament and decreased to 100 μA per filament as the filament current decreased. After the test, measurement showed filament resistance had increased to unacceptable values. These filaments were sent to GSFC for examination. Decel-neutralizer assembly S/N 07 was rebuilt with new tantalum-yttrium wire purchased from GE, the sample GE wire supply having been exhausted. The new wire was also subjected to EOS operational testing, and test filaments had accumulated nearly 3000 hours of operation at this time. The test continued, and the filaments passed 8000 hours of operation. The decel-neutralizer assembly was conditioned in the 1' x 3' chamber. The LN_2 control system failed during conditioning, resulting in pressure as high as 10^{-4} torr. Emission data was not taken during the high-pressure incident, but emission was about 1000 μA at the end of conditioning. After conditioning, the filament resistances were readjusted to lower values in an attempt to compensate for the resistance changes that had been seen during the investigation to date. This assembly was then subjected to single-axis vibration and operated on CLPC 07 in the 2' x 6' vacuum system. During the test, pressure was between 5 x 10^{-6} and 3 x 10^{-7} torr. Suring 75 hours of operation, filament No. 2 current telemetry decreased from 3.65V (2.4A) to 2.82V (1.8A). During 35 hours of operation, filament No. 1 current telemetry decreased from 3.85V (2.6A) to 3.64V (2.3A). After the test, microscopic examination of the filaments showed that, near the middle, the diameter of filament No. 2 was approximately 0.0035 inch and the diameter of filament No. 1 was approximately 0.006 inch, suggesting that the increase in resistance was produced by physical loss of filament material. This observation was corroborated by measurements made on the samples submitted to GSFC. Filament degradation was tentatively ascribed to reaction with residual oxygen.

New filaments were installed on decel-neutralizer assembly S/N 08 and the conditioning procedure was carried out. The filaments were operated for 90 hours at a chamber pressure of 3×10^{-7} torr. Resistance and emission were normal and very stable.

The neutralizer assembly was installed on CLPC S/N 07 and operated briefly in the 1' x 3', chamber where filament temperature measurements could be made. The purpose of this test was to confirm that, in operation on the CLPC, the filaments operated at the predicted temperature. Test data showed the filaments to be operating within 10° C of the predicted temperature, 1760° C (optically measured and uncorrected for emissivity and window). CLPC and neutralizer were then operated in the 2' x 6' chamber, where each filament ran stably for about 10 hours. Electron emission was normal.

This neutralizer was next assembled on CLPC 08 and operated in the 2' x 6' chamber. After normal operation had been verified with the cryowall chilled and the chamber pressure at approximately 3×10^{-7} torr LN_2 flow to the cryowall was stopped to evaluate the effect of pressure on filament operation. It was observed that as chamber pressure rose from 3×10^{-7} to 10^{-4} torr, electron emission fell from 1400 μA to 500 μA and neutralizer heater current telemetry fell from 3.75V to 3.61V. At this point the filament was turned off.

When the chamber pressure had been reduced to 8×10^{-6} by introducing LN_2 in the cryowall, the filament was again operated. Emission returned to 1500 μA and filament current to 3.69V in approximately 2 hours. During this period pressure dropped to 10^{-6} torr. The chamber pressure was allowed to stabilize at 3×10^{-6} torr without LN_2 in the cryowall. Emission was adequate, but heater current decreased gradually. After 12 hours of operation at this pressure, the filament failed. Microscopic examination showed a rough black appearance suggesting chemical attack.

While tests were being made on various neutralizer filaments, measurements were also made on CLPC units. Neutralizer transformer load lines, or voltage-current curves, were remeasured and compared with original data. In the case of CLPCs S/N 07 and 01, the new data differed slightly from the old, but not enough to support the hypothesis that filaments were being degraded by overheating. Measurements of the temperature sensitivity of telemetry readings indicate that part (but not all) of the apparent decrease in neutralizer heater current observed is associated with CLPC temperature change rather than physical change of the filaments. On the basis of these experiments, it was concluded that unstable neutralizer performance was associated with filament operation in inadequate vacuum. Specifications on acceptable vacuum level were revised down to pressures below 10^{-6} torr.

Decel-neutralizer assembly S/N 07 was rebuilt with the purchased GE wire. This assembly underwent conditioning in the 1' x 3' chamber at a pressure of 4×10^{-7} torr.

Emission and heater current were normal. After the test, the measured resistance of one filament had increased 40%. Since this filament operated normally in conditioning, it was installed on CLPC 07 for an exploratory test in the 2' x 6' chamber. The cryowall was flooded with LN_2 and chamber pressure was in the low 10^{-7} range. Emission and heater current were normal, but cold resistance remained 40% too high after this test. It was concluded that the clamps were not making good contact until the filament became hot. The assembly was returned to fabrication for rework with new wire.

The original sample GE wire had been annealed at the factory. Handling characteristics of the new wire indicated it had not been similarly annealed. At the suggestion of GSFC and in order to avoid similar clamping problems, the purchased GE wire was annealed in lots at 1000° C in 10^{-7}

torr vacuum prior to installation on neutralizer systems. In addition, improved filament cleaning procedures were added and greater care taken to avoid contamination of filaments after cleaning.

