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Arcjet System Integration Development

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FOREWORD

Significant contributions to the technical effort for the Arcjet System Integration Development program were made by J. R. Valles and R. C. Evans for electromagnetic compatibility, W. P. Goldstein for the propellant feed system and arcjet interfaces, T. J. Fraker for thermal-vacuum test coordination, F. R. Wohrman for FLTSATCOM qualification model satellite assembly and test, and C. E. Vaughan (Rocket Research Company) for the arcjet system. P. F. Neary was responsible for the related helium cryopanel effort performed under TRW capital funding. Technical direction and support was ably provided by F. M. Curran, L. M. Carney, and C. J. Sarmiento of the NASA-Lewis Research Center.

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1. SUMMARY

Compatibility between an arcjet propulsion system and a communications satellite was verified by testing a Government-furnished, 1.4 kW hydrazine arcjet system with the FLTSATCOM qualification model satellite in a 9.1-meter (30-foot) diameter thermal-vacuum test chamber. Background pressure was maintained at 10^{-5} torr during arcjet operation by cryopumping the thruster exhaust with an array of 5 K liquid helium cooled panels. Power for the arcjet system was obtained from the FLTSATCOM battery simulator. Spacecraft telemetry was monitored during each thruster firing period. No changes in telemetry data attributable to arcjet operation were detected in any of the tests. Electromagnetic compatibility data obtained included radiated emission measurements, conducted emission measurements, and cable coupling measurements. Significant noise was observed at lower frequencies. Above 500 MHz, radiated emissions were generally within limits, indicating that communication links at S-band and higher frequencies will not be affected. Other test data taken with a diagnostic array of calorimeters, radiometers, witness plates, and a residual gas analyzer evidenced compatible operation, and added to the data base for arcjet system integration.

Two test series were conducted. The first series only included the arcjet and diagnostic array operating at approximately 0.1 torr background pressure. The second series added the qualification model spacecraft, a solar panel, and the helium cryopanels. Tests were conducted at 0.1 torr and 10^{-5} torr. The arcjet thruster was canted 20° relative to the solar panel axis, typical of the configuration used for stationkeeping thrusters on geosynchronous communications satellites.

2. INTRODUCTION

Arcjet stationkeeping systems will be used on future communications satellites as an upgrade for catalytic monopropellant and/or electrothermal hydrazine thrusters in performing inclination control maneuvers. Arcjets run on the same hydrazine propellant as existing thrusters and provide higher performance. Since they use the same propellant, they can be operated from existing propellant feed systems and are compatible with dual mode propulsion systems. Before spacecraft manufacturers were willing to risk arcjet operations, however, there had to be a clear demonstration that arcjets are compatible with communications satellites.

The objective of the Arcjet System Integration Development (ASID) program was to verify compatibility between an arcjet system and next generation communications satellites by testing an arcjet system with a high fidelity spacecraft simulator in a vacuum chamber. The thruster was to be fired with hydrazine propellant at a power level of 1.4 kW. The power conditioning unit (PCU) was to be run from a realistic spacecraft bus.

The Government-furnished arcjet system was developed by Rocket Research Company under NASA-Lewis Research Center (NASA-LeRC) sponsorship (see Reference 1 for a description of the arcjet system). The high fidelity spacecraft simulator employed was the FLTSATCOM qualification model communications satellite (see Appendix A for a description of the spacecraft). The FLTSATCOM battery simulator was employed as the spacecraft bus for powering the arcjet system.

North-south stationkeeping for current communication satellites is provided by either low-thrust monopropellant hydrazine thrusters, hydrazine resistojets, or bipropellant engines. The spacecraft integration issues of previous concern have been contamination from the thruster plume, radiated and conducted thermal fluxes, and momentum impacts. These issues have been assessed by analytical predictions of plume characteristics and calculation of the effects, and resolved by proper placement of thrusters on the spacecraft and incorporation of protective shielding. Flight history of many satellites has proven these techniques to be successful.

The integration issues for hydrazine arcjets are in many aspects similar to those addressed previously. The propellant decomposition basic species are similar to those of hydrazine thrusters. While the thrust levels are significantly below those of bipropellant engines (~22 N, 5 lbf) and monopropellant hydrazine thrusters (~5 N, 1 lbf), they are equivalent to those of hydrazine resistojets (~0.18 N, 0.040 lbf). A major issue not associated with standard chemical propulsion thrusters is the arcjet's radiated and conducted electromagnetic compatibility (EMC).

An arcjet propulsion system presents the unique challenge of controlling radiated emissions from the arc and the plume, where shielding cannot be applied effectively. The dominant concern is radiated emissions in the satellite receiver bands. No EMC measurements of the arcjet plume were reported in the Reference 2 survey. Also, the fact that an arcjet generates a broadband noise spectrum warranted a thorough characterization of arcjet radiated emissions, particularly in satellite receiver frequency ranges.

There is a possibility that an arcjet plume could intercept the transmitted communications signal. The potential disruption or distortion of communication signals by the operation of the 1.5-kW class arcjet has been studied, in detail, at the NASA-LeRC (Reference 3). Based on an analytical plasma slab plume model interacting with a 4-GHz signal, the study concluded that the dominant transmission loss mechanism is refraction of the signal rather than absorption or reflection and that, unless the propagation path passes very close to the arcjet, there is negligible beam attenuation due to reflection. Even though signal refraction occurred, it was not significant in the antenna far field. As communication satellite frequencies increase, the impact of this interaction will decrease. At this time, this interaction is not considered a problem.

In order to accomplish program objectives, the activity flow illustrated in Figure 2-1 was implemented. In Task 1, test program definition, work was performed to identify spacecraft interactions and interfaces with the arcjet system, isolate critical issues, and develop a test plan to address these issues during subsequent tasks. Arcjet system

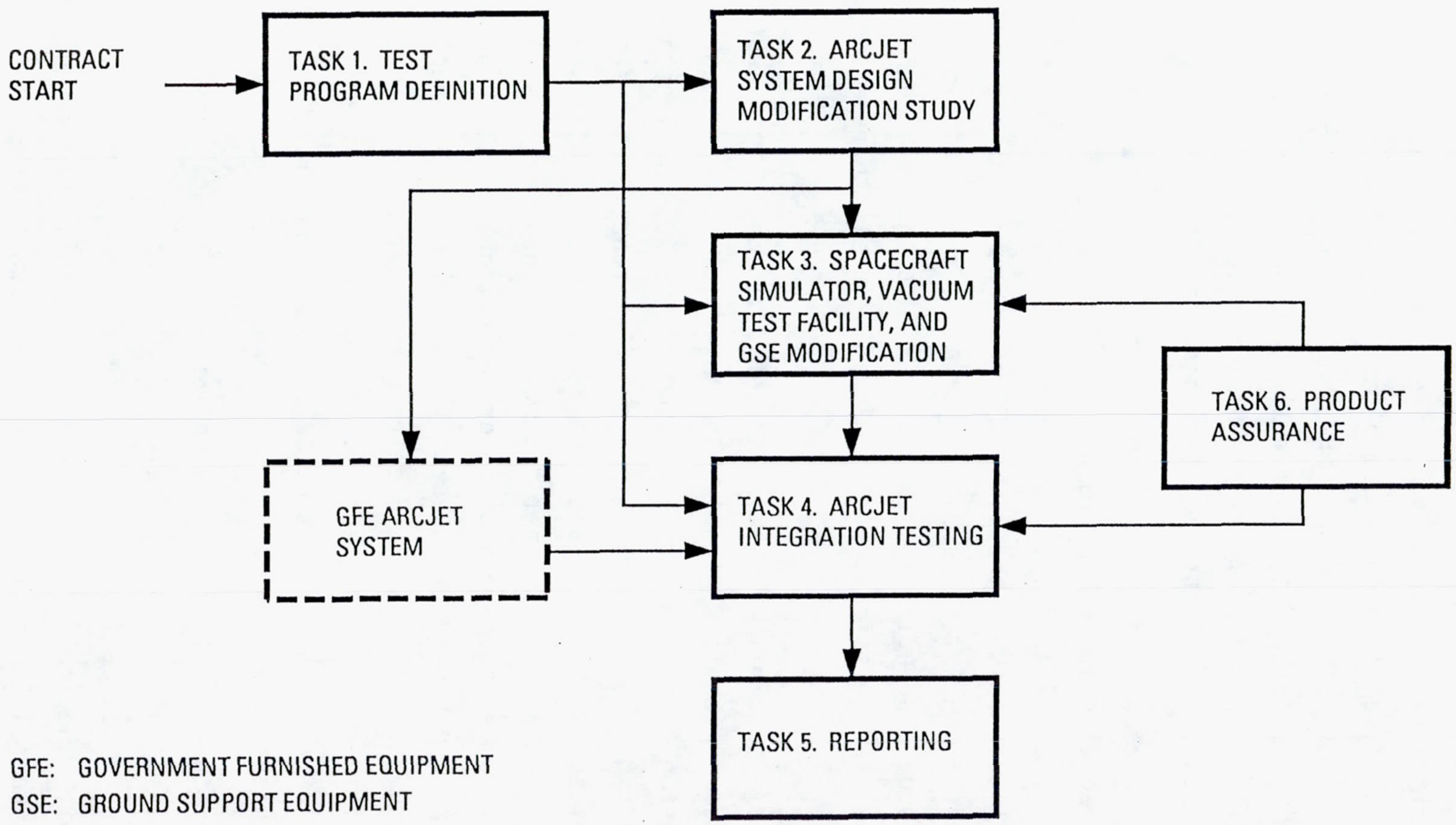


Figure 2-1. ASID Activity Flow Diagram

design modifications, necessary for the conduct of the test program, were identified in Task 2. They were implemented before the GFE arcjet system was delivered for integration testing. Any modifications necessary to the spacecraft simulator, vacuum test facility, or ground support equipment were identified and implemented in Task 3. An existing FLTSATCOM qualification model communications spacecraft was used for the high fidelity simulator. The arcjet system was mounted in a stationkeeping location adjacent to the qualification model spacecraft in a 9.1-meter (30-foot) diameter vacuum test facility, which permitted arcjet operation at less than 10^{-5} torr with hydrazine propellant at full thrust during Task 4 testing.

Task 5 provided for program reporting. Task 6, product assurance, was primarily concerned with measuring instrument calibrations.

Significantly, the ASID program (1) verified compatibility of the 1.4 kW hydrazine arcjet system with the FLTSATCOM communications satellite, and (2) measured the radiated electromagnetic emissions from the arcjet system at a sufficiently low background pressure such that its exhaust plume was free to expand without collisions with background gases. Also, tests were conducted in a sufficiently large thermal-vacuum test chamber to mitigate chamber wall effects.

3. TEST PROGRAM DEFINITION

Preparatory to defining the ASID test program, a list of arcjet interfaces, their associated specifications, and issues generic to next generation communications satellites was initiated. The resulting list is shown in Table 3-1. Critical interfaces were identified as electromagnetic interference and plume impingement. Accordingly, a test plan was developed to concentrate an obtaining data which addresses these critical issues.

Table 3-1. Arcjet Interfaces

Interface	Specification	Issues Generic to Next Generation Communications Satellites
Electromagnetic interference (EMI)*	MIL-STD-461 MIL-STD-462	Conducted EMI introduced into the spacecraft power bus by the PCU
Conducted		Radiated EMI emitted from the PCU, high-voltage cable, the engine, and the plume
Radiated		
Plume impingement*	MIL-P-26536	Thermal impact on solar arrays and other spacecraft surfaces
		Momentum exchange with solar arrays and other spacecraft surfaces
		Mass deposition on sensitive spacecraft surfaces
Thermal	MIL-STD-1540	Conducted heat flux from the engine and plume impinging on the solar arrays and thermal control surfaces
		Heat dissipation from PCU baseplate
		Radiated heat flux from the engine
Electrical		Spacecraft/arcjet grounding
		Unregulated input voltage
		Power/performance profile
		Energy management
Mechanical		Launch environments
Radio frequency (RF)		Transmission through the arcjet plume
		• To ground stations • To TDRS • Crosslink to other spacecraft
Other subsystems		Optical interference (glow)

*Critical
TDRS: Tracking and Data Relay Satellite

4. EQUIPMENT TESTED

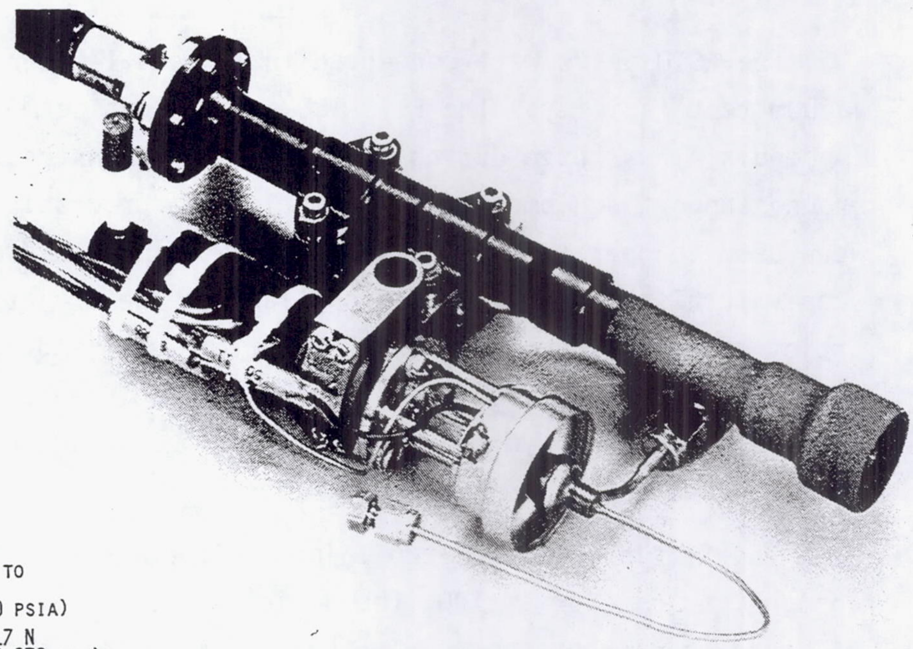
The principal test article for the ASID program was a Government-furnished 1.4 kW hydrazine-fueled arcjet thruster system. The arcjet uses the energy input from an electrical arc for enthalpy augmentation of hydrazine propellant, in the process boosting the specific impulse performance to about 450 seconds. The arcjet system consists of three major components: (1) the arcjet thruster, (2) the power conditioning unit (PCU), and (3) the interconnecting power cable that runs between the thruster and the PCU. The thruster and PCU are shown in Figures 4-1 and 4-2, respectively.

The arcjet thruster consists of the thruster body (or arcjet), the gas generator that decomposes the hydrazine propellant, and the thruster control valve and fluid resistor that control propellant flow and pressure. Energy is added to the decomposition gases primarily through heating in the arc column. The arc originates at the cathode tip, passes through a constrictor, and attaches to the diverging part of the nozzle (anode).

Power to the arcjet is provided and controlled by the PCU, a dc-dc isolated power converter that steps up the spacecraft power bus voltage to the thruster arc voltage (approximately 100 Vdc), and regulates the arc current during thruster firing. The PCU also provides a brief high-voltage pulse (approximately 4000 Vdc for a few microseconds) to initiate the arc after the gas flow has been established.

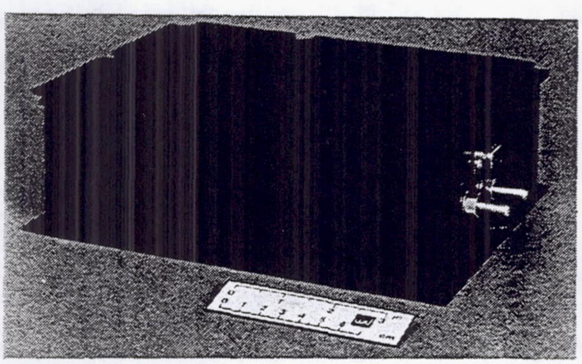
Power from the PCU to the thruster is delivered via the power cable. The cable is triaxial with the center conductor connected to the thruster's cathode. The inner shield that is also a power path, is attached to the thruster's anode; the outer shield that carries no power is connected to chassis ground.

The arcjet system had four principal interfaces with the supporting test equipment. These are: (1) a structural mount and heat-sink for arcjet cooling; (2) a hydrazine propellant feed fitting that provides the arcjet with a propellant flow; (3) a primary power connector that supplies 28 Vdc current to the PCU; and (4) a command/telemetry interface for monitoring and controlling the operation of the thruster.



PROPELLANT: HYDRAZINE (N_2H_4)
INLET PRESSURE = 20.3 x 10^6 TO 11.5 x 10^6 (300 TO 170 PSIA)
THRUST = 0.20 TO 0.17 N (0.045 TO 0.038 LBF)
SPECIFIC IMPULSE = 450 SEC (AVERAGE)
ELECTRICAL POWER = 1260 W
WEIGHT = 1.4 KG (3.0 LB)

Figure 4-1. Arcjet Thruster



INPUT VOLTAGE = 25 TO 32 VDC
OUTPUT VOLTAGE = 95 TO 125 VDC
START-UP VOLTAGE = 4000 VDC
INPUT CURRENT = 35 TO 70 ADC
OUTPUT CURRENT = 12 TO 16 ADC
WEIGHT = 4.0 KG (8.9 LB)
BASEPLATE TEMP. = - 10 TO 55°C
POWER DISSIPATION = 140 W MAX
POWER EFFICIENCY = 90%

Figure 4-2. Power Conditioning Unit

5. TEST FACILITIES AND EQUIPMENT

The ASID tests were conducted in TRW's 9.1-meter (30-foot) diameter vacuum test facility. The FLTSATCOM qualification model spacecraft (Appendix A) was used during compatibility demonstration tests. FLTSATCOM ground support equipment and automatic data processing equipment (ADPE) were used to operate the qualification model. A hydrazine propellant supply furnished pressurized propellant to the arcjet under test. The arcjet operated from the FLTSATCOM battery simulator and had its own independent command and telemetry readout equipment. Consumable test materials included hydrazine, liquid nitrogen, liquid helium, witness plates, data tapes, and printout paper.

