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AUXILIARY PROPULSION SYSTEM FLIGHT PACKAGE

C.R. Collett

Hughes Aircraft Company
Space and Communications Group
Los Angeles, CA 90009

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16. Abstract

A program is described under which Hughes Aircraft Company developed, flight qualified, and integrated on an Air Force technology satellite a flight test Ion Auxiliary Propulsion System (IAPS). The IAPS Flight Package consists of two identical Thruster Subsystems and a Diagnostic Subsystem. Each thruster subsystem (TSS) is comprised of an 8-cm ion Thruster-Gimbal-Beam Shield Unit (TGBSU); Power Electronics Unit (PEU); Digital Controller and Interface Unit (DCIU); and Propellant Tank, Valve and Feed Unit (PTVFU) plus the requisite cables. The Diagnostic Subsystem (DSS) includes four types of sensors for measuring the effect of the ion thrusters on the spacecraft and the surrounding plasma. Flight qualification of IAPS, prior to installation on the spacecraft, consisted of performance, vibration and thermal-vacuum testing at the unit level and performance, and thermal-vacuum testing at the subsystem level. Mutual compatibility between IAPS and the host spacecraft was demonstrated during a series of performance and environmental tests after the IAPS Flight Package was installed on the spacecraft. After a spacecraft acoustic test, performance of the ion thrusters was reverified by removing the TGBSUs for a thorough performance test at Hughes Research Laboratories (HRL). The TGBSUs were then reinstalled on the spacecraft. The IAPS Flight Package is ready for flight testing when Shuttle flights are resumed.

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FOREWORD

The program described in this report resulted in a flight qualified Ion Auxiliary Propulsion System (IAPS) Flight Package which was integrated onto an Air Force technology spacecraft. The work which produced these results was performed by personnel from two Hughes Aircraft Company organizations - Space and Communications Group (S&CG) and Hughes Research Laboratories (HRL), under the direction of NASA's Lewis Research Center (LeRC). Functions provided by S&CG included: program management; development of the Digital Controller and Interface Unit (DCIU) and the Diagnostics Subsystem (DSS); and production and flight qualification of the Power Electronics Units (PEU), Propellant Tank, Valve and Feed Units (PTVFU), Digital Controller and Interface Units and Diagnostic Subsystem. HRL responsibilities consisted of production and flight qualification of the Thruster-Gimbal-Beam Shield Unit (TGBSU), and Thruster Subsystem testing. Integration of the completed IAPS Flight Package onto the host spacecraft was a joint S&CG-HRL effort.

Key contributions were made to this program by the following individuals:

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SUMMARY

Under this contract, Hughes Aircraft Company developed, flight qualified, and integrated on an Air Force technology satellite a flight test Ion Auxiliary Propulsion System (IAPS). The IAPS Flight Package consists of two identical Thruster Subsystems and a Diagnostic Subsystem. Each thruster subsystem (TSS) is comprised of an 8-cm ion Thruster-Gimbal-Beam Shield Unit (TGBSU); Power Electronics Unit (PEU); Digital Controller and Interface Unit (DCIU); and Propellant Tank, Valve and Feed Unit (PTVFU), plus the requisite cables. The Diagnostic Subsystem (DSS) includes four types of sensors for measuring the effect of the ion thrusters on the spacecraft and the surrounding plasma. Flight qualification of IAPS, prior to installation on the spacecraft, consisted of performance, vibration and thermal-vacuum testing at the unit level and performance and thermal-vacuum testing at the subsystem level. Mutual compatibility between IAPS and the host spacecraft was demonstrated during a series of performance and environmental tests after the IAPS Flight Package was installed on the spacecraft. After a spacecraft acoustic test, performance of the ion thrusters was reverified by removing the TGBSUs for a thorough performance test at Hughes Research Laboratories (HRL). The TGBSUs were then reinstalled on the spacecraft. The IAPS Flight Package is ready for flight testing when Shuttle flights resume.

SECTION 1

INTRODUCTION

Typical uses for spacecraft auxiliary propulsion include:

- Stationkeeping (North-South and East-West)
- Station change
- Atmospheric drag makeup in low orbit
- Attitude control (both direct and by momentum wheel dumping).