Using annealed purchased GE wire, decel-neutralizer assembly S/N 08 was rebuilt, conditioned, and put through flight acceptance vibration and thermal-vacuum testing as part of the S/N 08-13 microthruster system. These tests were completed without incident at a pressure of 3×10^{-7} torr with LN_2 in the cryowall. Preliminary data indicated improved emission for this neutralizer at low ion beam currents, but after initial turnon, emission was similar to that of neutralizers on other flight units.

Decel-neutralizer assembly S/N 07 was rebuilt with annealed GE wire and underwent conditioning and single-axis random vibration. Acceptance testing with simulated ionizer and ion beam was undertaken on CLPC 07 in the 2' x 6' vacuum chamber. Chamber pressure was 5×10^{-7} torr with LN_2 in the cryowall. Emission began above 1 mA per filament but fell as low as 428 μA per filament during the test. Pressure and heater current were normal. As pressure dropped to 4×10^{-7} torr, emission increased to 640 μA. Examination of data indicated that the filaments were good and that the emission suppression was the result of a contaminant, probably oxygen, since no cesium was present to act as an oxygen getter. Supporting this hypothesis is the affinity of tantalum for oxygen. To verify the hypothesis, the neutralizer was operated in the 1' x 3' chamber at a pressure of 10^{-7} torr. Emission was initially suppressed, but normal emission was achieved after an hour of operation, indicating that the contaminant had been evaporated away in the improved vacuum.

The 07 neutralizer assembly had been adequately demonstrated by the above tests. However, to verify the pressure hypothesis and to avoid any possible doubt, GSFC instructed that the S/N 07-12 microthruster system be completely reassembled and resubjected to the complete flight acceptance thermal vacuum test. Pressure for this test was 2×10^{-7} torr. Emission was normal, and the test was completed without incident.

At the conclusion of the investigation both flight units had demonstrated normal performance. The probable cause of the trouble was identified as high residual oxygen partial pressure.

5.3 SUPPRESSED NEUTRALIZER EMISSION INVESTIGATION

When microthruster system tests were conducted aboard ATS IV, unexplained low neutralizer emission was observed during tests 4 and 5. One possible cause for the low reading would be that the neutralizer was operating emission limited. Examination of microthruster flight acceptance test data indicated that emission rise times for neutralizers undergoing initial turnon were of the order of 20 seconds. Some instances during the acceptance test required as long as 5 minutes for emission recovery after switching neutralizers. However, even this period of time is much too short to explain the phenomenon observed in flight. Two hypotheses appear reasonable. The neutralizer emission could be sensitive to the history of the extraction field. After a long rest period or exposure to atmosphere, there might be some field-sensitive surface effect. Alternatively, some constituent of the residual atmosphere could suppress emission. The following tests were undertaken at the suggestion of GSFC to examine these possibilities.

To investigate the effect of the absence of electric field on subsequent neutralizer emission, two 0.007-inch-diameter Ta-Y neutralizers were assembled on a test fixture duplicating the ATS microthruster experiment. A metal rod was used to simulate the cesium ion beam. The experimental setup is shown in Fig. 2. The filaments were placed in a 1' x 3' vacuum