The test program had two major test series. In the first series, designated Test Series 100, the arcjet was operated alone at approximately 0.1 torr chamber pressure. In the second series, designated Test Series 200, the FLTSATCOM qualification model spacecraft was also operated with the arcjet at a chamber pressure below 10^{-5} torr.

The test configuration layouts for Test Series 100 and 200 are shown in Figures 5-1 through 5-3. The basic differences between the test series are the addition of the FLTSATCOM qualification model spacecraft, solar array panel, and liquid helium panels to the test configuration for Test Series 200. The FLTSATCOM qualification model spacecraft was mounted on its test fixture inside the vacuum test facility. Support fixtures and a support platform were provided for the arcjet, PCU, antennas, and solar array panel. A work platform provided for access to the spacecraft, test articles, antennas, and instrumentation during installation and removal from the test facility. The power cable connecting the arcjet and PCU was routed along the top of the support platform for viewing by the antennas, and beneath the support platform to bring it inside the spacecraft cavity. Diagnostic instrumentation (calorimeters, radiometers, witness plates) were mounted on the solar panel and at various stations in the arcjet exhaust ranging from -90 to +120 degrees from the thruster centerline. Four liquid helium panels and associated Dewar maintained low background pressure (for free plume expansion) during arcjet thrusting periods. A port-mounted

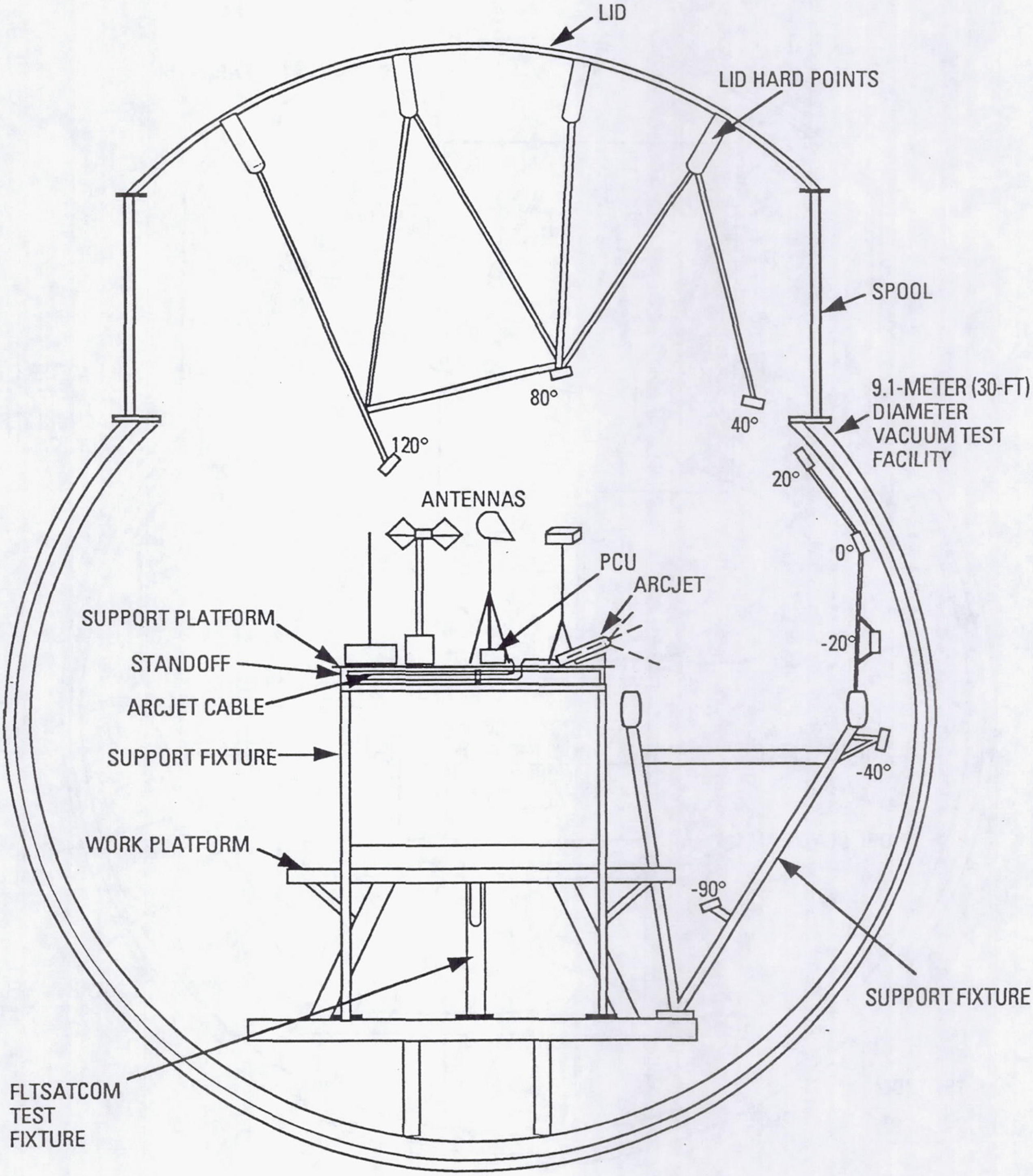


Figure 5-1. Test Series 100 Configuration

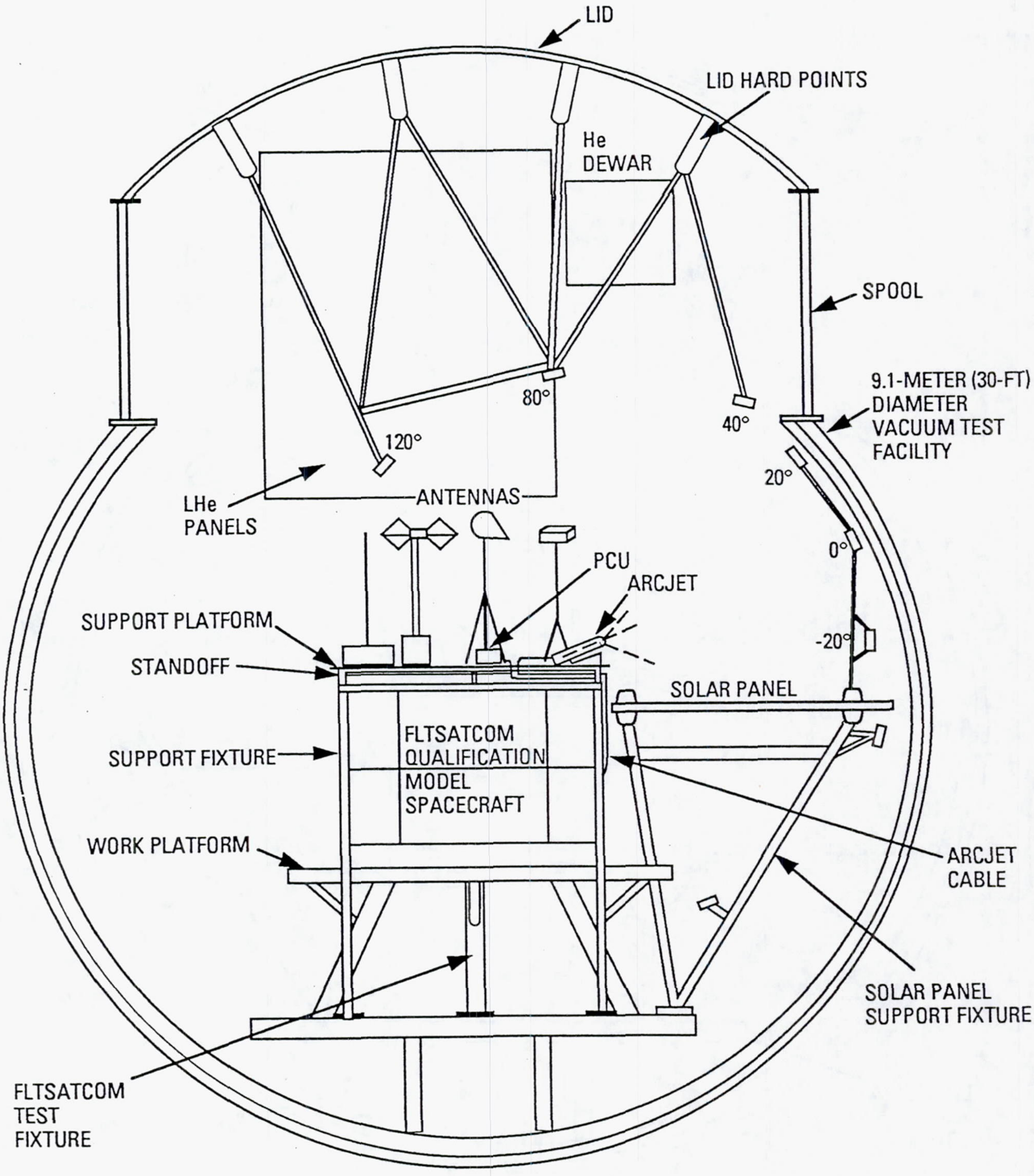


Figure 5-2. Test Series 200 Configuration

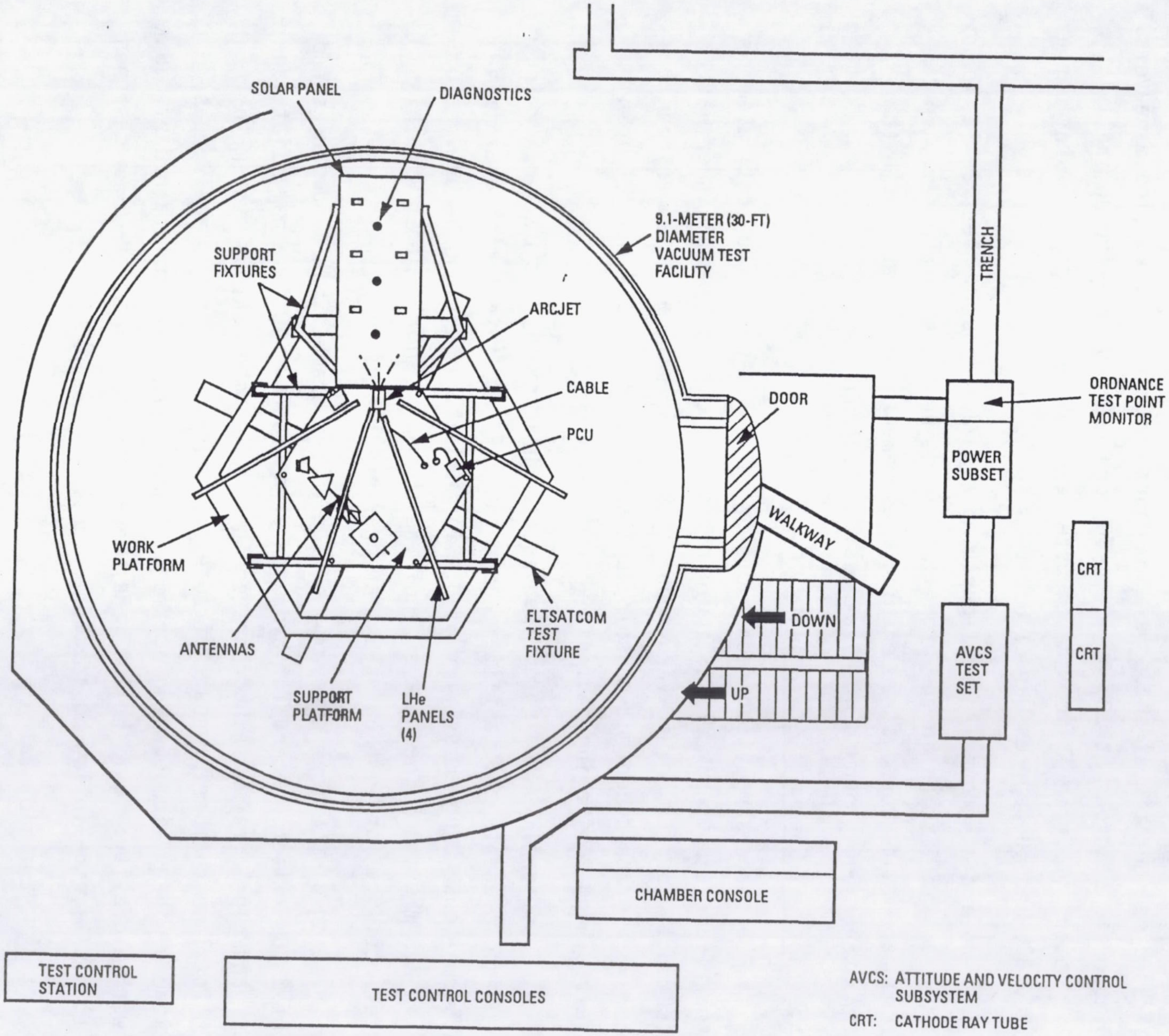


Figure 5-3. Test Series 200 Configuration, Top View

residual gas analyzer observed exhaust species. Chamber pressure was measured by an ion gauge. The thruster was canted 20 degrees from the spacecraft solar array axis, thereby simulating the orientation likely to be used on operational spacecraft for north-south stationkeeping maneuvers. Diagnostic stations at 20, 0, -20, -40, and -90 degrees were nominally 2.3 meters (7.5 feet) from the thruster exit plane. Diagnostic stations at 120, 80, and 40 degrees were 1.8 meters (6 feet) away.

The arcjet grounding configuration was varied during Test Series 200. A dielectric fitting in the propellant feedline and a vacuum relay in the thruster mount ground strap enabled measurements to be taken with the thruster anode grounded or electrically floating.

5.1 Thermal-Vacuum Test Facility

The space simulation test facility has a 9.1-meter (30-foot) diameter spherical vacuum chamber, a liquid nitrogen cooled spherical inner wall (shroud), four cryogenic vacuum pumps, a liquid helium cooled cryopanel array, a graphic control console, and associated storage tanks, piping, valves, and monitoring devices.

Functionally, the shroud serves as a heat sink. Its dull black inner surface presents the test item and spacecraft under test with a minimum thermal absorbing emissivity of 0.9 for radiation wavelengths between 0.38 and 2.6 microns. The back side of the shroud is bright metal with high reflectivity for low heat transfer characteristics.

Each of the four cryopumps on the vacuum chamber has a pumping speed of 25,000 liters/second for hydrogen or nitrogen. An internal, flat panel cryopumping array was incorporated into the chamber shroud system to maintain a chamber pressure of 10^{-5} torr during periods of active gas loads. The helium pumping portions of this array were maintained at 4.5 K with a gravity liquid helium (LHe) dewar system. The system was designed to satisfy the following specifications:

LHe flow rate	330 liters/sec
H_2 pumping speed	7.5×10^6 liters/sec
N_2 pumping speed	3.8×10^6 liters/sec
Heat load	250 watts

The LHe system consists of four internal panels, positioned in the vertical direction. Two panels are 2.7 by 3.2 meters (8'9" by 10'6"); two panels are 2.7 by 2.4 meters (8'9" x 8').

5.2 Spacecraft Simulator

The FLTSATCOM qualification model was used as a high fidelity communications spacecraft simulator for test purposes. The qualification model and its ground support equipment are described in Appendix A.

5.3 Propellant Storage and Feed System

The hydrazine feed system was a closed pressurized system. The hydrazine tank with its associated pressurization and flow controls were located outside the environmental chamber, except for the propellant line connecting to the thruster itself. The feedline inside the vacuum chamber was thermally controlled to prevent freezing of the hydrazine due to radiation cooling. All venting from the feed system was routed outside the building. An aspirator was provided for purging the lines of hydrazine prior to and during disassembly.

A schematic diagram of the propellant storage and feed system is shown in Figure 5-4. The propellant cart is shown in Figure 5-5.

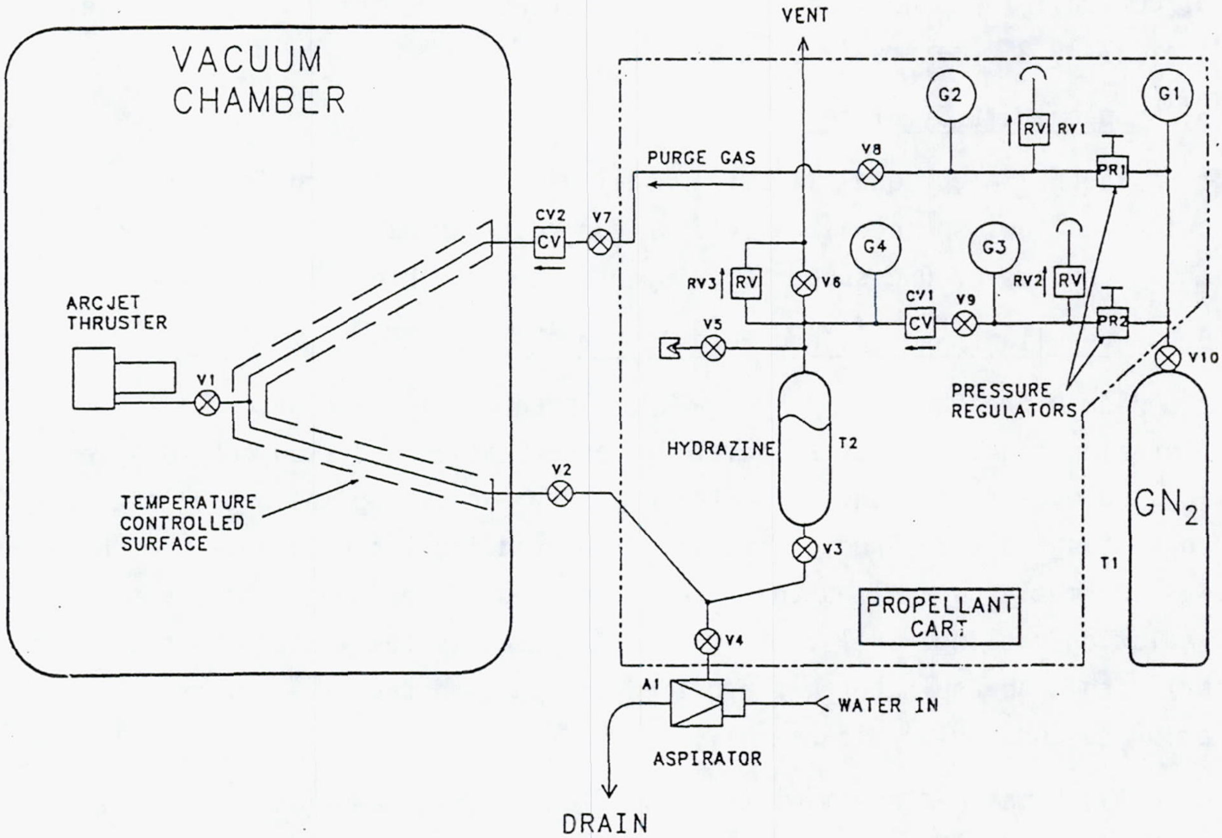
5.4 Test Support Equipment

The arcjet system was powered from the FLTSATCOM battery simulator. It also had a command interface unit for energizing its propellant valve, and for turning its PCU on and off. Telemetry signals from the arcjet system were routed directly to data recording equipment outside the environmental test chamber.