Of these applications, one of the most demanding is the long-term North-South stationkeeping (NSSK) for advanced communication satellites in geostationary orbit. North-South stationkeeping requires low average thrust but high total impulse. These requirements are uniquely matched by the characteristics of ion thrusters. The weight saving offered by the high specific impulse of an ion propulsion system can provide significant economic benefits when applied to NSSK. The Ion Auxiliary Propulsion System (IAPS) program is intended to demonstrate that ion propulsion is ready to provide these benefits. Under this contract, IAPS has been developed, flight qualified, and integrated on the Air Force technology satellite P888 in preparation for a flight test. IAPS is ready for flight testing when Shuttle flights resume.

The mission model for the IAPS flight test is based on providing stationkeeping of a 1000-kg geostationary satellite for seven years with four body-mounted 8-cm-diameter thrusters canted at 45 deg to North-South and fired in pairs once per day. This mission imposes a flight test requirement of 2,557 cycles of 2.76 h of thrusting per cycle for a total thrusting time of 7,055 h. With 2 h for startup and cooldown per cycle, a minimum of 507 days is needed to achieve the required thrust duration and number of cycles. Because the mission model also requires simultaneous dual thruster operation, the IAPS Flight Package incorporates two thruster systems, oriented at 90 deg to each other.

The critical performance parameters which will be measured during the flight test are thrust, specific impulse, and total system input power. These parameters and thruster system reliability will be evaluated as a function of operating time and thrust cycles. Any effects on performance resulting from dual thruster operation will also be determined. In addition, thruster operation will be demonstrated in a number of alternative operating modes of potential importance to users.

SECTION 2

SYSTEM DESCRIPTION

The IAPS flight package consists of two Thruster Subsystems (TSS) and a Diagnostic Subsystem (DSS). Each TSS consists of the same units: a Thruster-Gimbal-Beam Shield Unit (TGBSU); a Power Electronics Unit (PEU); a Digital Controller and Interface Unit (DCIU); and a Propellant Tank, Valve, and Feed Unit (PTVFU). The units of a TSS are shown in Figure 1. Each thruster subsystem is mounted in a module that attaches to the surface of the spacecraft. TSS No. 1 is mounted in the "-Z" (zenith) module (Figure 2) which in orbit has the thruster pointing outward away from the Earth. TSS No. 2 is mounted in the "-X" or Ram/Wake module (Figure 3) in which the thruster alternately points along or opposite to the spacecraft velocity vector. The electronics units of the diagnostic subsystem are in the -Z module, and the sensors are distributed between the two modules as shown in Figures 2 and 3. The location of the IAPS modules on the spacecraft is shown in Figure 4. Each of the IAPS thruster subsystems weighs 27.4 kg, and the diagnostic subsystem weighs 29.0 kg for a total IAPS Flight Package weight of 83.7 kg (including 17.3 kg of mercury). Weights and dimensions of the individual units are presented in the following sections.

2.1 THRUSTER SUBSYSTEM

The IAPS thruster subsystem is based on an engineering model (EM) thruster system developed under NASA Contract NAS 3-18917. The EM thruster system is comprised of an 8-cm diameter mercury electron-bombardment ion thruster mounted on a gimbal, a PEU, a Digital Interface Unit (DIU) and a propellant tank with associated feedline. Five major modifications to the EM system were incorporated during the development of IAPS:

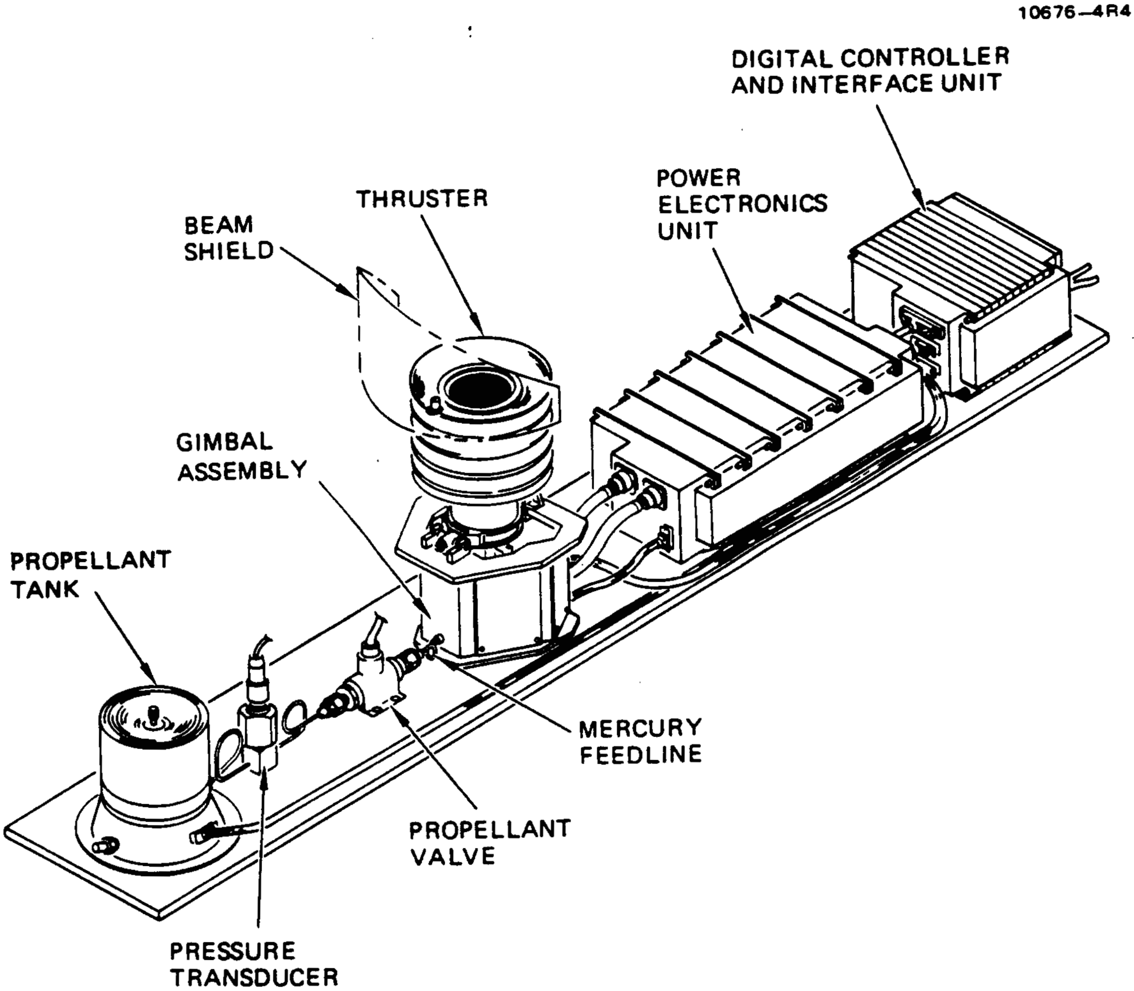

Figure 1. Units of Thruster subsystem.

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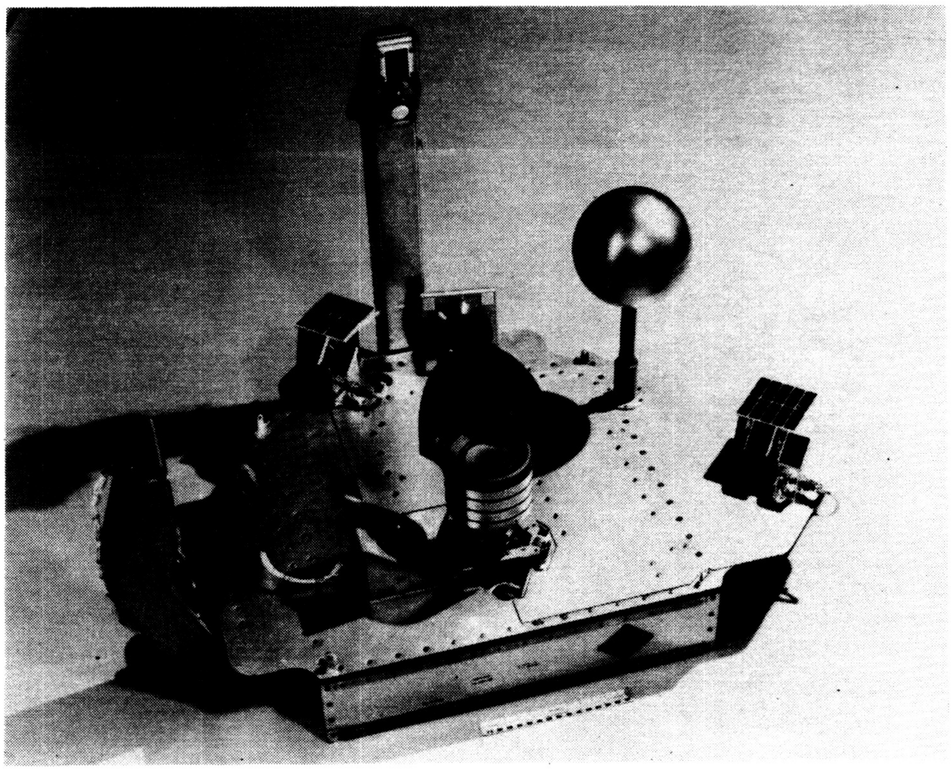