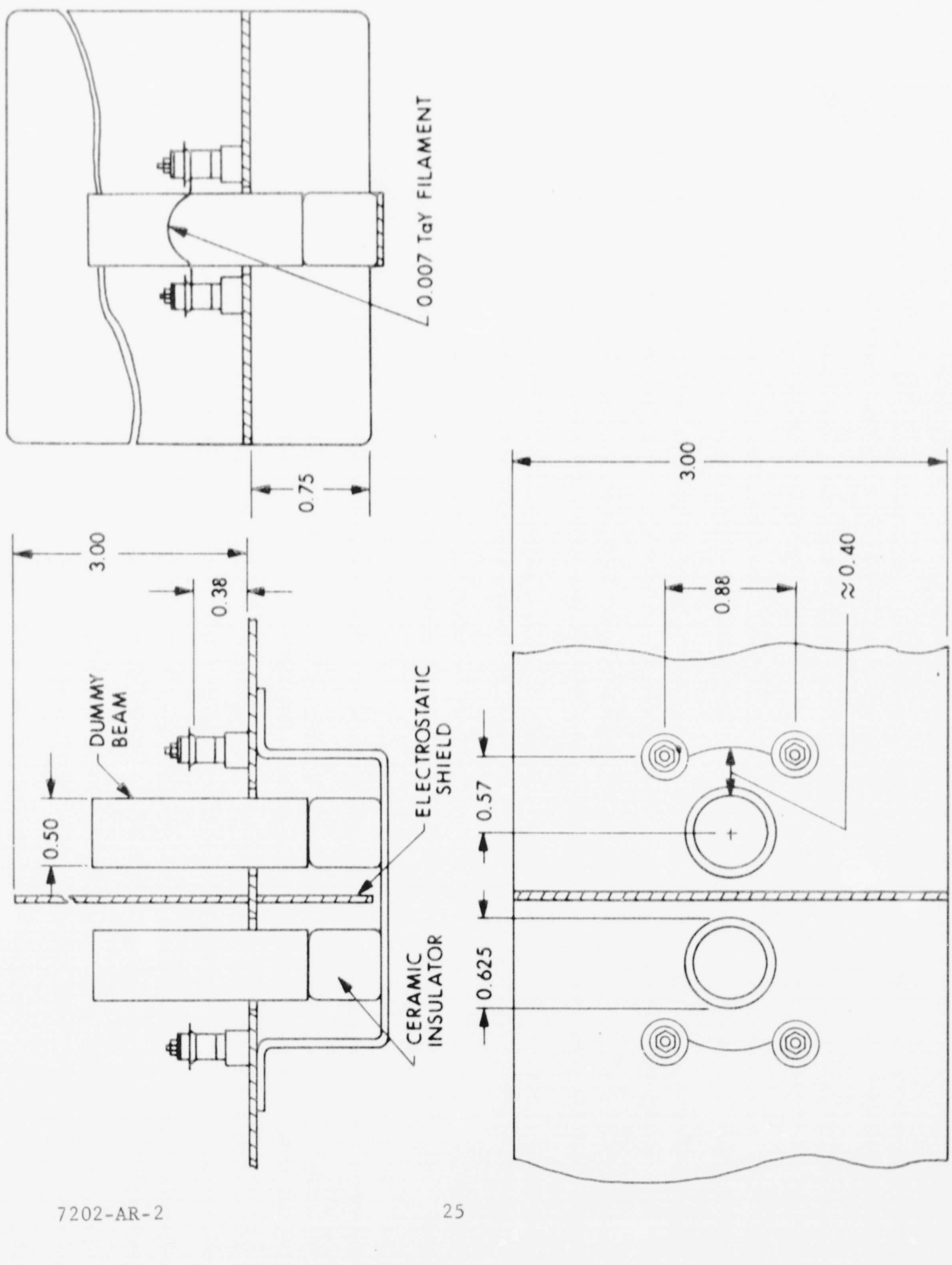

Figure 2. Experimental Neutralizer Configuration

test facility, pumped to 2×10^{-7} torr, and operated according to normal neutralizer conditioning procedures with the exception that one filament was not exposed to any extraction field during the first 21 hours of conditioning. Also, the experiment was conducted with 2.40A filament current in each element, the lowest current expected in flight operation. Electric field was then applied, and the emission from the two filaments was compared. Emission was 950 μA at 100V beam potential from the control filament and 720 μA on the test filament conditioned without field.

Emission at 1000V beam potential was 990 μA for the control filament and 820 μA for the test filament; at 3000V, 1110 and 910 μA respectively. Emission on both filaments was somewhat lower than normal; after 20 hours of conditioning, filaments usually produce 1 mA of emission. The filaments were allowed to continue operating with extraction field on both. Emission from the test filament increased during the next 19 hours to 840 μA, still low but comparable with the control and well above the 300 μA seen on the orbital flight. Since the test was not conclusive, a repeat was scheduled.

The second test employed new filaments and the conditioning proceeded for 48 hours before field was applied to the test filament. Chamber pressure was 2×10^{-7} torr throughout the test. The longer period was used in an effort to separate time from field effects. The control filament again was exposed to field from the beginning of the test. At the beginning of the test the control filament produced 700 μA at 100V beam potential. After 48 hours the control filament produced 1 mA. The test filament was subjected to field and produced 900 μA at 100V. The emission was in the space-charge-limited regime to approximately 200V and in the emission-limited regime above 300V. At 1000V the test filament produced 1.13 mA and the control filament 1.41 mA.

Although both the first and the second test results indicated lower emission from the test filament than from the control filaments, the effect did not appear to be a strong one. The differences in emission that were seen were no larger than the filament-to-filament variations seen in the past. The conclusion drawn from these tests was that there is little or no field-sensitive effect on electron emission.

After the second field effect test the same neutralizer arrangement was retained in the vacuum facility and used to investigate the effects of partial pressures of various residual gasses. Test gasses used were oxygen, nitrogen, and nitrous oxide. Upper atmosphere data indicate that the major atmospheric constituents at the orbital altitude of interest are O_2, O, N_2, N, and in smaller amounts NO. During the tests conducted in the 1' x 3' vacuum facility, an ultraviolet lamp with emission at 1849Å and 2537Å was used to try to produce atomic specie from the molecular parent. Residual gas analysis was performed with a Veeco residual gas analyzer (RGA). Data from the analyzer verified the presence of the test gasses but did not confirm the production of their atomic constituents by UV bombardment. For example, no change was detected in the mass 14 peak when the UV lamp was turned on with N_2 being admitted to the chamber. The RGA produces a substantial quantity of atomic constituents in its ionization chamber and might be masking their presence in the main test chamber. In any event, no positive conclusion could be drawn about the presence of N or O in the tests conducted.