The instrumentation and control interface for the arcjet system is shown schematically in Figure 5-6.

5.5 Electromagnetic Compatibility Test Instrumentation

EMC measurements included conducted and radiated emissions from the arcjet system, cable coupling measurements, and ground current measurements. Table 5-1 lists the instruments, probes, and antennas used for various frequency ranges. Supporting test equipment was located outside the vacuum test chamber and was connected to the antennas, probes,



Symbol	Item
V1	Arcjet Disconnect Valve
V2	Propellant Valve
V3	Propellant Valve
V4	Aspirator Valve
V5	Fill Valve
V6	Vent Valve
V7	Purge Disconnect Valve
V8	Purge Valve
V9	Pressurization Valve
V10	Shutoff Valve
CV1	Regulation Isolation Check Valve
CV2	Purge Isolation Check Valve

Symbol	Item
RV1	G2 Protection Valve
RV2	G3 and G4 Protection Valve
RV3	Propellant Tank Relief Valve
G1	Supply Pressure Gauge
G2	Purge Pressure Gauge
G3	Pressurant Pressure Gauge
G4	Pressurant Pressure Gauge
T1	Nitrogen Gas Supply
T2	Propellant Tank
PR1	Purge Regulator
PR2	Pressurant Regulator
A1	Water Aspirator

Figure 5-4. Propellant Storage and Feed System Schematic

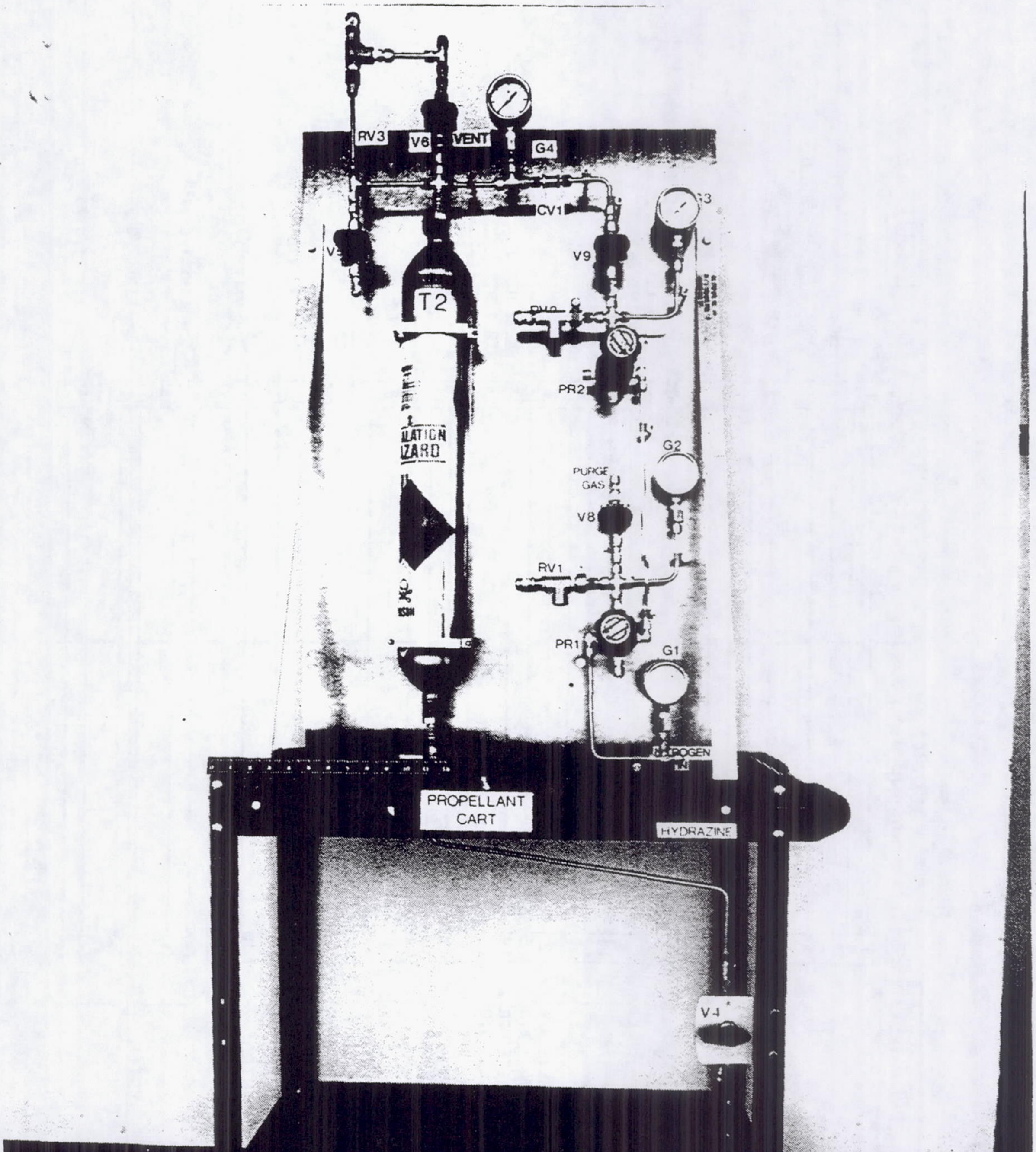


Figure 5-5. Propellant Cart

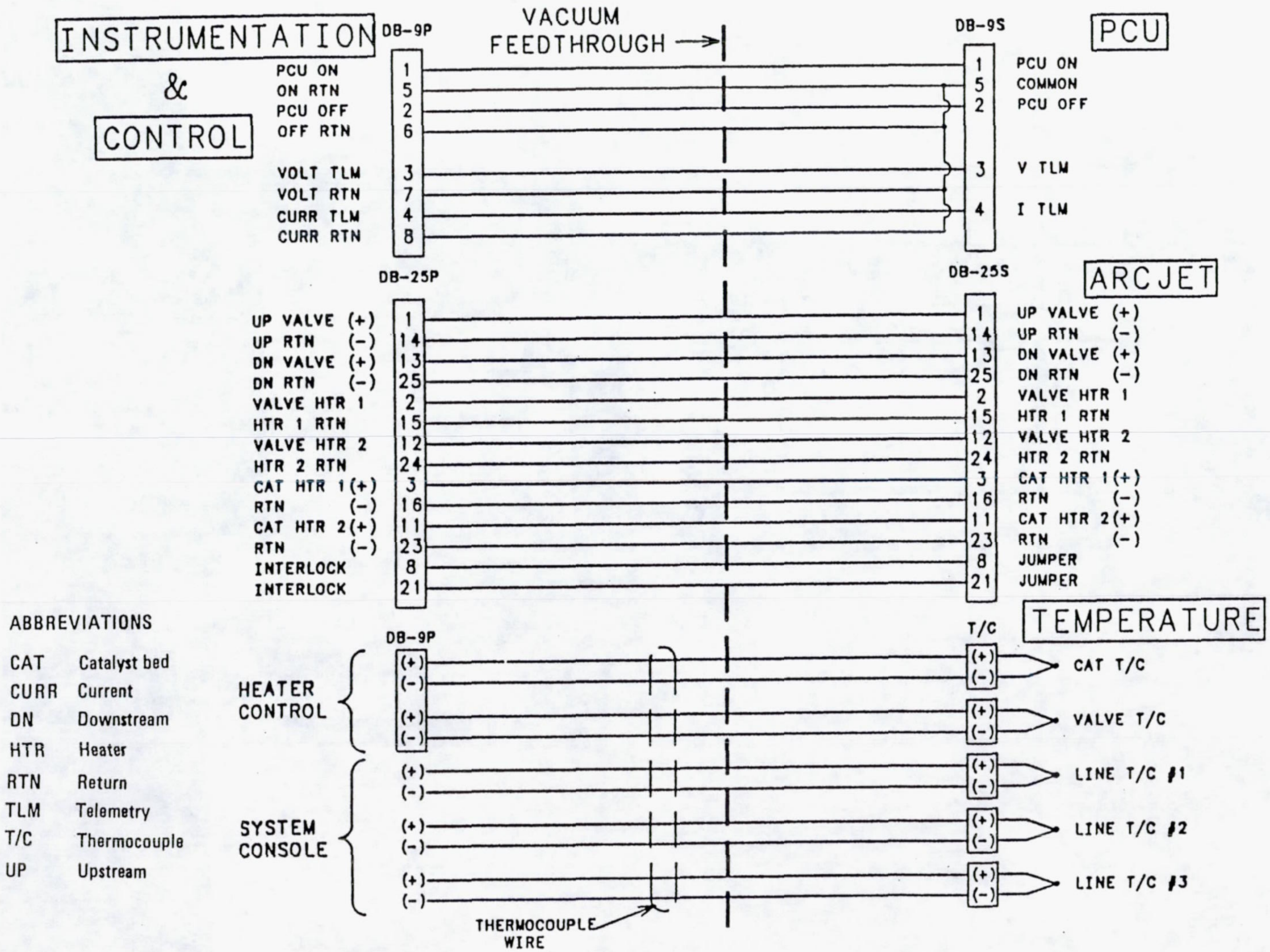


Figure 5-6. Arcjet Instrumentation and Control Interface

Table 5-1. Electromagnetic Compatibility Test Instrumentation

Measurement	Frequency Range	Probe/Antenna	Measuring Instrument
1) Primary power line conducted emissions current	1)	1)	1)
a) Steady-state	a) 100 Hz - 100 MHz	a) Current probe	a) Spectrum analyzer
b) Transient	b) DC-50 MHz	b) Current probe	b) Oscilloscope
2) Primary power line and command/telemetry line conducted emissions voltage	2)	2)	2)
a) Steady-state	a) 100 Hz - 100 MHz	a) FET voltage probe	a) Spectrum analyzer
b) Transient	b) DC-50 MHz	b) Voltage probe	b) Oscilloscope
3) Cable-to-cable coupling	3)	3)	3)
a) Steady-state	a) 100 Hz - 100 MHz	a) Special test probes	a) Spectrum analyzer
b) Transient	b) DC-50 MHz	b) Special test probes	b) Oscilloscope
4) Structure ground current	4)	4)	4)
a) Steady-state	a) 30 Hz - 100 MHz	a) Current probe	a) Spectrum analyzer
b) Transient	b) DC-50 MHz	b) Current probe	b) Oscilloscope
5) Radiated fields	5)	5)	5)
a) H-field	a) 30 Hz - 50 kHz	a) Loop antenna	a) Spectrum analyzer
b) E-fields	b) • 14 kHz - 30 MHz • 30 MHz - 200 MHz • 200 MHz - 10 GHz • 1 GHz - 10 GHz	b) • Rod antenna • Biconical antenna • Log periodic antenna • Horn antenna	b) Spectrum analyzer

test aids, and vacuum relay inside the chamber via electrical feedthroughs on test chamber ports. The vacuum relay was located at the thruster mount ground strap either to connect the thruster anode to ground or to isolate it from ground (permit it to float). Passive rod, loop, biconical, log-periodic, and horn antennas were mounted on top of the support platform inside the chamber (see Figures 5-1 and 5-2). Cable coupling test aids, radio frequency (RF) current probes, and DC current probes were mounted on the underside of the platform.

6. TEST PROCEDURES

Written test procedures were used during the ASID program for operating the thermal-vacuum test facility, operating the thruster, operating the propellant feed system, operating the FLTSATCOM qualification model spacecraft, and taking EMC measurements. The general sequence of events consisted of:

1) Pumping down the test chamber from atmospheric to vacuum conditions
2) Powering the FLTSATCOM qualification model spacecraft
3) Chilling the liquid nitrogen (LN_2) chamber shroud
4) Chilling the liquid helium (LHe) panels
5) Loading propellant into the feedlines and pressurizing the propellant
6) Turning on the battery simulator
7) Turning on the thruster
8) Taking test data during thruster operation
9) Turning off the thruster while recharging the batteries in the battery simulator
10) Repeating steps 6 - 8 as required
11) Turning off the thruster, depressurizing the propellant feed system, purging the propellant feedlines, and purging the thruster
12) Turning off and securing the test item, test equipment, and instrumentation
13) Returning the test facility to atmospheric conditions.

Test Series 100 was conducted at a nominal chamber pressure of 0.1 torr while the thruster was operating. Neither the LN_2 shroud nor the LHe panels were used in this test series. As mentioned earlier, Test Series 100 was conducted before installing the FLTSATCOM qualification model spacecraft.

Three periods of active arcjet firing took place during Test Series 100, including a number of turn-on and turn-off cycles (primarily during the last firing period). The arcjet operated as anticipated. The first firing period lasted 95 minutes. The second firing period lasted 120 minutes. The third firing period lasted 185 minutes.

During Test Series 100, a nitrogen bleed was briefly introduced into the test chamber to raise the background pressure to 3 torr with the thruster operating. This was done to look at the influence of chamber pressure on electromagnetic emissions from the test item. All EMC measurements during Test Series 100 were taken with the arcjet anode grounded.

During Test Series 200, the thruster was operated from the FLTSATCOM battery simulator for 2 hours at a test chamber pressure of 115 microns, and for 2 hours at 9×10^{-6} torr during the test series. The FLTSATCOM satellite was powered during this time period. Additional testing, with the satellite dormant, was performed for 1-3/4 hours with the thruster operated from a power supply at a chamber pressure 9×10^{-6} torr. An additional 1/2-hour operation from the battery simulator was conducted with the satellite dormant. The chamber pressure was increased, via a nitrogen bleed, up to 5×10^{-4} torr for most of this 1/2-hour period.

Electromagnetic compatibility data obtained during this test series include radiated emission measurements, conducted emission measurements, and cable coupling measurements. These measurements were taken both with the anode grounded and the anode floating. Measurements were taken with the arcjet powered from the battery simulator and with it powered from a separate power supply. During the 1/2-hour nitrogen bleed, at a chamber pressure of 5×10^{-4} torr, the anode was grounded. The dielectric fitting in the propellant feed line measured 21 ohms to ground prior to testing at 9×10^{-6} torr.