Figure 2. IAPS -Z Module.

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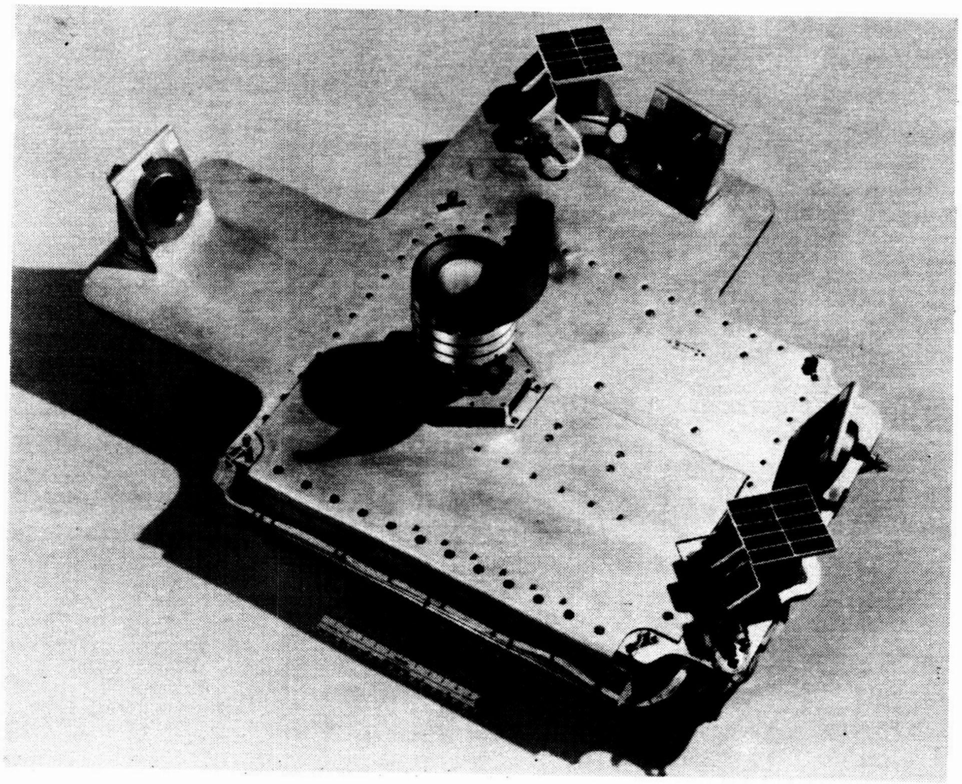

Figure 3. IAPS -X Module.