The procedure followed for each test was the same. Only one filament was operated. The background pressure was between 10^{-7} and 2×10^{-7} torr. A gas analysis was performed, and emission was measured with 100V beam potential and 2.40A filament current. The filament was turned off and the test gas admitted through a bleed valve. The gas flow was allowed to stabilize for at least 30 minutes. When the chamber pressure was stable, residual gas analysis was run to verify that only the test gas was being admitted. The filament was then operated at 2.40A and emission was recorded as a function of time. The beam potential was 100 volts.

In this series of tests emission suppression was very evident with oxygen, some suppression was seen with nitrous oxide, and none was seen with nitrogen. Results for the gasses tested are given in Table II. All the tests conducted with oxygen were run with the same filament, and all other tests in the series were conducted with the second filament.

The rise in emission in test 5 was due to the experimental procedure of keeping filament current constant. In the presence of oxygen the filament current began to decrease gradually. This is the same effect reported in Subsection 5.2. At the time those tests were made it was supposed that oxygen was the contaminant. The emission suppression tests reported in this subsection confirm that theory. The current was manually increased to maintain 2.40A, resulting in a filament temperature 100^{o} C hotter than normal. During the test it was thought that oxygen was carrying away some of the filament material as TaO. The increase in operating resistance of the filaments appeared to be permanent, thus supporting this view. Examination after removal from the test, however, showed little cold resistance change, 0.130 to 0.134 ohm, and the filament had retained a constant diameter.

During this series of tests the RGA did not indicate very high quantities of N_2O or NO when nitrous oxide was admitted to the chamber. The molecular oxygen and nitrogen were very evident, however. This observation threw some doubt on the validity of the nitrous oxide data.

A second pair of filaments was operated to obtain more data at partial pressures below 10^{-6} torr. The new filaments were conditioned for 50 hours. The procedure for introducing test gasses was the same as above.

TABLE II

EFFECTS OF VARIOUS GASSES
ON NEUTRALIZER EMISSION

Test No.	Test Gas	Pressure ($\times 10^{-6}$ torr)	UV Lamp	Emission at Start of Test (μA)	Emission After 30 min (μA)	Emission After 1 hr (μA)	Emission After 2 hr (μA)	Comments
1	O_2	2	Off	1180	415	----	----	
2	None	0.3	Off	450	660	----	----	Recovery from test 1
3	O_2	1	Off	1110	660	----	----	
4	O_2	3.8	Off	600	480	420	----	Filament current decreasing with time
5	O_2	3.8	Off	730	1200	----	----	Filament current readjusted to 2.40A
6	O_2	3.8	On	1200	1170	----	----	T_{fil} 100°C above normal
7	N_2	1.4	Off	1320	1400	1420	1400	
8	N_2	0.9	Off	1380	1370	----	----	
9	N_2	0.9	On	1370	1340	1370	----	
10	N_2O	0.9	Off	1120	940	860	850	Little N_2O or NO seen
11	N_2O	0.8	On	800	----	780	760	
12	None	0.4	Off	760	920	950	----	Recovery from test 11

Data was collected for vacuum chamber pressures of 4×10^{-7}, 8×10^{-7}, and 10^{-6} torr. The background pressure was between 10^{-7} and 2×10^{-7} torr. Gasses tested were oxygen, nitrogen, and nitrous oxide. Filaments were operated for 2 hours at a partial pressure of the test gas, then allowed to recover at background pressure. The operation was then repeated at the next higher test pressure. Data are presented in Table III. Figures 5-3 through 5-6 show the time history of filament emission.

The first filament was operated in oxygen at each partial pressure. The same filament was then operated in nitrogen and then in nitrous oxide. The second filament was operated in nitrogen to determine if prior operation in oxygen had permanently affected the first filament. Some emission suppression was seen with all gasses. Nitrogen had little effect, while oxygen produced the greatest suppression and nitrous oxide caused suppression intermediate between the other two. The resistance of the first filament increased slightly with each gas introduced, including nitrogen. The final cold resistance increased from 0.128 ohm to 0.132 ohm. The gradual increase in resistance explains the increase in starting emission with each test, since the filament was maintained at 2.40A heating current. The second filament, operated only in nitrogen, had a starting cold resistance of 0.128 ohm and a final resistance of 0.129 ohm. No significant difference in emission due to nitrogen was noted between the filament that had been exposed to oxygen and the one that had not.

The second series of tests confirmed the results of the first. Oxygen and nitrous oxide cause substantial emission suppression; nitrogen causes little emission suppression. Both N_2O and NO were detected in substantial amounts when nitrous oxide was admitted to the chamber with the RGA during the second test.