EMC power line conducted emissions and radiated emissions limits were derived by examining corresponding limits applied to the FLTSATCOM and TDRS communication satellites. The limits (see Figures 6-1 through 6-4) are considered reasonable for a unit integrated into a communications satellite. The radiated emissions limits are for units contained entirely

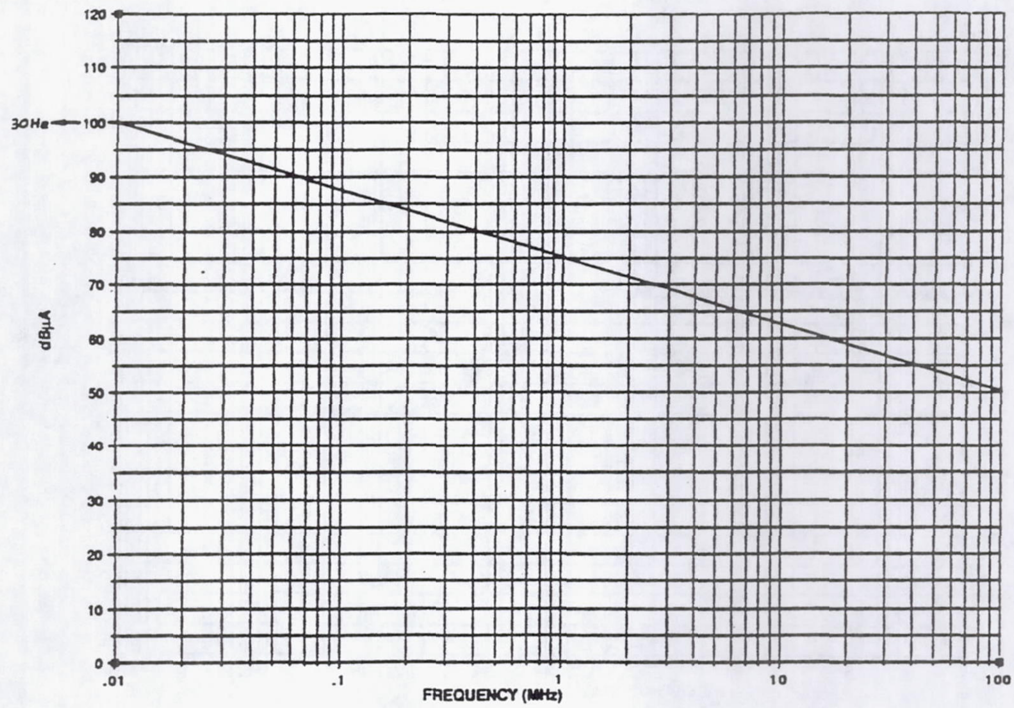


Figure 6-1. Limit for CE03 Narrowband Emissions

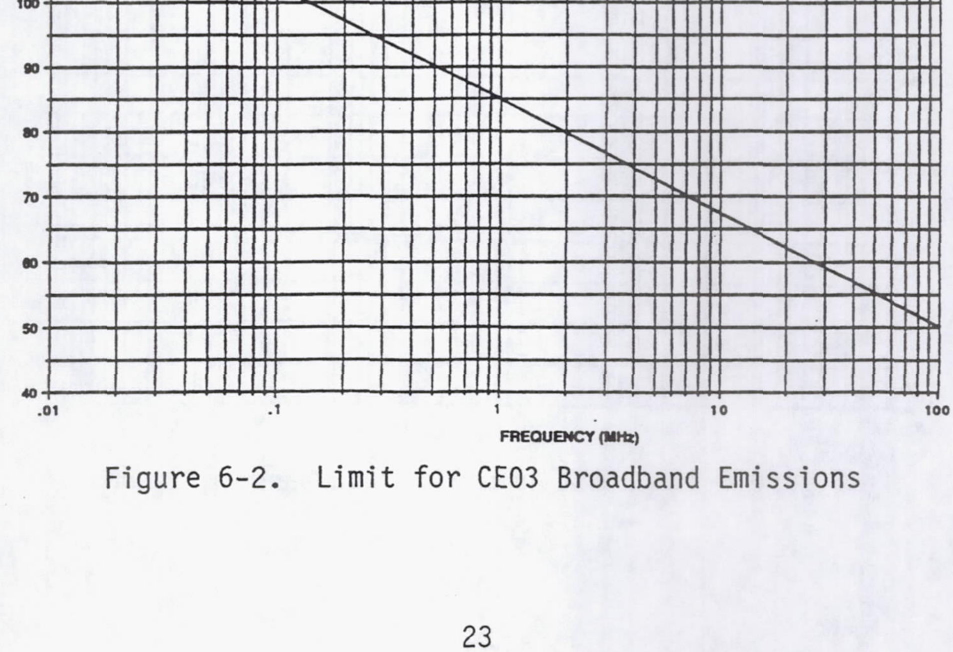


Figure 6-2. Limit for CE03 Broadband Emissions

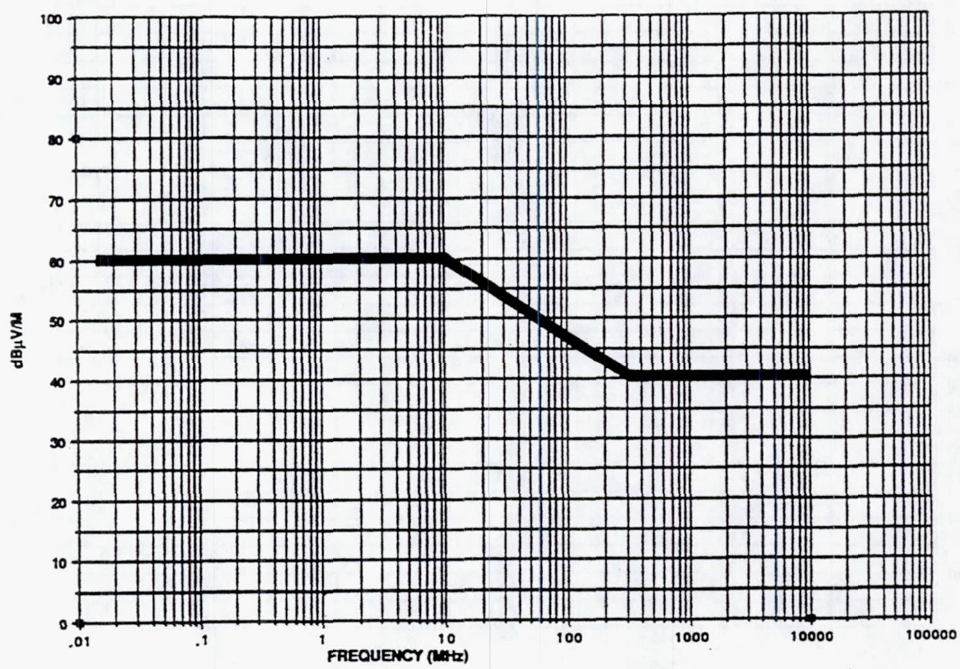


Figure 6-3. Limit for RE02 Narrowband Emissions

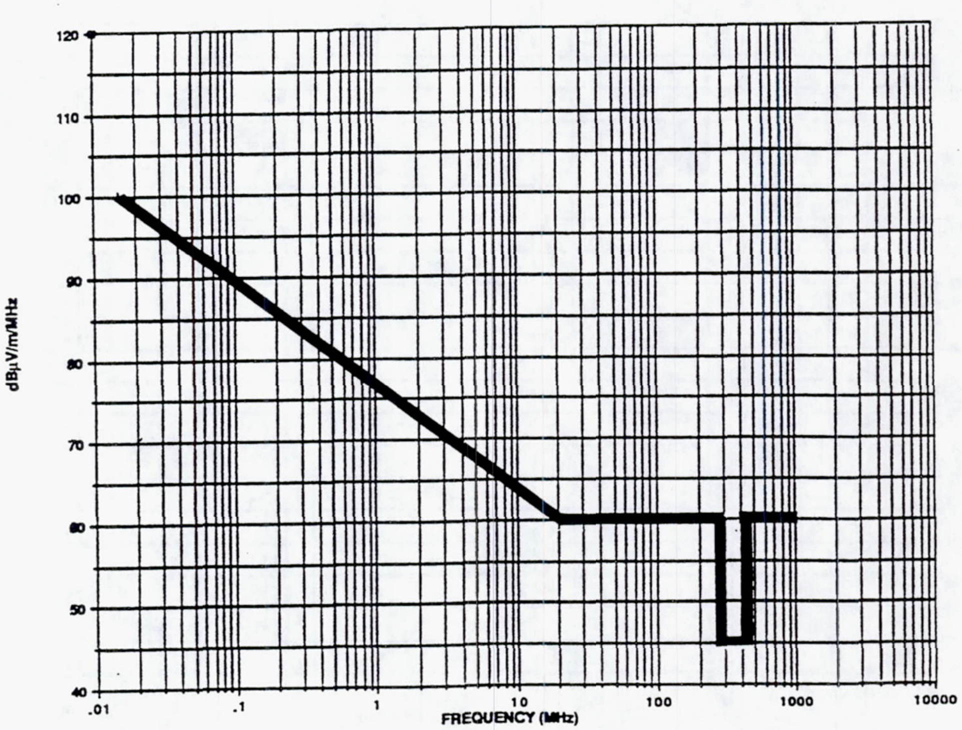


Figure 6-4. Limit for RE02 Broadband Emissions

within the satellite equipment compartment. For units or portions of units located outside the equipment compartment, the broadband radiated emissions limit must be decreased from 45 dBμV/m/MHz to 20 dBμV/m/MHz over the 300 MHz to 400 MHz frequency range, and the narrowband radiated emissions limit must be decreased from 40 dBμV/m to 10 dBμV/m over the 300 MHz to 10 GHz frequency range. The portion of power cable located outside the equipment compartment and the arcjet thruster should be tested to the tighter limits.

The FLTSATCOM qualification model spacecraft was configured as described in Appendix A. The Telemetry, Tracking and Command Subsystem (TT&C), Reaction Control Subsystem (RCS), Attitude and Velocity Control Subsystem (AVCS), and that part of the Electrical Power and Distribution Subsystem (EPDS) related to these subsystems were powered and monitored during the test. The UHF/SHF Communications Subsystem and related power converters and switching assemblies (EPDS) were not powered. The AVCS was configured to a normal on-orbit mode with a simulated sensor error input. The TT&C was configured in the bypass mode (i.e., no command encryption). Telemetry and command interface was via hardline.

7. TEST RESULTS

Typical thruster operating conditions, at 9×10^{-6} torr, were:

Feed pressure	14.2×10^6 Pa (210 psig)
Arc voltage	97 volts
Arc current	11.8 amperes

Residual gas analyzer measurements, at this chamber pressure, are shown in Figure 7-1. Mass peaks are seen at 2, 4, and 28, indicating a background presence of hydrogen, helium, and nitrogen in the ratio of 14:1:2, respectively, based on the amplitude of the analyzer signals observed.

During test, the spacecraft was commanded to the baseline configuration which was maintained during the periods of thruster firing. Telemetry was monitored during each thruster firing period to detect any change in state or status of any of the telemetered parameters for the active subsystems (TT&C, AVCS, RCS and EPDS). No changes in telemetry data attributable to thruster firing were detected in any of the tests. Changes which occurred during the test periods were typical of normal operation or peculiar to the test setup. These changes occurred with the same magnitude and frequency before and after test periods when the thruster was not operating.

During Test Series 200, the radiometers mounted 120°, 80°, and 40° from the thrust axis (see Figure 5-2) and the calorimeters mounted 80° and 40° from the thrust axis were 1.8 meters (6 feet) from the thruster exit plane. The calorimeters mounted at 20°, 0°, -20°, and -40° were 2.3 meters (7.5 feet) from the thruster exit plane. A maximum absorbed heat flux of 253 watts/m^2 (80 Btu/hr/ft^2), equivalent to 0.18 sun, was observed at the calorimeter on the thrust axis during thruster operation. Figure 7-2 shows typical calorimeter data at locations from -20 to 80 degrees. Figure 7-3 compares typical calorimeter and radiometer data at locations from 40 to 120 degrees.

Witness plates from the tests were examined and found to be qualitatively clean.

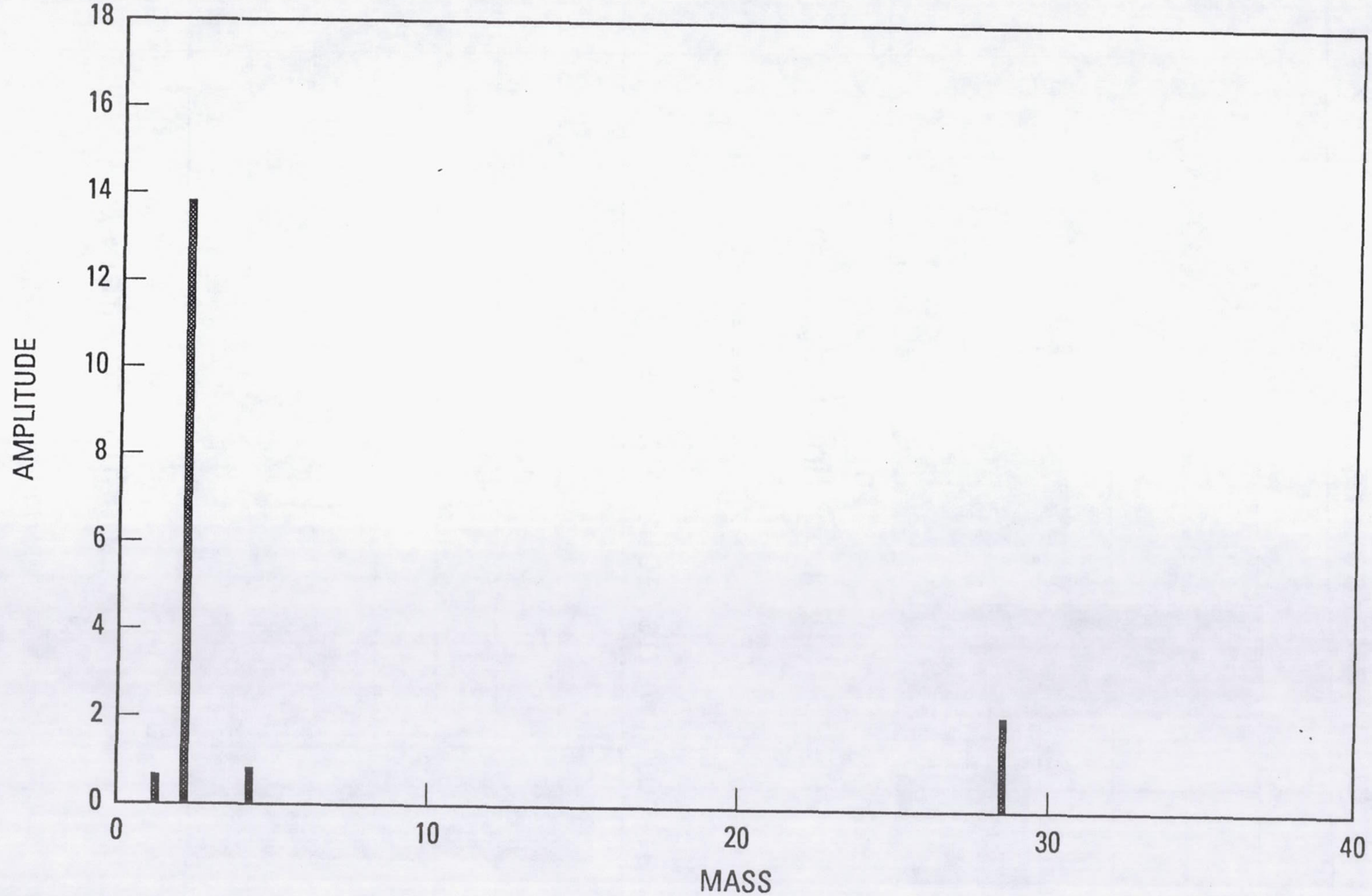


Figure 7-1. Residual Gas Analyzer Spectrum During Thruster Operation at 9×10^{-6} torr Chamber Pressure

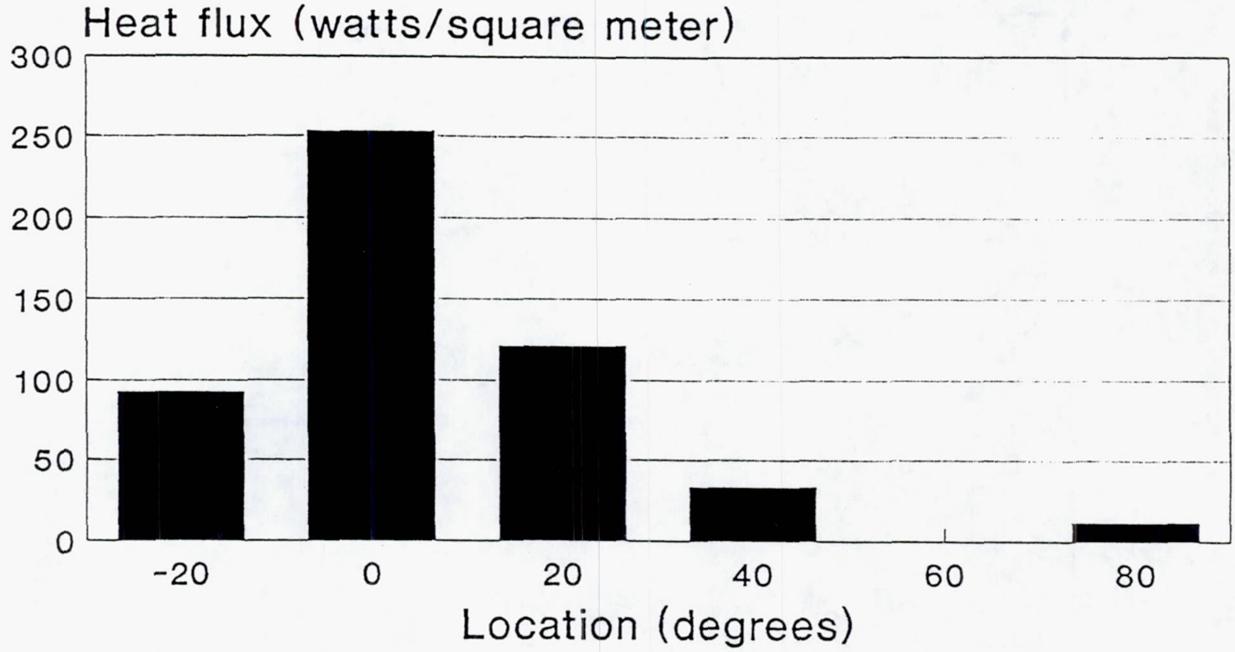


Figure 7-2. Calorimeter Data

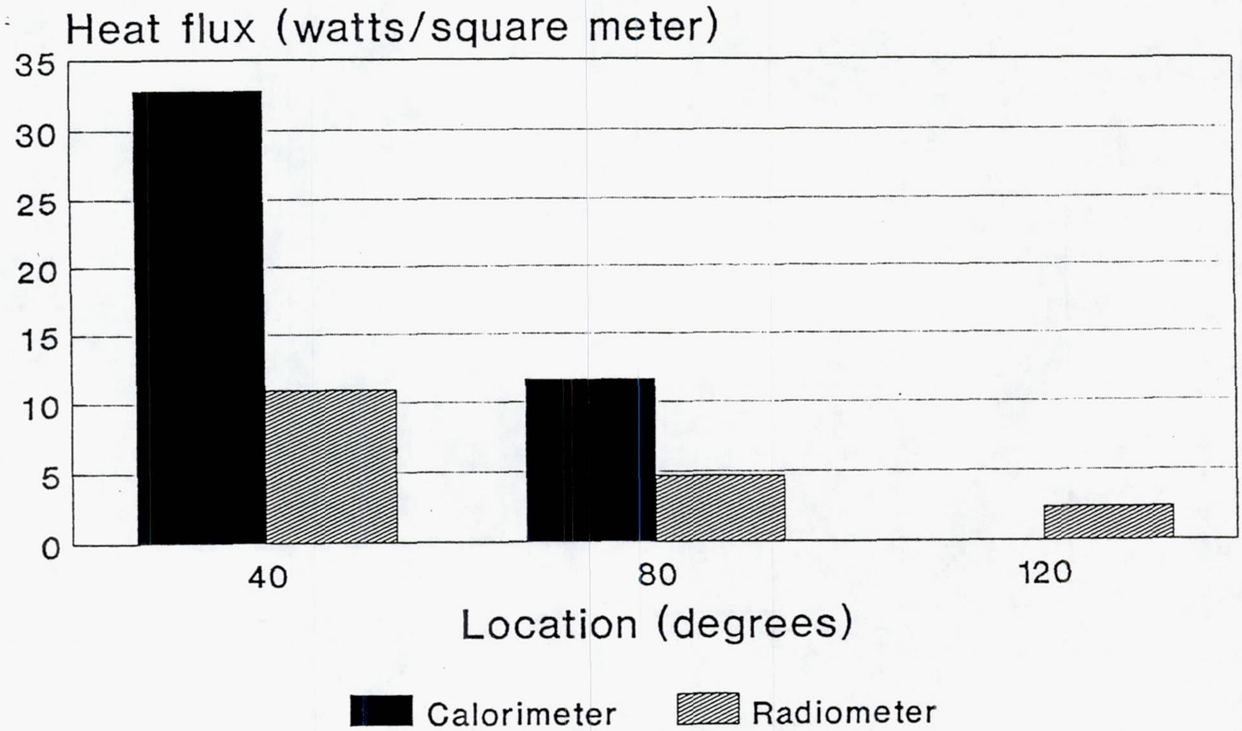


Figure 7-3. Calorimeter and Radiometer Data

The following EMC data were taken with the anode grounded at chamber pressures of 9 x 10^{-6} torr. Both MIL-STD-461C and tailored EMC limits are shown in the figures presented. Tailored limits, for typical communications satellites, are discussed above in Section 6.