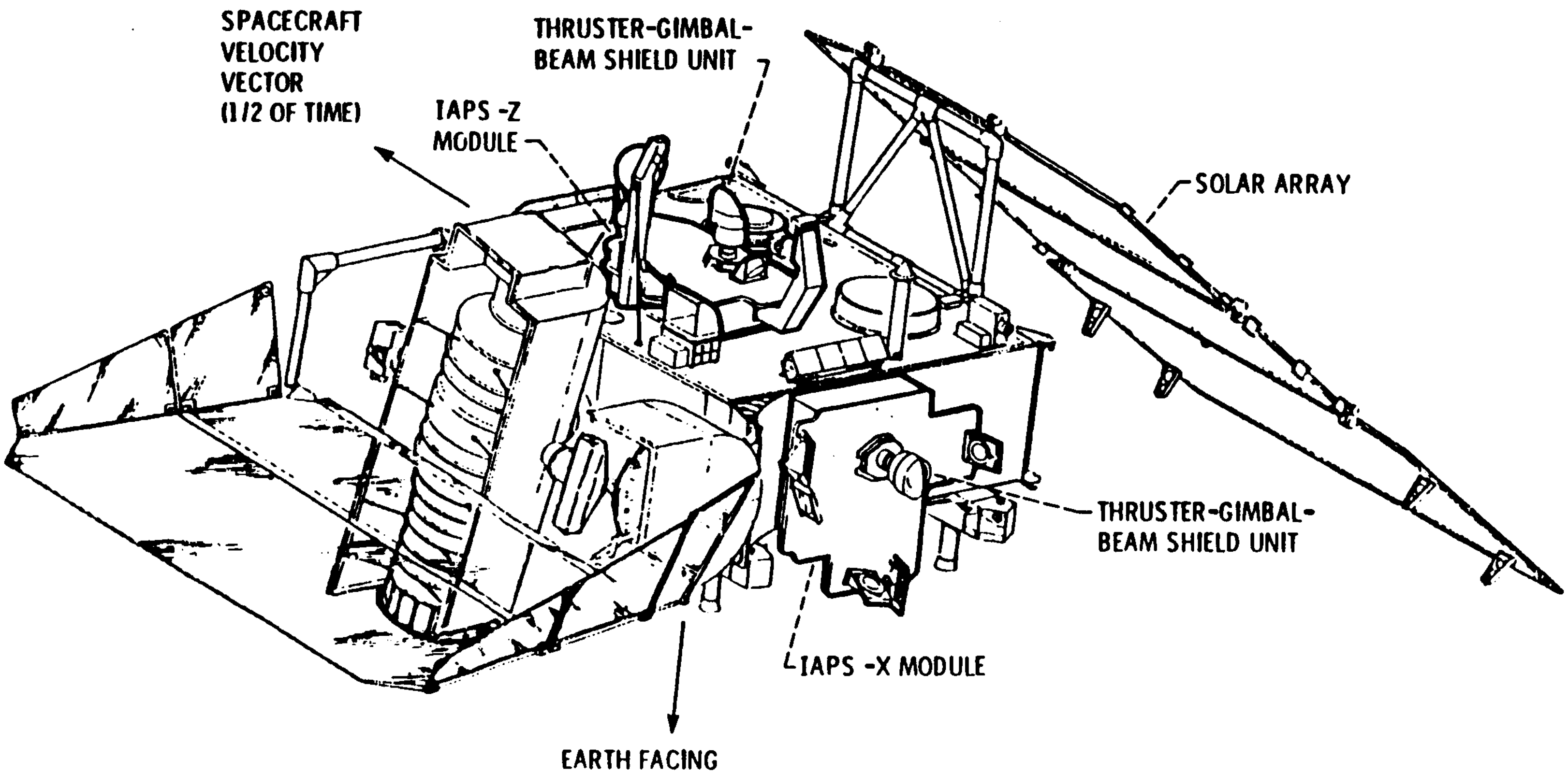

Figure 4. Location of IAPS modules on spacecraft.

1. An asymmetric beam shield was added to the thruster as a consequence of the mission model specification of body-mounted thrusters canted at 45 deg to North-South. This shield serves to protect spacecraft solar arrays or other sensitive surfaces downstream of the thruster grid plane from thruster efflux. The beam shields are not required for the planned IAPS flight test mission, but were included so that their effect on thruster efflux can be verified.

2. A neutralizer switch was added in the thruster grounding circuit to permit operation with the neutralizer common either floating or shorted to spacecraft ground, since users may require either configuration.

3. The cathode inserts in the thrusters were changed from rolled tantalum foil sprayed with an emissive mix to porous tungsten cylinders impregnated with an emissive mix.

4. A commandable latching valve was incorporated in the propellant feedline from the mercury reservoir to provide a second means of containment of the mercury during launch of the spacecraft. (The vaporizer is also able to contain the liquid mercury.)

5. The engineering model DIU was replaced with a Digital Controller and Interface Unit (DCIU) to provide flexible, self-contained, automatic programmed control of all thruster system operating modes. The DCIU also makes possible a simple spacecraft/thruster subsystem interface.

Each of the TSS units is described in the paragraphs that follow.