TABLE III

EFFECTS OF VARIOUS GASSES ON NEUTRALIZER EMISSION

Test No.	Test Gas	Chamber Pressure ($\times 10^{-6}$ torr)	Fil. No.	Emission Prior to Test (μA)	Emission After 2 hours (μA)	Emission After Recovery (μA)	Recovery Time (hr)
13	O_2	0.4	1	800	320	770	17
		0.8		770	235	838	17
		1.0		838	270	860	17
14	N_2	0.4	1	990	1000	960	1
		0.8		960	950	920	17
		1.1		950	890	935	1
16	N_2O	0.4	1	1225	835	1240	25
		0.8		1300	815	1300	17
		1.1		1300	835	1130	22
17	N_2	0.4	2	1030	1100	1100	17
		0.8		1170	1000	1020	3
		1.1		1110	1000		End test

5.4 CONCLUSION

A primary conclusion can be drawn from the preceding investigations. Oxygen present at pressures above 10^{-6} torr is adequate to suppress electron emission from and alter resistivity of tantalum filaments. In vacuum with partial pressures of oxygen well below 10^{-6} torr, emission is satisfactory and filament resistance is stable. Also, substantial emission suppression was seen with nitrous oxide, but little was noted with nitrogen. No conclusion can be made regarding the effects of N, O, and NO.