Narrowband and broadband radiated emissions are shown in Figures 7-4 and 7-5, respectively, over the frequency range from 14 kHz to 1 GHz, and in Figures 7-6 and 7-7, respectively, over the frequency range from 14 kHz to 8 MHz. The ordinate (vertical scale) was adjusted in Figures 7-6 and 7-7 to better read the radiated emissions in this range. Figures 7-8 and 7-9 show narrowband and broadband radiated emissions, respectively, over the frequency range from 1 to 4 GHz. Above 500 MHz, radiated emissions are generally within limits.

Conducted emissions in the PCU input power cable are shown for narrowband and broadband emissions, respectively, in Figures 7-10 and 7-11 over the frequency range from 15 kHz to 100 MHz.

Conducted emissions in the arcjet ground strap are shown in Figure 7-12 over the frequency range from 30 Hz to 15 kHz. Figures 7-13 and 7-14 show narrowband and broadband emissions, respectively, over the frequency range from 15 kHz to 100 MHz.

Cable coupling measurements are shown in Figures 7-15 through 7-18 over the frequency range from 15 kHz to 100 MHz. E-field probe narrowband and broadband measurements are presented, respectively, in Figures 7-15 and 7-16. H-field probe narrowband and broadband measurements are presented, respectively, in Figures 7-17 and 7-18.

The following radiated emissions data were taken with the anode floating at chamber pressures of 9 x 10^{-6} torr. Narrowband and broadband emissions are shown in Figures 7-18 and 7-19, respectively, over the frequency range from 14 kHz to 1 GHz, and in Figures 7-21 and 7-22, respectively, over the frequency range from 14 kHz to 8 MHz. The ordinate was adjusted in Figures 7-21 and 7-22 to better read the radiated emissions in this range.