2.1.1 Thruster-Gimbal-Beam Shield Unit

The prime function of the Thruster-Gimbal-Beam Shield Unit (TGBSU) is to convert electrical energy and liquid propellant flow into a directed thrust by the production of a high velocity beam of mercury ions. The expelled ion beam is electrically "neutralized" by the injection of electrons into the beam from a plasma-bridge neutralizer which is included in the thruster. The TGBSU consists of three parts: the 8-cm mercury-fed ion thruster, which generates 5 mN (1.1 mlb) of thrust; the gimbal assembly, which provides the mechanical capability to adjust the direction of the thrust vector at least 10 deg in any azimuthal direction; and the beam shield, which controls the emission of undesirable off-axis particles in a limited direction. Performance characteristics and physical dimensions of the TGBSU are presented in Figure 5.

2.1.2 Power Electronics Unit

The PEU processes the spacecraft +70-V bus power into the various voltages and currents that are required by the IAPS ion thruster. There are eleven power supplies within the PEU. Four of the supplies provide ac power for the resistance heaters in the thruster, two cathode heaters, and two vaporizer heaters. Two supplies provide a high level ignition voltage and two additional supplies provide low level operating voltages for the discharge cathode keeper and neutralizer cathode keeper. The remaining three supplies generate the discharge voltage for the anode and the ion accelerating voltages for the screen and accelerator electrodes. Analog control signals for those PEU power supplies which produce variable outputs are supplied by the DCIU. The PEU itself provides the high speed analog control required for regulation and self-protection. Analog outputs, representative of the PEU output voltages and currents, are sent to the DCIU as feedback for the power supply control circuits and for generating telemetry outputs.

A PEU is about 39 cm long, 20 cm wide, 11 cm high, and weighs 7.5 kg.

2.1.3 Digital Controller and Interface Unit

Because the Digital Interface Unit of the engineering model TSS did not have the required autonomous control capability, it was necessary to develop a DCIU under this program. The DCIU includes the circuits from the EM DIU that were applicable to the DCIU design requirements. The primary purpose of the DCIU is to

TGBSU SUMMARY SPECIFICATIONS

Parameter	Value
Thrust level	5 mN (1.1 mlb)
Specific impulse (nominal)	2500 sec.
Thruster input power	130 W
Gimbal input power	14 W
Thrust deflection angle	0 to 10 deg
Mass	3.8 kg
Size	
Length	524 mm
Diameter of ground screen	170 mm
Radius of beam shield	127 mm
Gimbal base	165 x 173 mm

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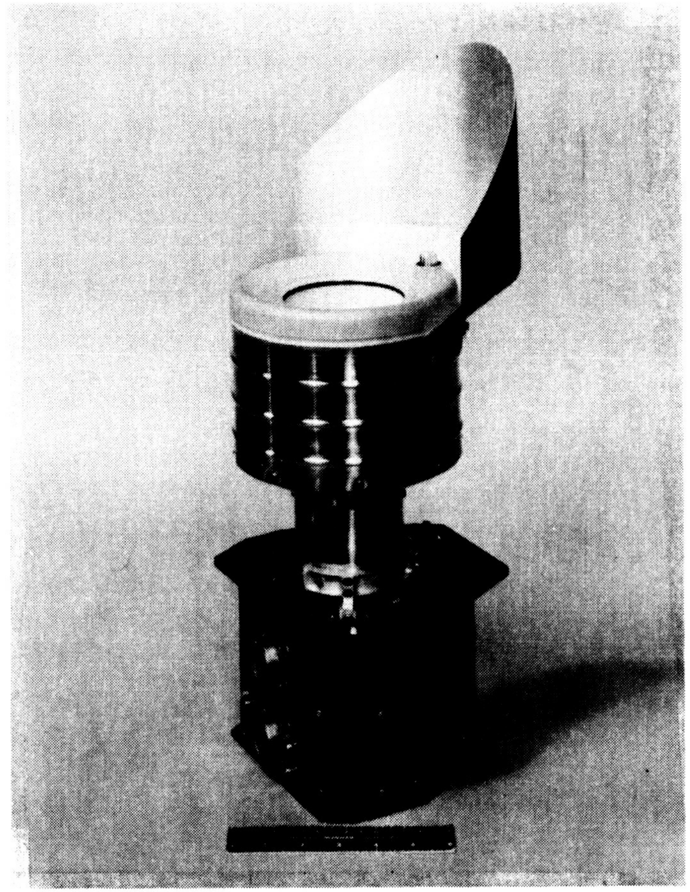

Figure 5. Performance characteristics and dimensions of the Thruster-Gimbal-Beam Shield Unit.

provide automatic control for in-flight operation of the Thruster Subsystem. The thruster is controlled by a microprocessor control system, which uses algorithms stored in its ROM and system-status information supplied from the PEU, to generate the appropriate PEU power supply control signals.