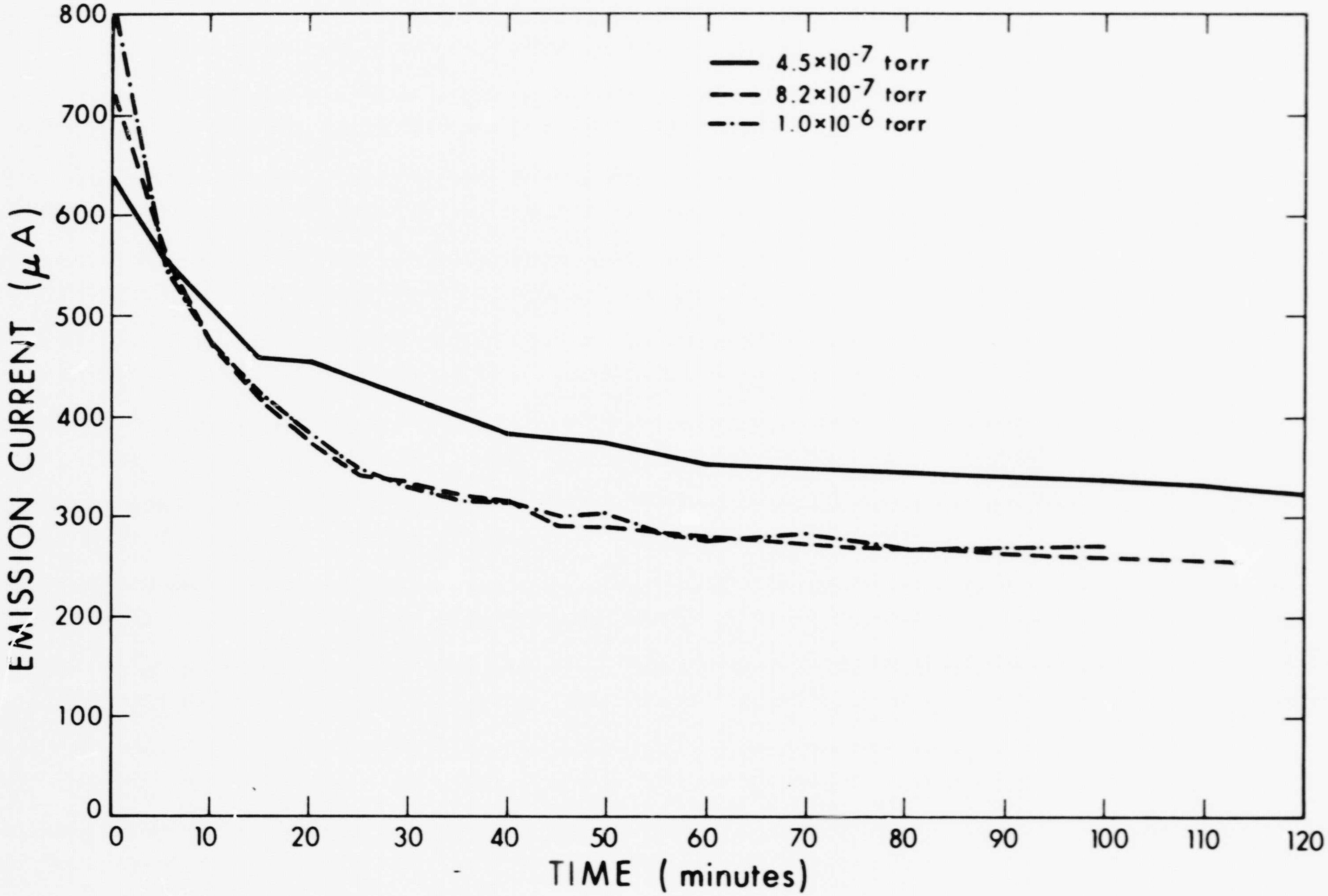

Figure 3. Filament No. 1 Emission at Selected O_2 Partial Pressures

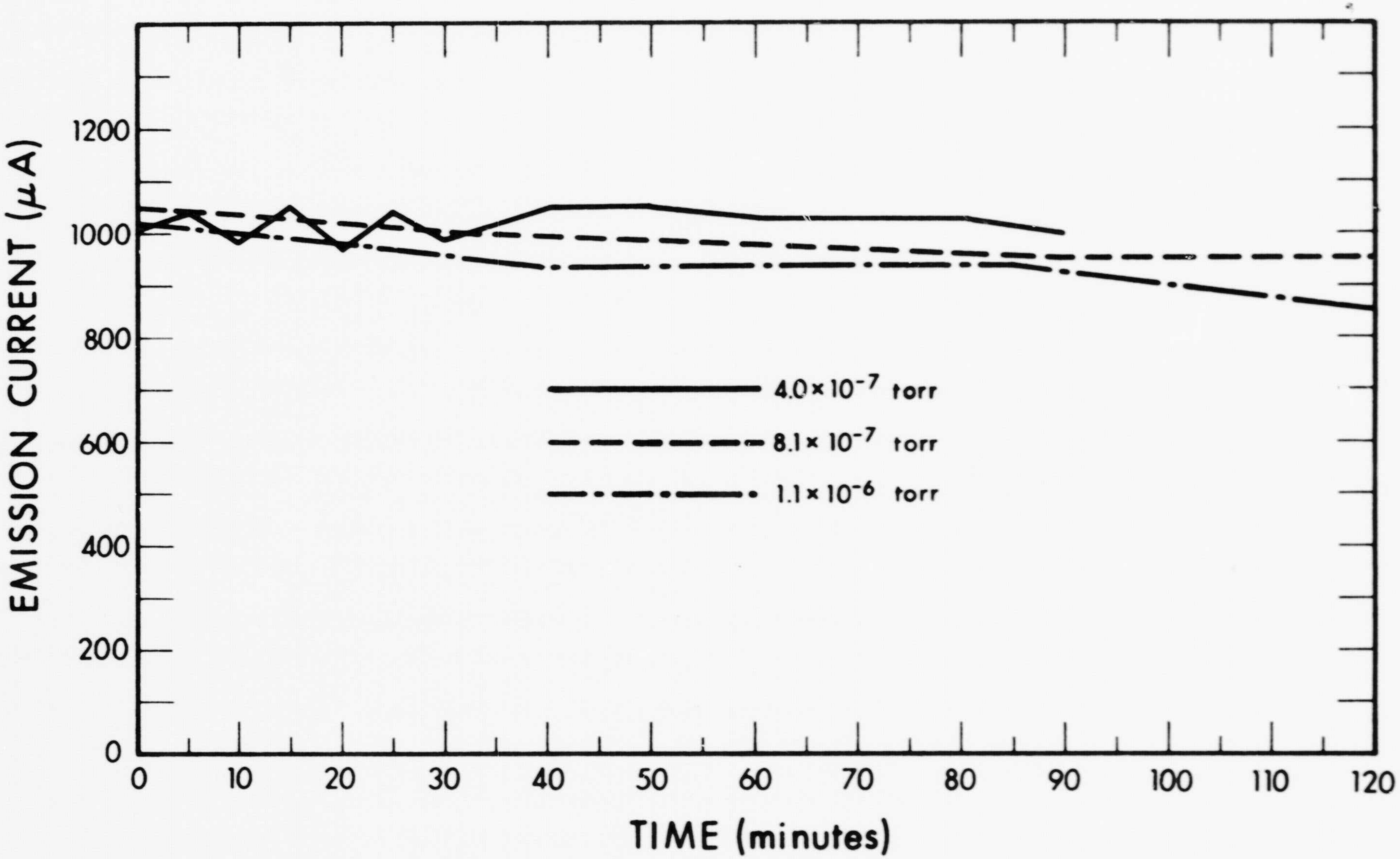

Figure 4. Filament No. 1 Emission at Selected N_2 Partial Pressures

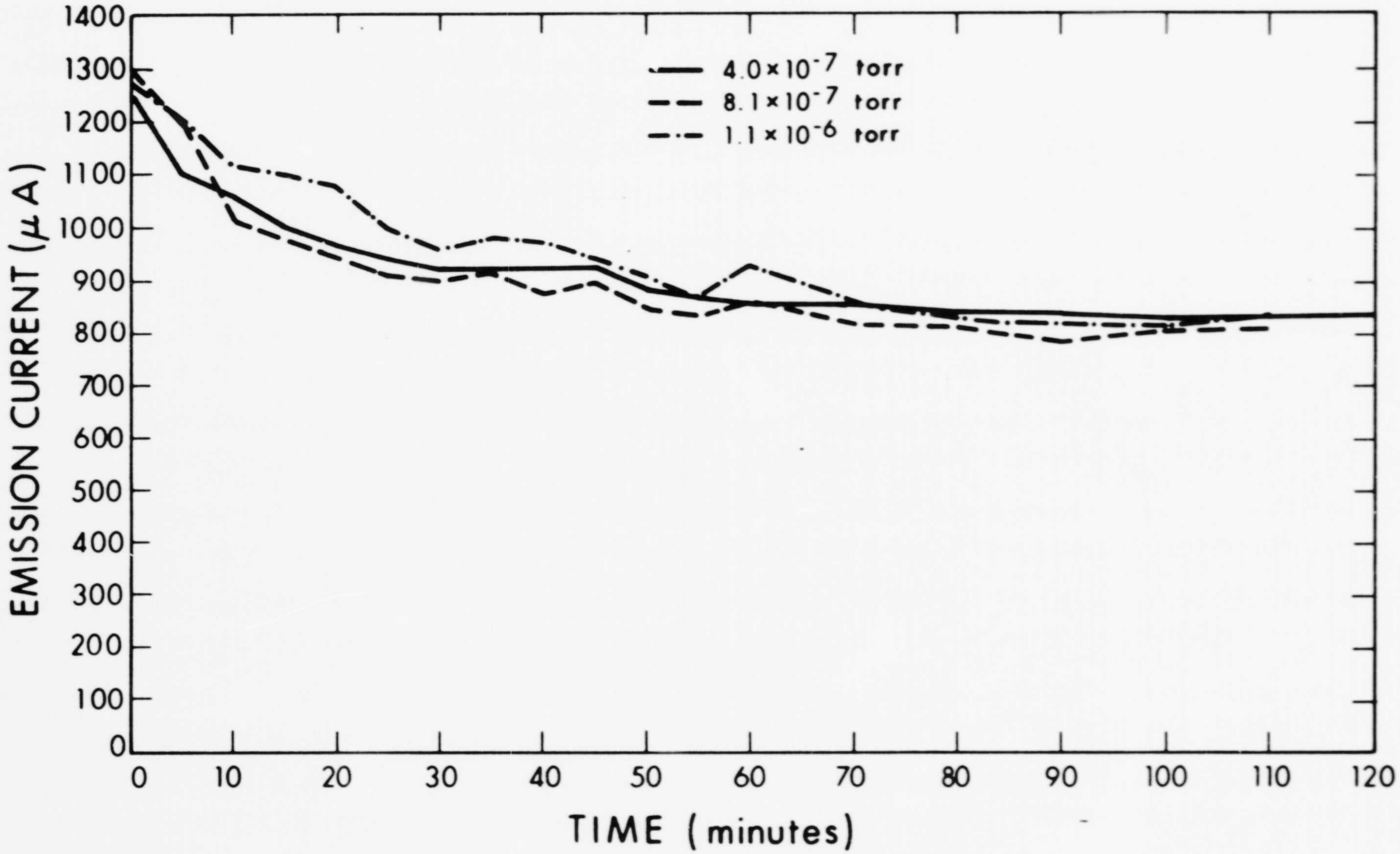

Figure 5. Filament No. 1 Emission at Selected N_2O Partial Pressures

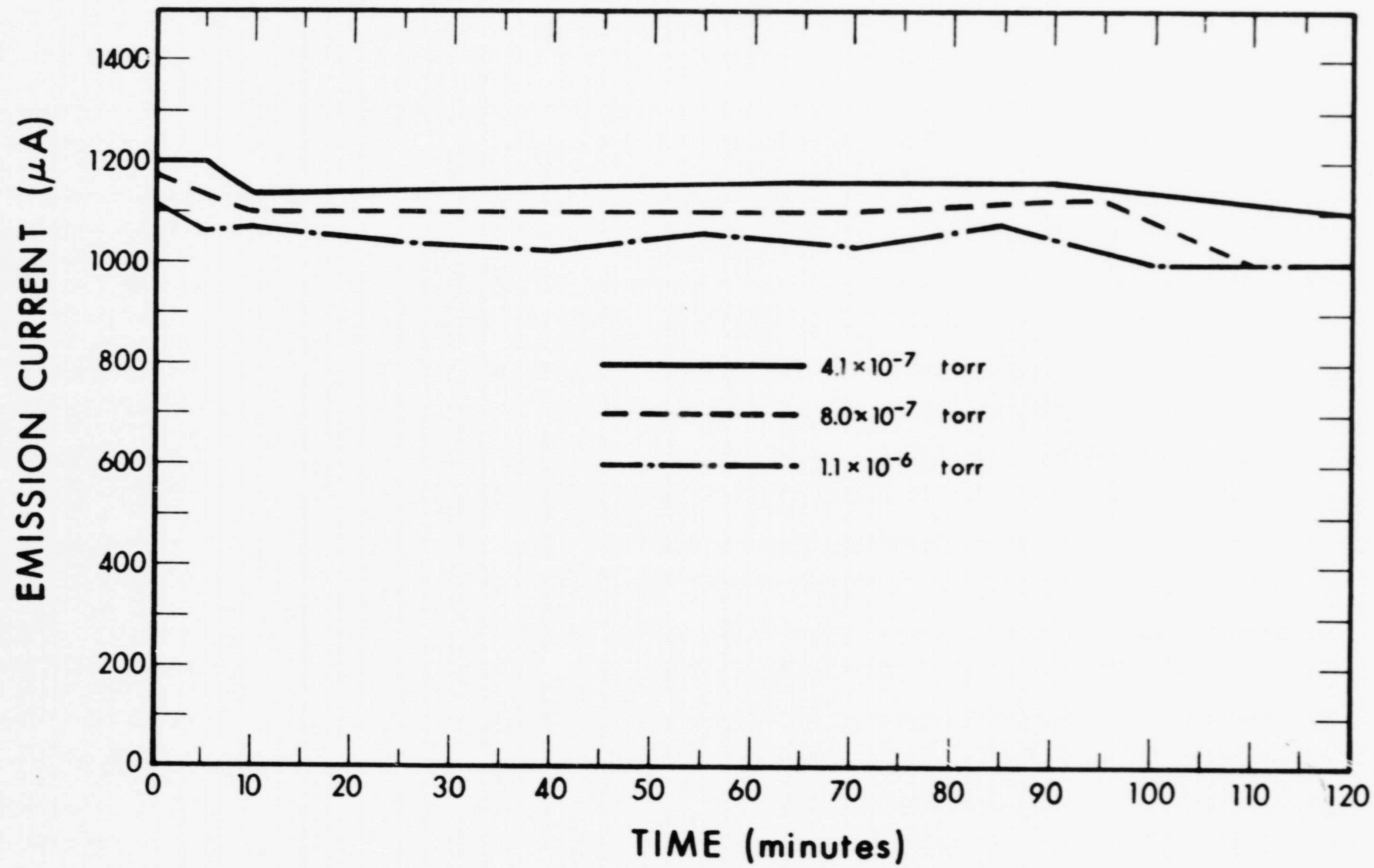

Figure 6. Filament No. 2 Emission at Selected N_2 Partial Pressures

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SECTION 6

PROTOTYPE UNIT

During August and September the prototype unit (which had completed qualification testing earlier in the program) was refurbished by reassembling the thruster subsystem according to established procedures with a new ionizer, new neutralizer filaments, a new valve, and a cleaned and reloaded cesium reservoir. After completion of subsystem preparation, the thruster and CLPC were assembled and the system was operated in vacuum to determine that operation was normal. Following successful completion of this test, the unit was stored pending further testing at Goddard Space Flight Center.

During March the refurbished prototype system was delivered to GSFC. Tests at GSFC revealed an open 1-megohm resistor in one of the CLPC V output lines. The unit was returned to EOS, where the resistor was replaced and the CLPC thoroughly checked out. On March 21 the system was redelivered to GSFC.

SECTION 7

THRUSTER FEED SYSTEM SHELF-LIFE TEST