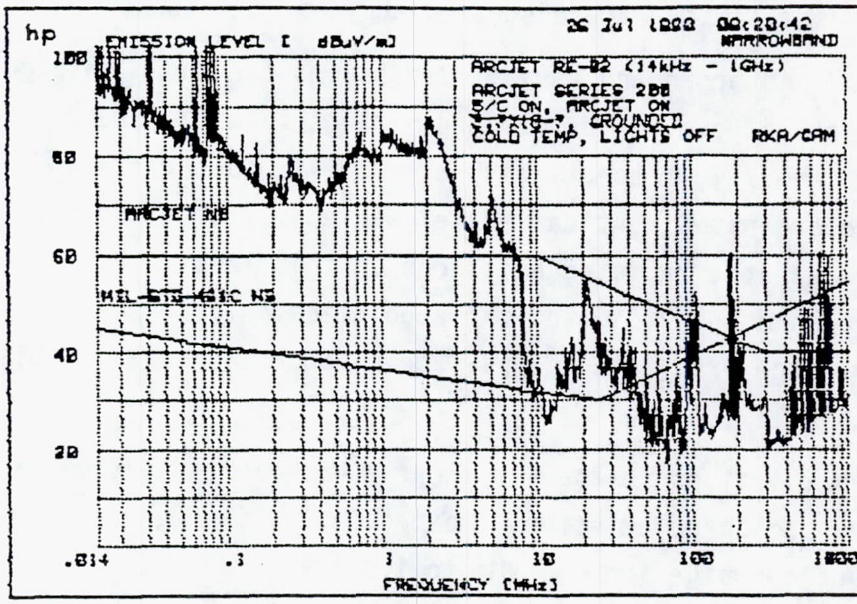


Figure 7-4. Narrowband Radiated Emissions, 14 kHz to 1 GHz

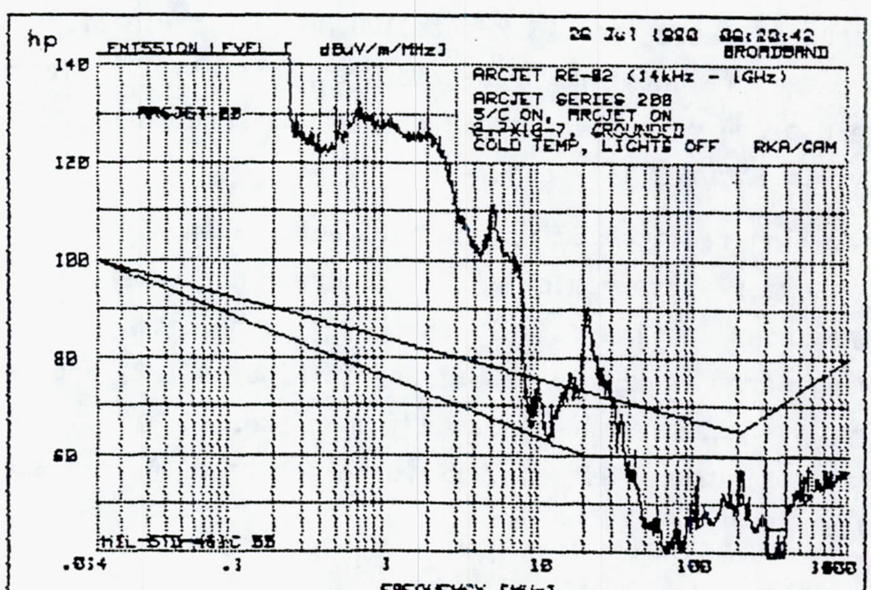


Figure 7-5. Broadband Radiated Emissions, 14 kHz to 1 GHz

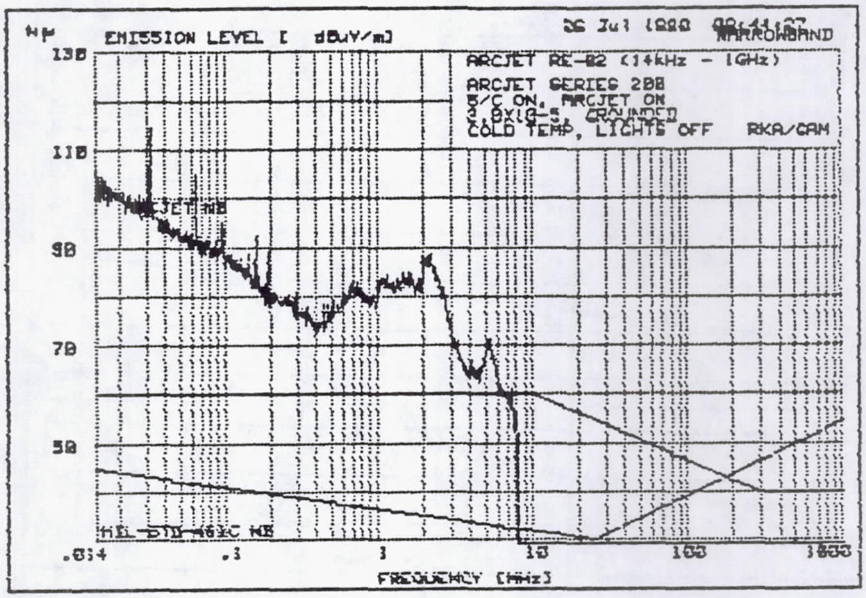


Figure 7-6. Narrowband Radiated Emissions, 14 kHz to 8 MHz

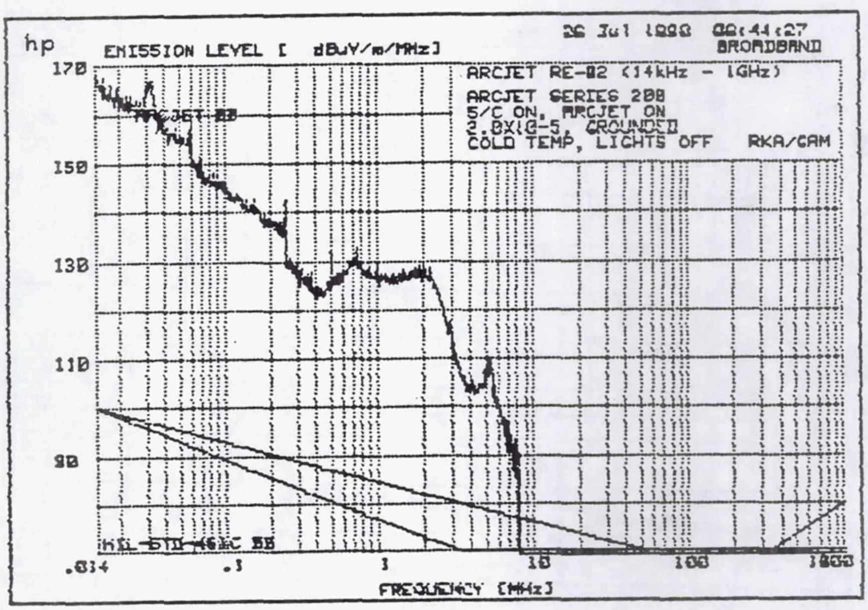


Figure 7-7. Broadband Radiated Emissions, 14 kHz to 8 MHz

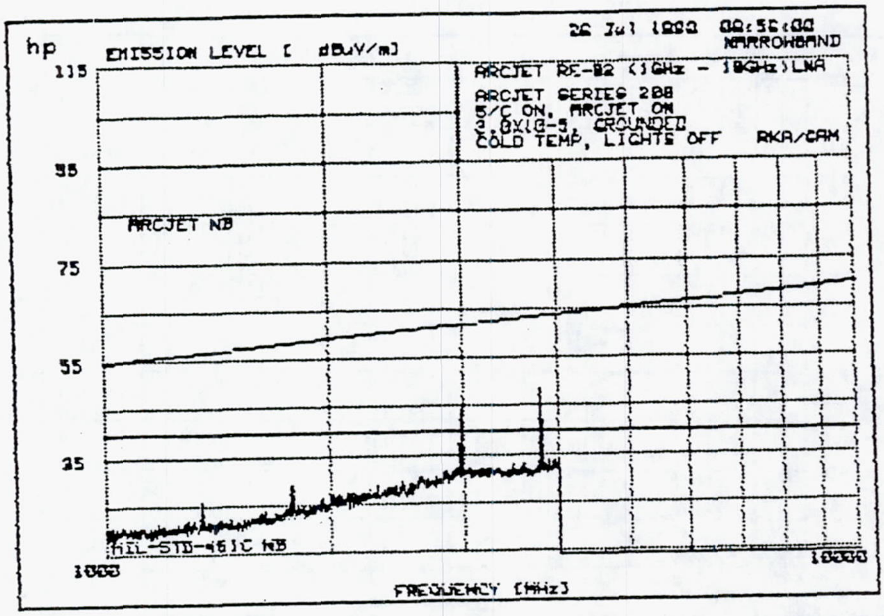


Figure 7-8. Narrowband Radiated Emissions, 1 to 4 GHz

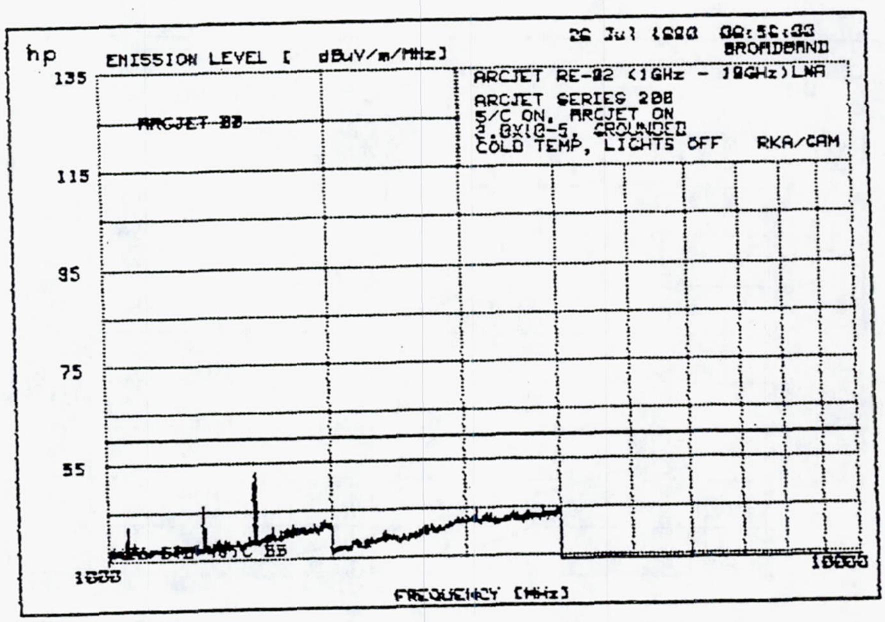


Figure 7-9. Broadband Radiated Emissions, 1 to 4 GHz

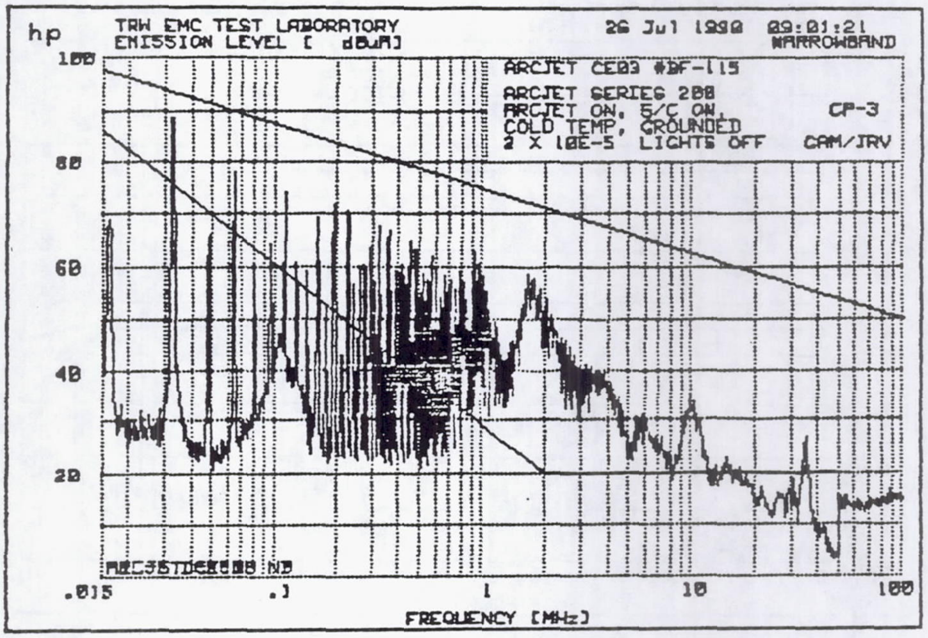


Figure 7-10. Narrowband Conducted Emissions, PCU Input Power, 15 kHz to 100 MHz

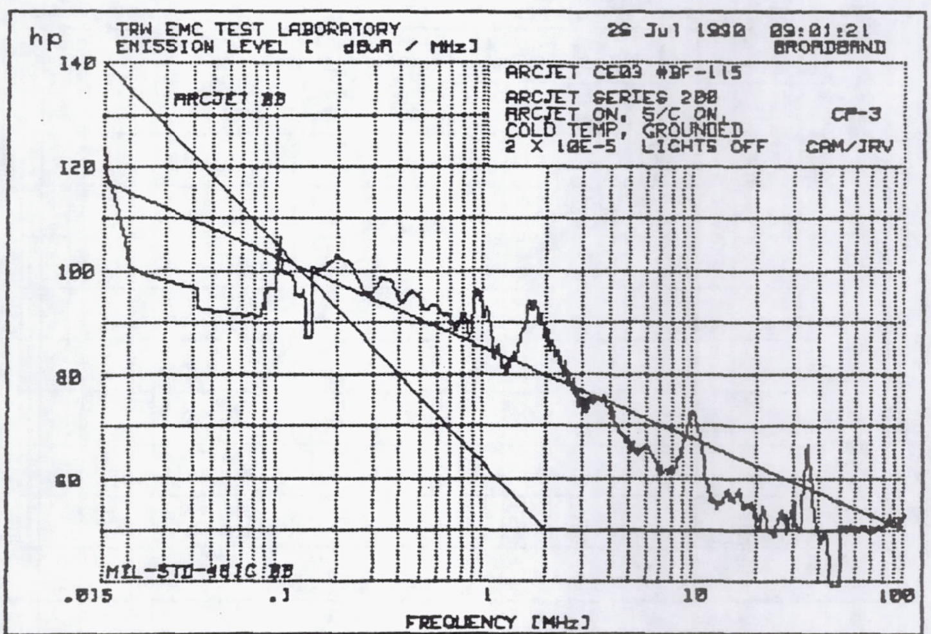


Figure 7-11. Broadband Conducted Emissions, PCU Input Power, 15 kHz to 100 MHz

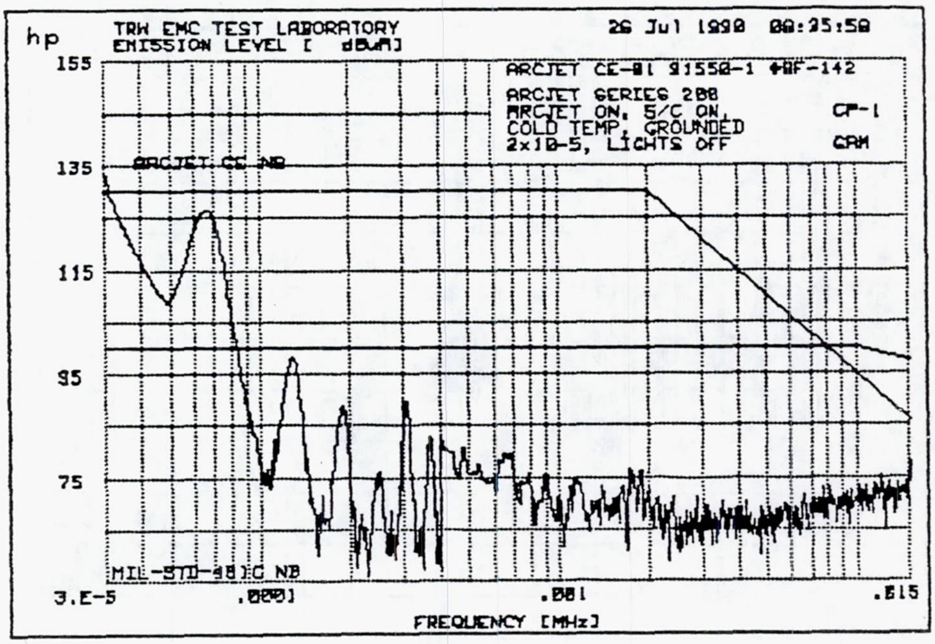


Figure 7-12. Conducted Emissions, Arcjet Ground Strap, 30 Hz to 15 kHz

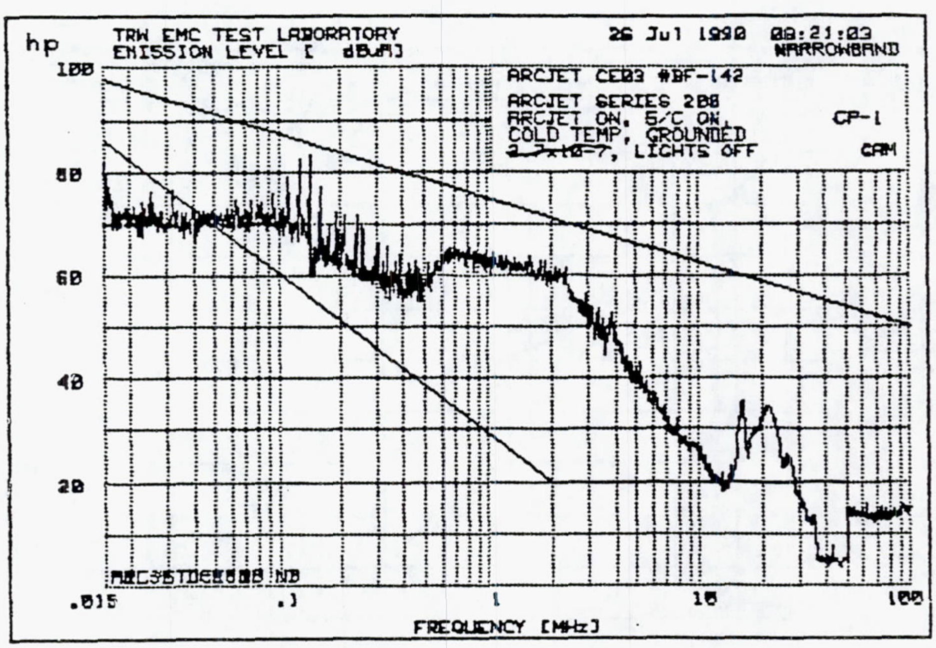


Figure 7-13. Narrowband Conducted Emissions, Arcjet Ground Strap, 15 kHz to 100 MHz

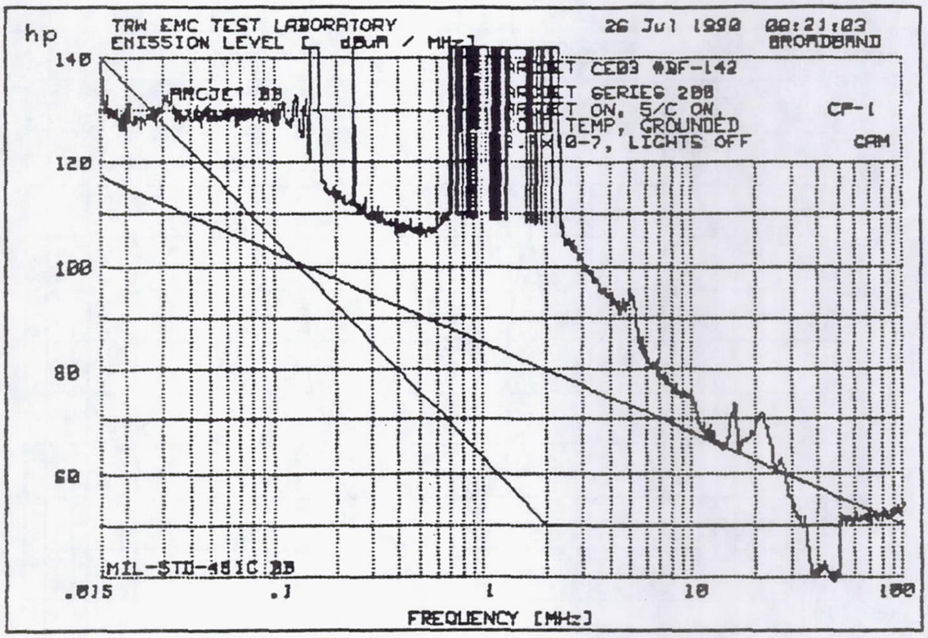


Figure 7-14. Broadband Conducted Emissions, Arcjet Ground Strap, 15 kHz to 100 MHz