A number of thruster operating modes or stable conditions are accommodated by the firmware program in the DCIU. The ten operational states and the permitted transitions between states are shown in Figure 6. (Each state has a legal transition to OFF which is omitted for clarity.) The DCIU program has routines for recovering from a large number of minor abnormal conditions without intervention from external control, and it also includes a monitor which checks operating conditions once per second for existence of conditions requiring application of these routines. The philosophy of operation is that the DCIU logic protects in every case against situations which could be detrimental to the thruster or spacecraft and, if necessary, shuts down the system and waits for ground operator intervention.

The orbit of the IAPS spacecraft is such that the DCIU must accommodate two conditions that would not be encountered in geosynchronous orbit applications: (1) a wide range of thermal conditions resulting from eclipses and orientation of the solar array with respect to the spacecraft, and (2) the necessity of operating most of the time out of contact with the ground tracking stations. As a consequence of satisfying these special requirements, the IAPS DCIU is also capable of satisfying the requirements that would exist for most other mission applications.

A second function of the DCIU is to provide a simple electrical interface between the IAPS thruster subsytem and the spacecraft. All power to the TSS and all other electrical signals to and from the TSS are routed through the DCIU via one power and two signal cables.

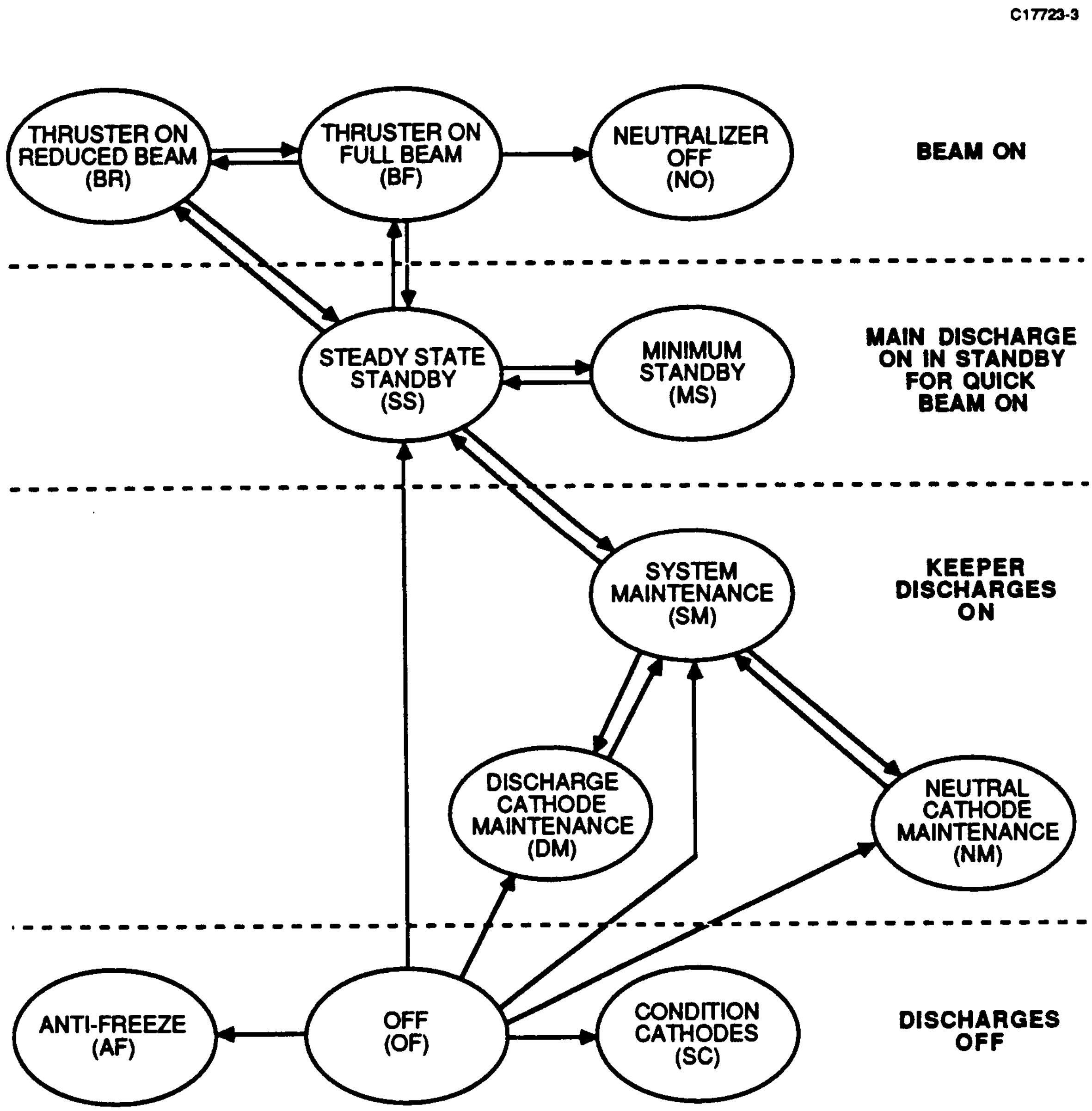

Figure 6. IAPS preprogrammed operational states and allowed interstate transitions.

Two types of commands are sent to the DCIU from the spacecraft: discrete commands and serial magnitude commands. Serial magnitude commands are provided to the DCIU in the form of a 16-bit command word. These commands execute a variety of functions, the prime one being to initiate the transition to one of the various stable thruster operating states shown in Figure 6. Other actions controlled with serial magnitude commands include selection of preset operating points for PEU power supplies that have adjustable outputs, execution of gimbal operation, loading of data into RAM for use in the automatic sequences, and adjustment of a number of operational constraints or permissive limits. The two functions controlled with discrete commands are propellant valve operation and neutralizer switch operation.