The thermally actuated valve and evacuated and sealed cesium reservoir combination appears to be an ideal solution to the feed system problem. Before the approach could be fully accepted, however, two questions needed to be answered. First, is the system capable of maintaining internal vacuum over the period (several months to a year) between flight acceptance testing and spacecraft launch? Second, at the end of this period, will the valve operate properly or will operation be compromised by vacuum cold-welding, corrosion, etc.?

On May 13 a test was conducted to evaluate the performance of the cesium feed system after approximately 11 months of storage in air. Thruster subsystem u12-9 had last been operated on June 15, 1967, and since then had been stored in the ambient laboratory environment. Periodic Pirani gauge readings verified maintenance of vacuum in the reservoir. The electrodes were cleaned, thermocouples were attached to valve and reservoir, and the thruster was installed and pumped down in the vacuum chamber normally used for microthruster system tests. Following normal operating procedure, ionizer heater power and high voltage were applied, followed in 2 hours by vaporizer heater power (all supplied in this test by laboratory power supplies). The vaporizer temperature was allowed to reach approximately 320° C, but no beam current was observed. Vaporizer power was removed and the vaporizer and valve assembly allowed to cool. Again the vaporizer was heated to 320° and again no beam current was observed. All power was then removed from the thruster for approximately 20 minutes. The normal startup sequence was repeated, and this time the valve opened, beam current was observed, and the proper relationship between beam current and vaporizer heater power was verified. A leaky insulator made thruster operation somewhat unstable, but the