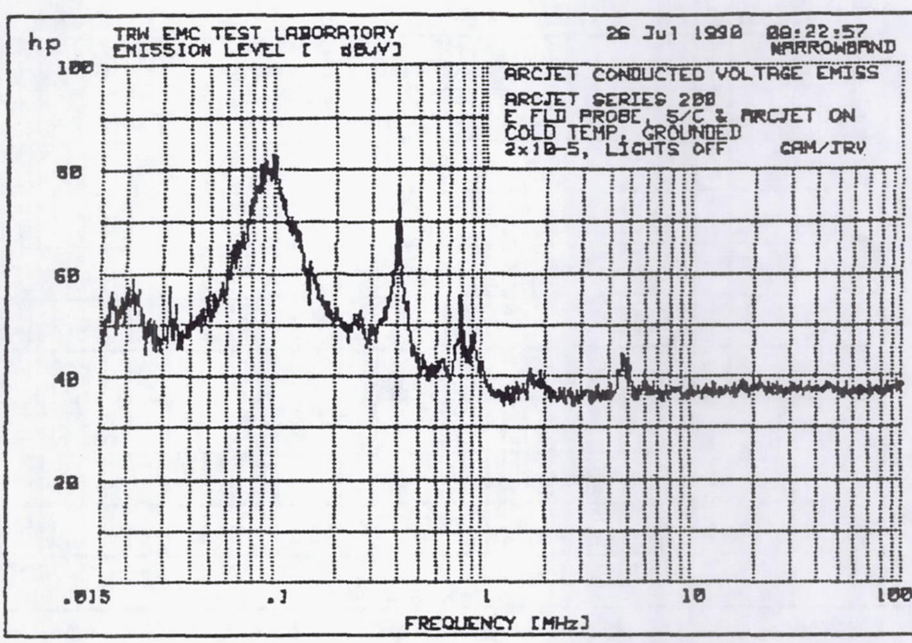


Figure 7-15. Narrowband E-Field Cable Coupling, 15 kHz to 100 MHz

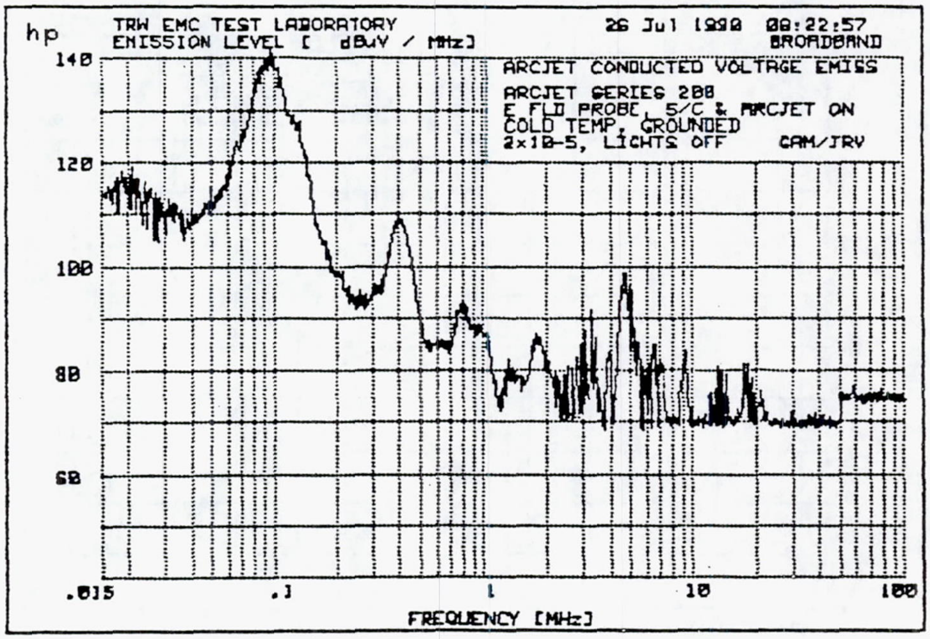


Figure 7-16. Broadband E-Field Cable Coupling, 15 kHz to 100 MHz

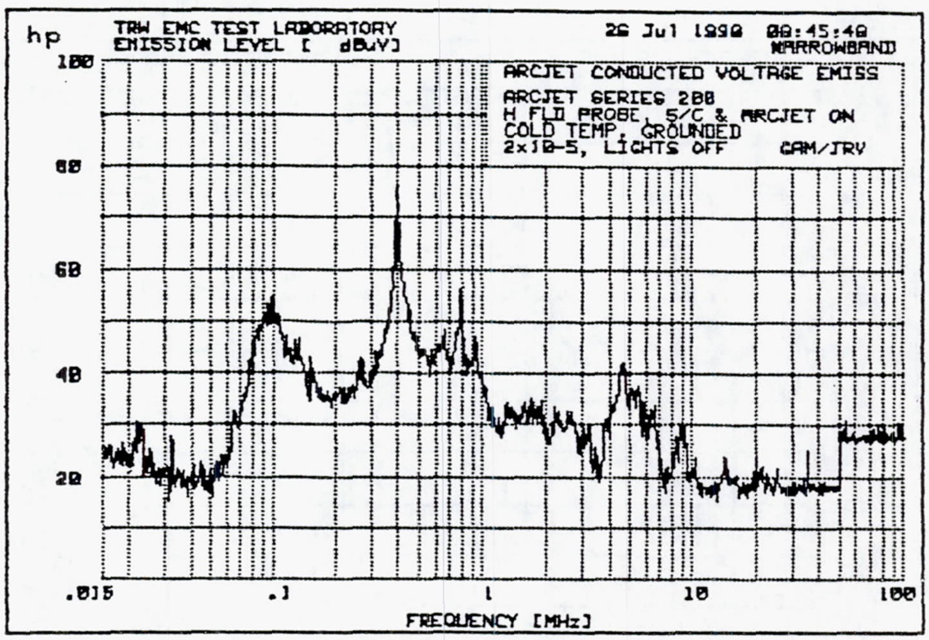


Figure 7-17. Narrowband H-Field Cable Coupling, 15 kHz to 100 MHz

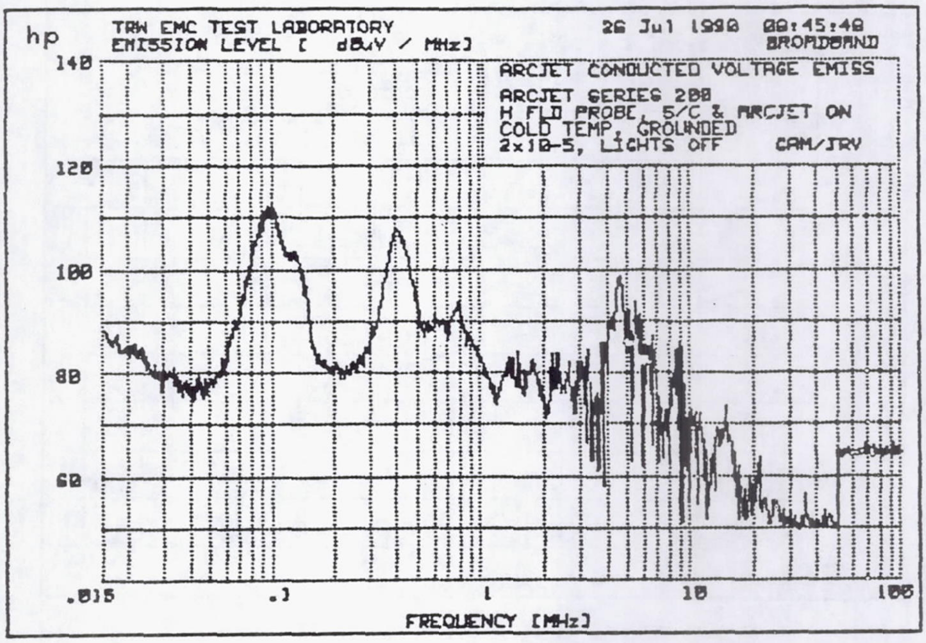


Figure 7-18. Broadband H-Field Cable Coupling, 15 kHz to 100 MHz

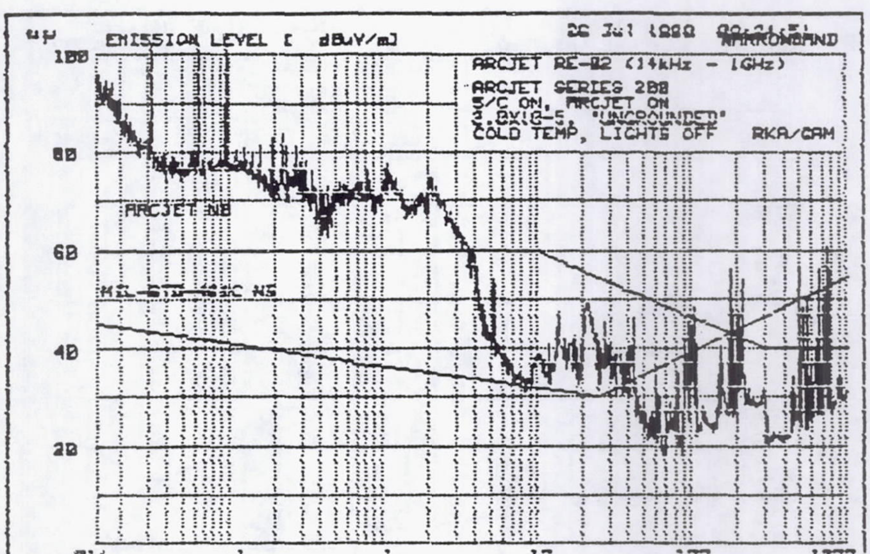


Figure 7-19. Narrowband Radiated Emissions, Floating Anode, 14 kHz to 1 GHz

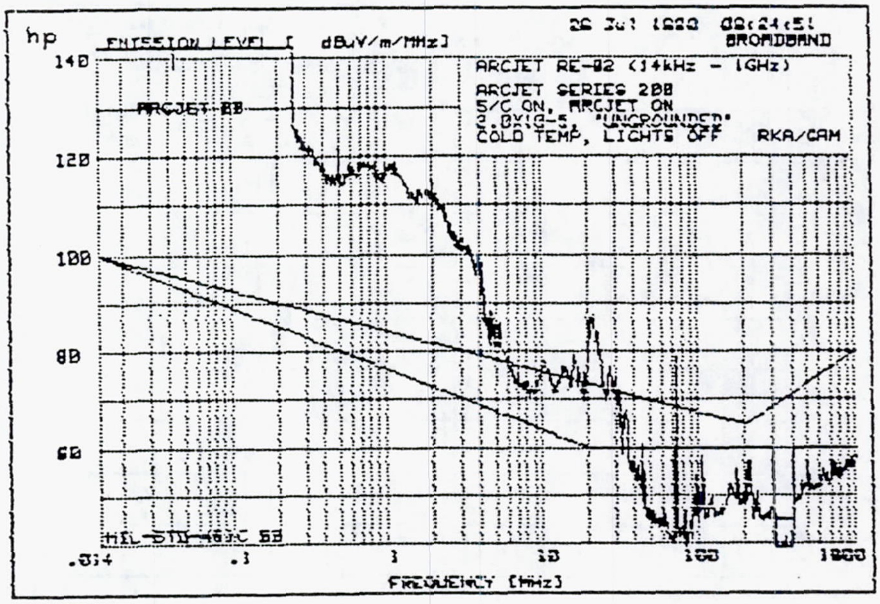


Figure 7-20. Broadband Radiated Emissions, Floating Anode, 14 kHz to 1 GHz

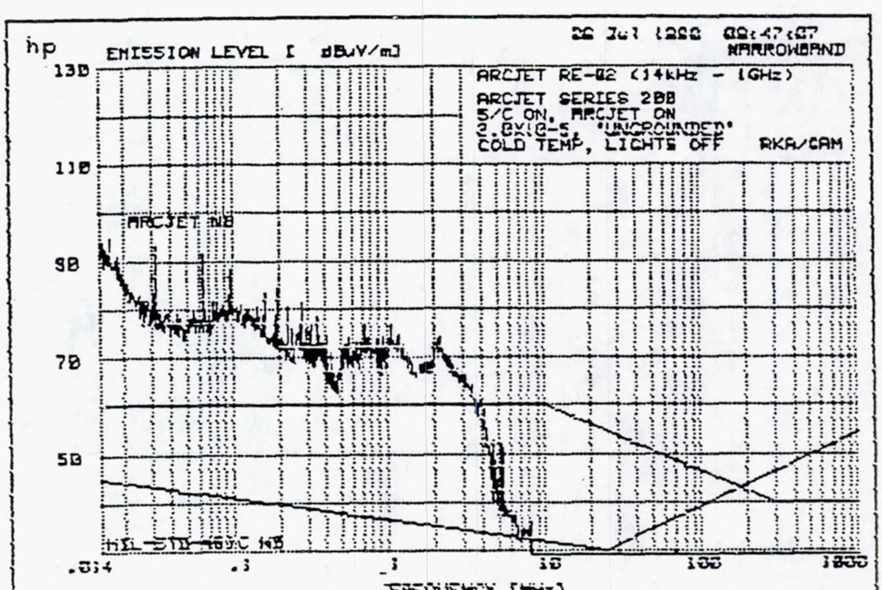


Figure 7-21. Narrowband Radiated Emissions, Floating Anode, 14 kHz to 8 MHz

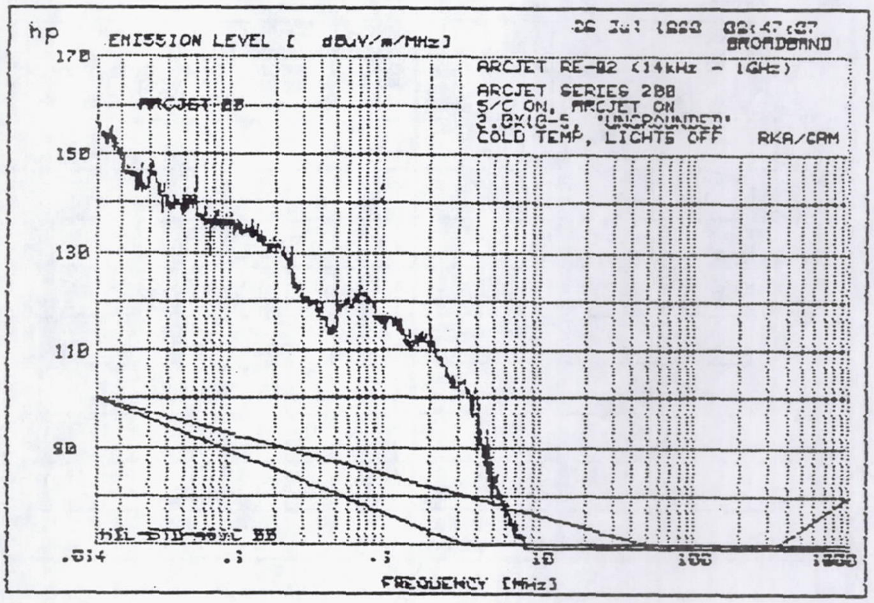


Figure 7-22. Broadband Radiated Emissions, Floating Anode, 14 kHz to 8 MHz

The following radiated emissions data were taken with the anode grounded at various chamber pressures (5 x 10^{-4} torr, 0.1 torr, and 3 torr).

Narrowband radiation emissions at 5 x 10^{-4} torr are shown in Figure 7-23 over the frequency range from 14 kHz to 1 GHz.

Narrowband and broadband radiated emissions at 0.1 torr are shown in Figures 7-24 and 7-25, respectively, over the frequency range from 14 kHz to 1 GHz, and in Figures 7-26 and 7-27, respectively, over the frequency range from 14 kHz to 1 MHz. The ordinate was adjusted in Figures 7-26 and 7-27 to better read the radiated emissions in this range. Figures 7-28 and 7-29 show narrowband and broadband radiated emissions at 0.1 torr, respectively, over the frequency range from 1 to 10 GHz.

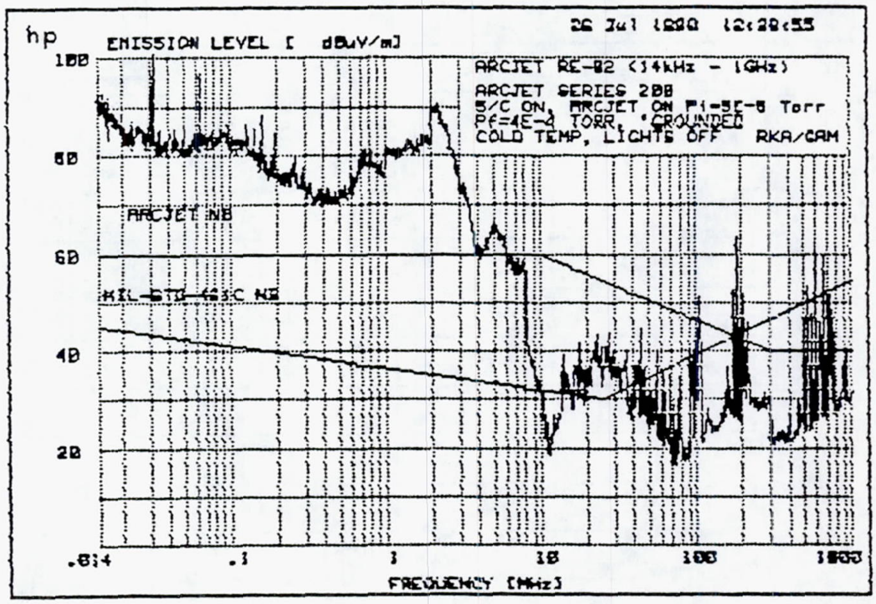


Figure 7-23. Narrowband Radiated Emissions at 5 x 10^{-4} torr, 14 kHz to 1 GHz

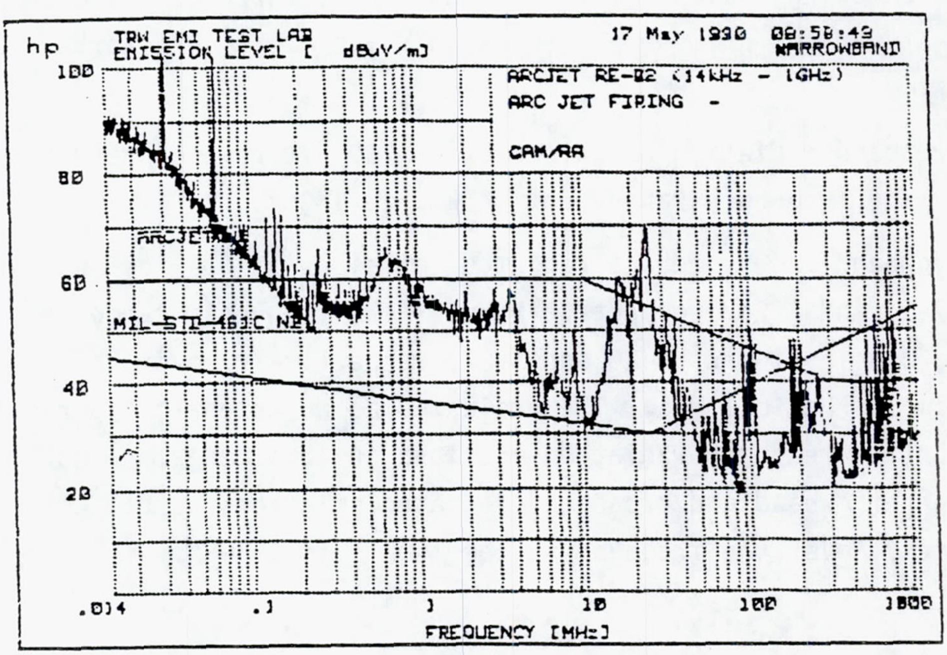


Figure 7-24. Narrowband Radiated Emissions at 0.1 torr, 14 kHz to 1 GHz

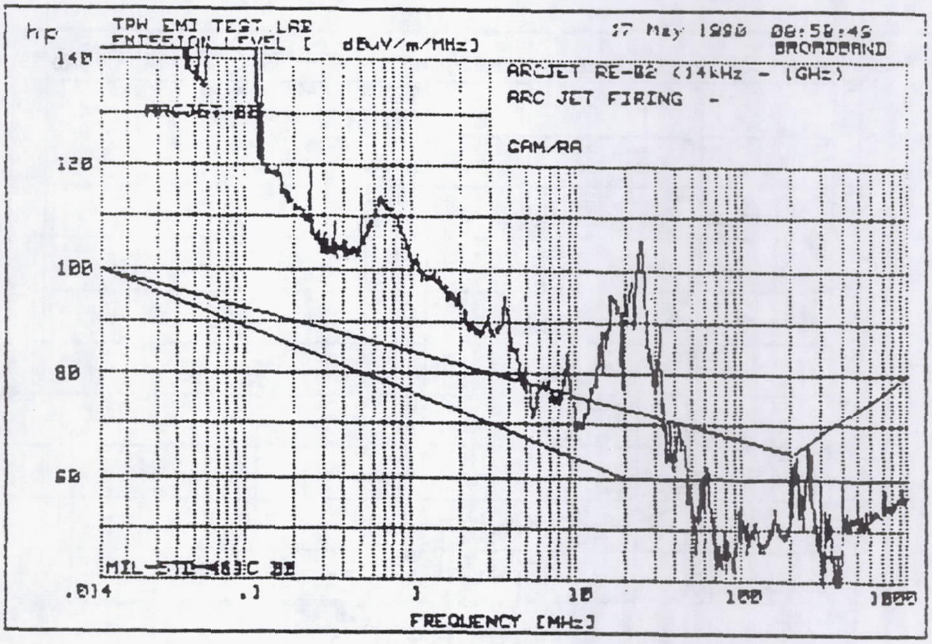


Figure 7-25. Broadband Radiated Emissions at 0.1 torr, 14 kHz to 1 GHz

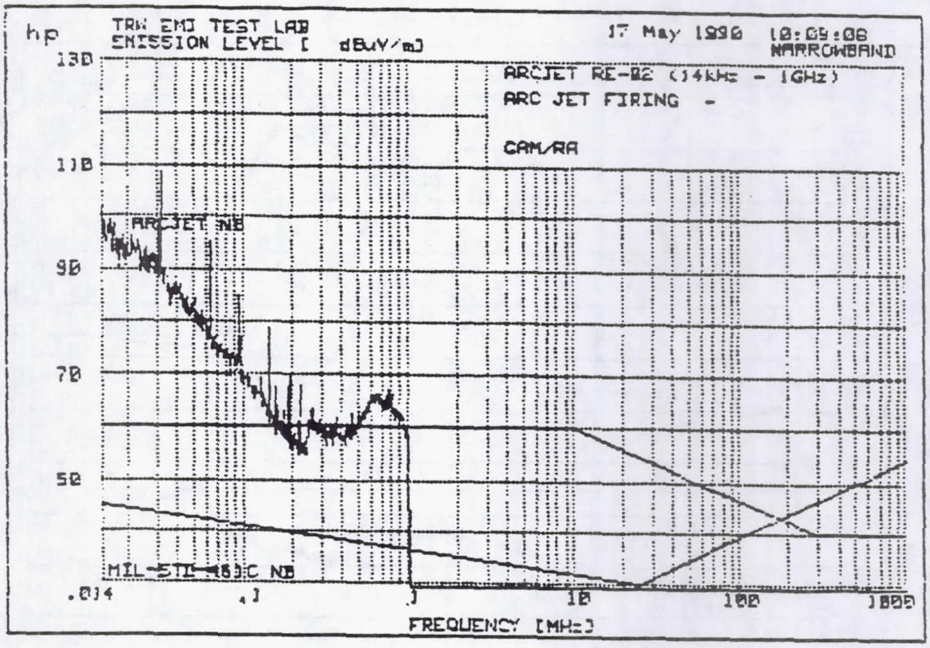


Figure 7-26. Narrowband Radiated Emissions at 0.1 torr, 14 kHz to 1 MHz

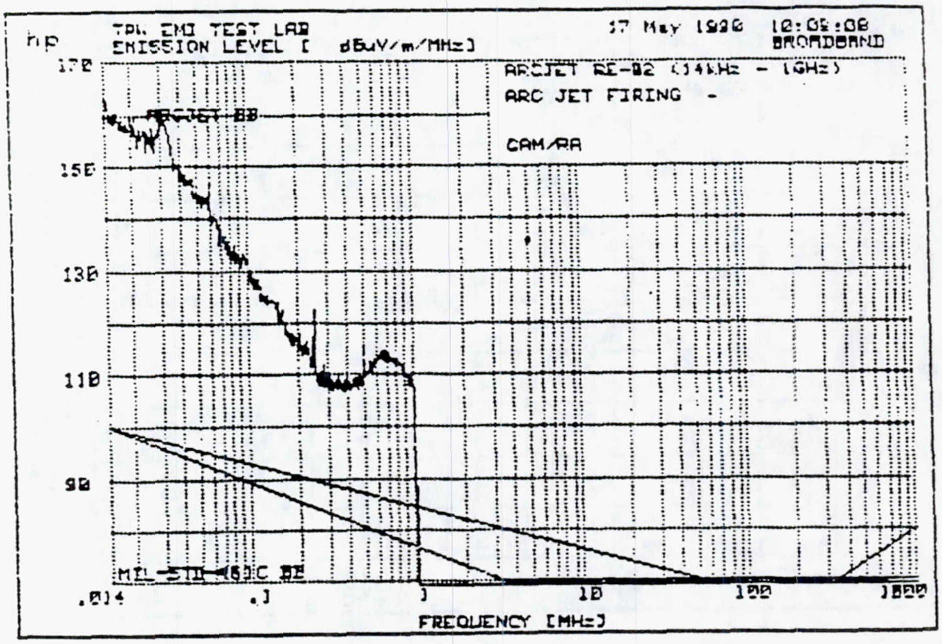


Figure 7-27. Broadband Radiated Emissions at 0.1 torr, 14 kHz to 1 MHz

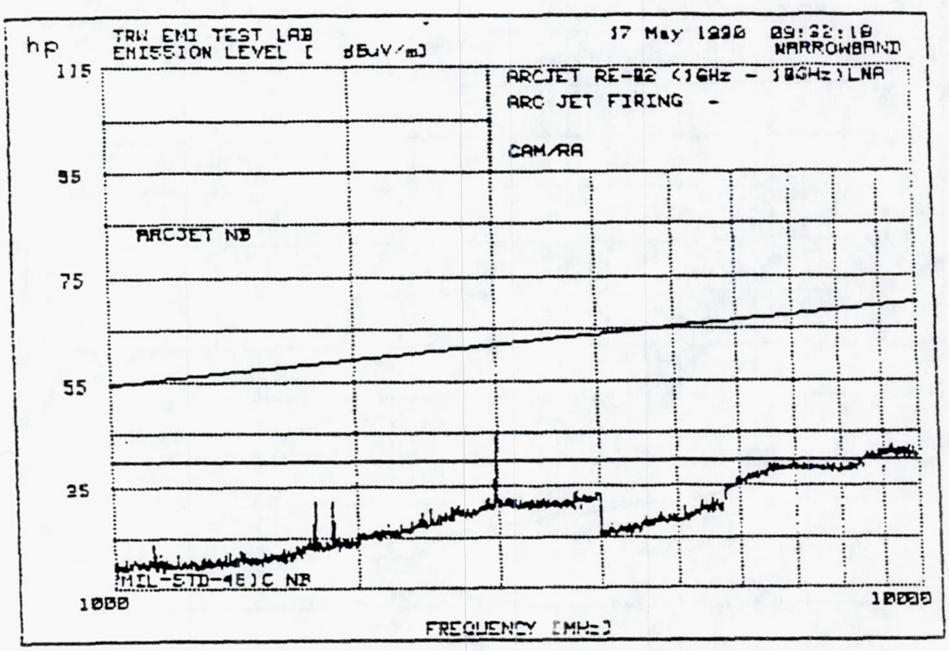


Figure 7-28. Narrowband Radiated Emissions at 0.1 torr, 1 to 10 GHz

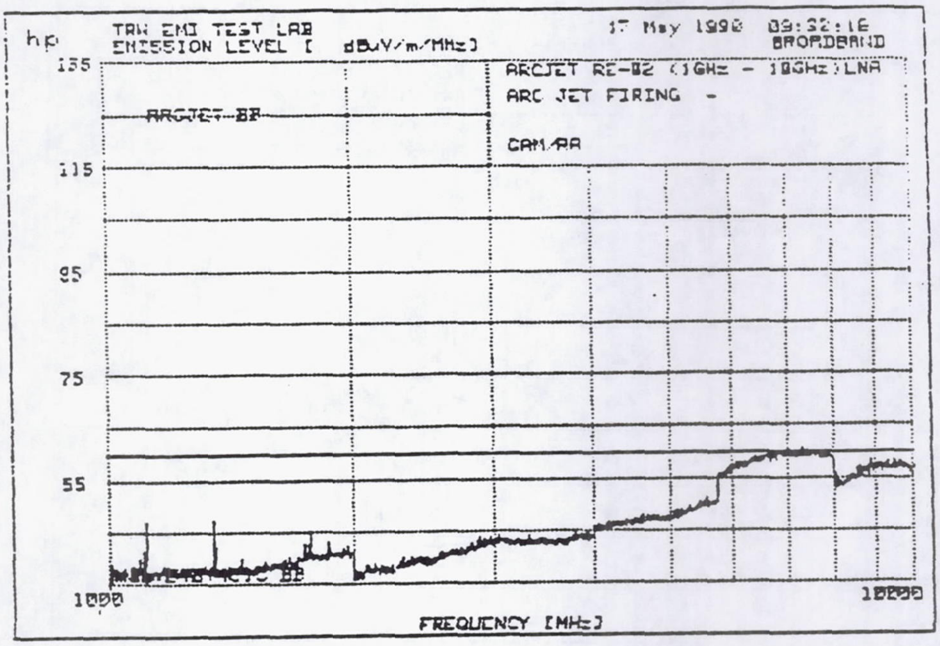


Figure 7-29. Broadband Radiated Emissions at 0.1 torr, 1 to 10 GHz

Narrowband radiated emissions at 3 torr are shown in Figure 7-30 over the frequency range from 14 kHz to 10 MHz.

A number of arcjet transient measurements were taken during Test Series 100. Transient responses were characteristically slow, and as a consequence, no significant emissions were observed.

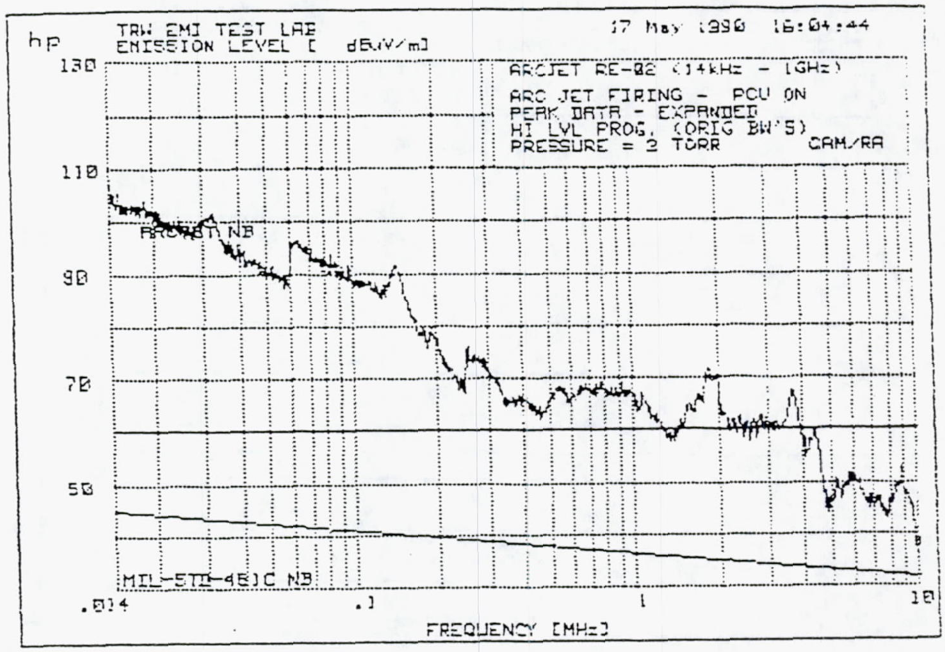


Figure 7-30. Narrowband Radiated Emissions at 3 torr, 14 kHz to 10 MHz

8. DISCUSSION OF RESULTS

The principal objective of the ASID program was achieved when compatibility of the 1.4-kW hydrazine arcjet system was demonstrated by operating it next to the FLTSATCOM qualification model spacecraft in a thermal-vacuum space simulation environment at $<10^{-5}$ torr. At this low pressure, the mean free path between background gas collisions was approximately the same as the test facility diameter, enabling free exhaust jet expansion into the vacuum. Compatibility was demonstrated by virture of the fact that FLTSATCOM operation proceeded normally, without any evidence of arcjet interference, or without any indication of arcjet presence on monitored signals from the satellite. This was evidenced during periods of arcjet transient (turn-on and turn-off) and steady-state operation.

The LHe panels were very effective in pumping arcjet exhaust gases during periods of thruster operation. Nitrogen and ammonia exhaust were condensed on the panels, leaving hydrogen as the dominant species by a large margin. This was confirmed by residual gas analyzer measurements.

Thermal integration characteristics of the thruster and PCU appeared consistent with predictions. Although coolant fluid was used for test purposes, radiative dissipation to space should be adequate on a geosynchronous satellite. Useful calorimeter and radiometer data were taken for confirmation of plume heating predictions. The calorimeter data show a rapid fall off in heat flux as measurements proceed away from the thrust axis. Comparing calorimeter and radiometer data at specific locations enables separation of the heat flux measured into radiated and plume convected components. Convection is more important, as expected, closer to the thrust axis.

The test duration was too short to accumulate contamination over a typical mission duration. Witness plate observations, however, evidenced good compatibility for the exposure period encountered.

Electromagnetic compatibility data show broadband noise above limits up to 40 MHz. Commercial satellites typically do not have equipment operating below UHF frequencies. Communication links at UHF frequencies and above would not be affected. On satellites having equipment that operates at lower frequencies, special attention must be taken to assure compatibility. This may be achieved by filtering, shielding, and location, as appropriate. The ASID test data, for conducted and radiated emissions, provide a sound data base for implementing and verifying EMC analyses.

The most likely spacecraft grounding configuration will ground the anode to structure. This will be done for spacecraft charge control purposes. The diagnostic data reported herein for anode floating conditions, and for various chamber background pressures, were taken to gain further insight into arcjet operation and its electromagnetic signature. These data serve as a starting point for further investigations, presently underway at NASA-LeRC, to better understand the source of radiated emissions from the arcjet system, and perhaps, to mitigate the noise levels seen at lower frequencies by implementing suitable design improvements.

9. CONCLUSIONS

Compatibility between arcjet propulsion systems and communications satellites was verified by testing a 1.4-kW hydrazine arcjet system and the FLTSATCOM qualification model satellite together in a space simulation facility at background pressures below 10^{-5} torr with the arcjet thruster in operation. The satellite performed nominally during periods of arcjet transient and steady-state operation. Telemetry data from the satellite showed no changes attributable to arcjet operation.

Radiated and conducted electromagnetic emissions from the arcjet system were measured at frequencies from 30 Hz to 10 GHz. In the frequency ranges of interest, at UHF and above, emissions were within typically tailored limits for communications satellites. Below 40 MHz, broadband noise was observed that exceeded these limits. Commercial satellites typically do not have sensitive equipment operating in this range. Special precautions may have to be taken to integrate the arcjet on satellites that have equipment potentially susceptible to noise at these lower frequencies. The data obtained on the ASID program is useful for performing and verifying electromagnetic compatibility analyses for communications satellite systems.

The ASID program specifically addressed and tested for critical arcjet integration issues. Prior analysis, and confirming data taken during test, indicate that arcjets are suitable for application and integration on next generation, geosynchronous communications satellite systems employing conventional hydrazine propellant storage and feed subsystems.

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2. Sovey, J. S., Carney, L. M., and Knowles, S. C. "Electromagnetic Emission Experiences Using Electric Propulsion Systems," Journal of Propulsion and Power, Vol. 5, No. 5, pp. 534-547.

3. Carney, L. M., "Evaluation of Communications Impact of a Low Power Arcjet Thruster," AIAA Paper 88-3105, July 1988.

APPENDIX A

FLTSATCOM QUALIFICATION MODEL SPACECRAFT

FLTSATCOM satellites are the spaceborne portion of a worldwide Navy, Air Force and Department of Defense communications system that enables communications between naval aircraft, ships, submarines, ground stations, Strategic Air Command and the presidential command networks. Each satellite consists of two major parts: a payload module (including antennas), and a spacecraft module, with a solar array. The payload and spacecraft modules are hexagonal, 7.5-feet wide (see Figure A-1). The payload module contains the communications equipment and antennas. Each of the six panels carries related communications components. The spacecraft module contains nearly all the other subsystem equipment, including the earth sensors, attitude and velocity control, telemetry, tracking and command, and electrical power and distribution, as well as the buried nonseparable apogee kick motor. The solar array is exposed to sunlight both in the folded and deployed configuration. Following injection into the final orbit, the array is deployed by articulated beams with spring-loaded hinges.

The spacecraft simulator used for the ASID tests was the FLTSATCOM qualification model. This is a fully integrated and functional spacecraft including telemetry, tracking and command (TT&C), attitude and velocity control (AVCS), electrical power distribution (EPDS), and UHF/SHF communications subsystems. However, other spacecraft components were not used. This includes the apogee kick motor, antennas, COMSEC units (for security reasons), and the substitution of simulators for the dual thruster modules. In addition, because of space limitations within the vacuum tank, the solar array was not be directly attached to the spacecraft. With the exception of the antennas and the COMSEC unit removals, this was the same hardware configuration that had been used in two previous FLTSATCOM EMC tests.

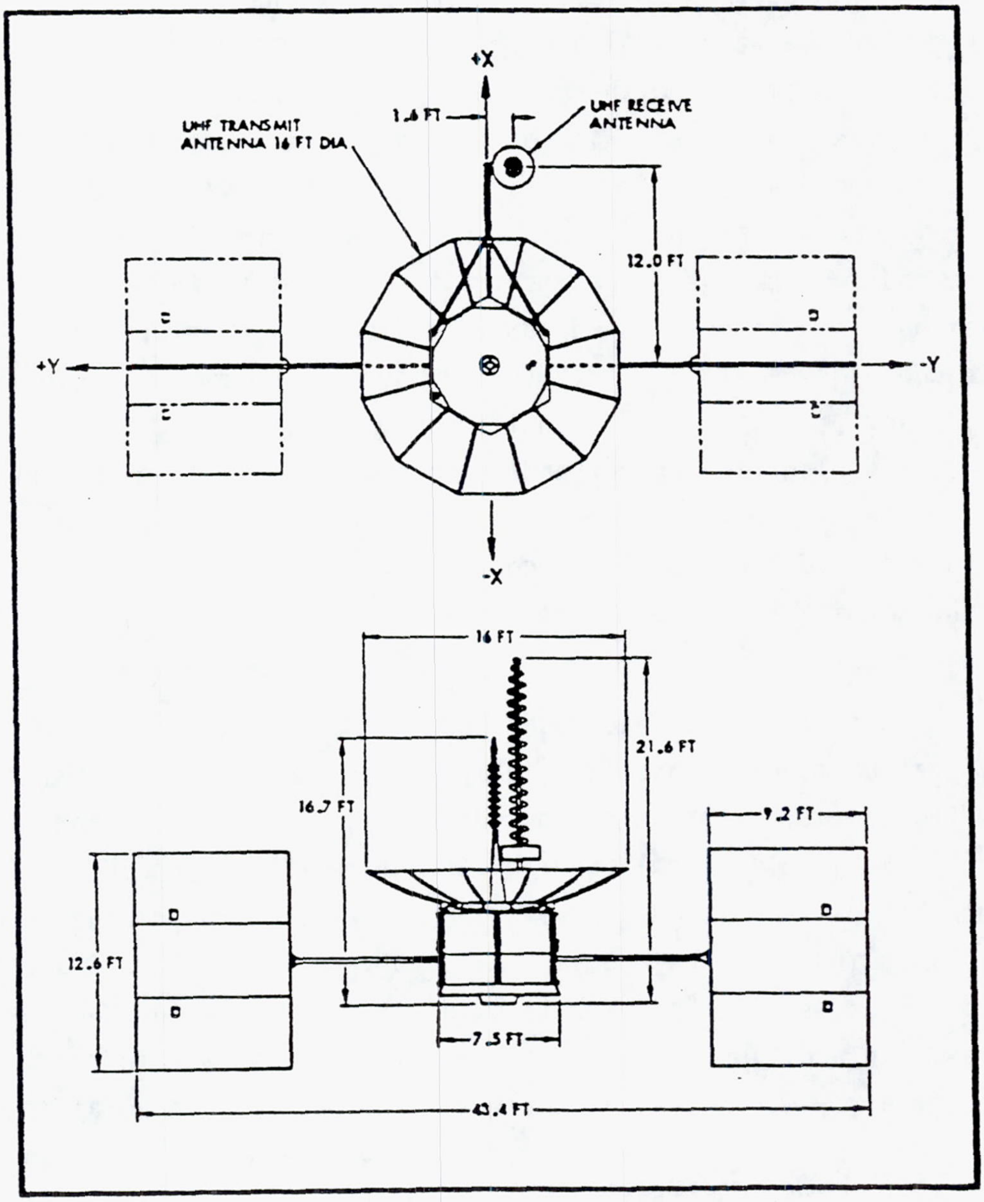

Figure A-1. FLTSATCOM Deployed Configuration

Spacecraft Ground Support Equipment

The FLTSATCOM Electrical Aerospace Ground Equipment (EAGE) consists of the system level test and support equipment required to support the spacecraft acceptance testing and launch operations. The EAGE required to support the ASID test was limited to AVCS Controls Subset, the Power Subset, the TT&C Subset, and the Automatic Data Processing Equipment (ADPE) Subset.

The AVCS Controls Subset consists of three major functions: stimulators, simulators, and monitors. This subset is packaged as a three-bay console. For this test, the simulators were used to provide sensor outputs to the AVCS electronics. Monitoring of thruster firings, attitude control system wheel speed, and other AVCS activities was accomplished via telemetry.

The Power Subset consists of a power console and an in-flight jumper simulator unit. These two units supply, control, monitor, and measure the primary power applied to the spacecraft during test operations.

The TT&C Subset is required to establish a two-way communications link with the spacecraft, to generate commands, and to analyze spacecraft telemetry and responses to command stimulations. The subset consists of the following complement of equipment:

- Single-Bay RF Console
- Three-Bay T&C Console
- Single-Bay Tape Recorder Console
- Single-Bay COMSEC Console

In addition, one drawer of the Ordnance Test Point Monitor is required to interface the spacecraft and the T&C console. Note that the RF and COMSEC consoles were not required to support the ASID tests.

Automatic Data Processing Equipment

The ADPE Subset in conjunction with the TT&C Subset mate the Data Acquisition System with the spacecraft's telemetry and command electronics subsystem. The ADPE Subset combines both automated and manual operational modes for real-time control and data monitoring of the FLTSATCOM spacecraft. Telemetry that is transmitted or hardlined to the system is presented for immediate review on CRTs and printed for subsequent analysis. In addition, an analog tape is used to record telemetry data for replay to verify any anomalies which may have occurred.

The primary purpose of the ADPE Subset during the ASID test was to establish the initial spacecraft configuration and monitor any status changes that occurred. The principal functions were: (1) real-time monitoring of telemetry, (2) CRT display of data and commands, and (3) command generation and verification.

Prior to the start of arcjet firing, the spacecraft was partially powered and configured to an on-orbit operating mode. The subsystems that were powered are TT&C, AVCS, reaction control subsystem (RCS), thermal, and that portion of the EPDS required to power these subsystems. The UHF/SHF communications subsystem and related power converters (EPDS) were not turned on during the test. The AVCS was configured to a normal on-orbit mode with simulated sensor input errors. The TT&C subsystem was configured to the bypass mode (i.e., no command encryption).

The baseline configuration was established at the start of the test and was maintained during arcjet operation. Spacecraft telemetry was monitored and recorded, and was reviewed at completion to determine if there were any detectable changes in the status of the telemetered subsystems (i.e., AVCS, TT&C, RCS, or EPDS). Note that due to the low sampling rate of the spacecraft telemetry (0.5 second for the mainframe and 32 seconds for the subframe), the spacecraft telemetry was not useful for detecting short-term changes in spacecraft status; the EMC sensors added for testing purposes were more capable of detecting transient effects.

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13. ABSTRACT *(Maximum 200 words)*

Compatibility between an arcjet propulsion system and a communications satellite was verified by testing a Government-furnished, 1.4 kW hydrazine arcjet system with the FLTSATCOM qualification model satellite in a 9.1-meter (30-foot) diameter thermal-vacuum test chamber. Background pressure was maintained at 10^{-5} torr during arcjet operation by cryopumping the thruster exhaust with an array of 5 K liquid helium cooled panels. Power for the arcjet system was obtained from the FLTSATCOM battery simulator. Spacecraft telemetry was monitored during each thruster firing period. No changes in telemetry data attributable to arcjet operation were detected in any of the tests. Electromagnetic compatibility data obtained included radiated emission measurements, conducted emission measurements, and cable coupling measurements. Significant noise was observed at lower frequencies. Above 500 MHz, radiated emissions were generally within limits, indicating that communication links at S-band and higher frequencies will not be affected. Other test data taken with a diagnostic array of calorimeters, radiometers, witness plates, and a residual gas analyzer evidenced compatible operation, and added to the data base for arcjet system integration. Two test series were conducted. The first series only included the arcjet and diagnostic array operating at approximately 0.1 torr background pressure. The second series added the qualification model spacecraft, a solar panel, and the helium cryopanels. Tests were conducted at 0.1 torr and 10^{-5} torr. The arcjet thruster was canted 20° relative to the solar panel axis, typical of the configuration used for stationkeeping thrusters on geosynchronous communications satellites.

14. SUBJECT TERMS

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