test was highly effective in contributing to confidence in successful space operation of flight models. The fact that some thermal cycling was required to open the valve is not indicative of a problem; this behavior has been observed before but is characteristic only of the initial opening. As long as the unit is maintained in a vacuum environment, subsequent valve openings are uneventful.

SECTION 8

NEW TECHNOLOGY

After a careful review of the activities of the reporting period, it has been concluded that there are no reportable items as defined by the New Technology Clause. Development of the microthruster systems was completed in the first year; the second year, reported in this document, was devoted to completion and testing of duplicate units, correction of malfunctions, and support of spacecraft operations.

SECTION 9

PROGRAM FOR NEXT REPORTING PERIOD

The program for the next reporting period consists of providing support as required for ATS-E spacecraft operations. This will consist of participation in spacecraft tests at Hughes Aircraft and at Cape Kennedy prior to launch and of participation in microthruster operation in synchronous orbit. In addition, tests and experiments at EOS will be conducted as required to support the above operations.

SECTION 10

CONCLUSIONS AND RECOMMENDATIONS

As a result of the testing and support operations described in this report, we conclude that the microthruster systems delivered for ATS-E are flightworthy and have an excellent chance of performing as anticipated aboard the satellite in orbit. Pending completion of the ATS-E flight experiment, no recommendations for further effort are submitted.