All information that is available concerning the operating status of the IAPS TSS comes from telemetry that is generated or processed in the DCIU. TSS telemetry consists of 32 eight-bit words, sampled once every 32 sec, and three bilevel and two analog signals, sampled once per sec. The 32 eight-bit words contain data from the PEU (e.g., power supply output voltages and currents) which have been converted to digital form in the DCIU, and other digital information generated in the DCIU such as mode status flags. In the spacecraft, the telemetry is recorded on an on-board tape recorder and is also available for real time transmission when the spacecraft is in contact with a ground station.

A DCIU is about 24 cm long, 24 cm wide, 12 cm high, and weighs 3.7 kg.

2.1.4 Propellant Tank, Valve, and Feed Unit

The mercury propellant used by each TSS is contained in a spherical reservoir under a positive expulsion pressure of 35 psia. The pressure is provided by compressed nitrogen gas which occupies about one-half the volume of the reservoir. The

GN_2/Hg interface is maintained by a flexible Butyl rubber bladder which moves as the mercury is expelled. The initial load of mercury in each reservoir (8.65 kg) is sufficient to provide ~11,000 h of nominal full-beam (72 mA) thruster operation. The PTVFU includes a latching solenoid valve to isolate the reservoir from the thruster, a sensor to monitor reservoir temperature, a pressure sensor in the feedline upstream of the valve to monitor the mercury pressure, and a valve for introducing the GN_2 pressurant.

A PTVFU weighs 10.18 kg (including 8.65 kg of Hg). The mercury reservoir is about 13 cm in diameter and 17 cm high.

2.2 DIAGNOSTIC SUBSYSTEM

A secondary objective of the IAPS flight test is to determine the field and particle interactions between the ion thrusters and the spacecraft. The measurement of thruster/spacecraft interactions includes: (1) deposition of volatiles (e.g., mercury) and nonvolatiles (e.g., molybdemun), (2) ion and electron fluxes received by the spacecraft surfaces, and (3) spacecraft potential as controlled by thruster operation. For this reason a diagnostic subsystem is included as part of the IAPS flight package. The IAPS Diagnostic Subsystem is designed to quantify the deposition of thruster efflux material deposition in the vicinity of the two ion thrusters and measure the spacecraft electrical potential with respect to the ambient plasma. The DSS is comprised of two quartz crystal microbalance (QCM) detectors, nine solar cell detectors, seven ion collectors, a potential probe, a Diagnostic Subsystem Control Unit (DSSCU), and a QCM electronics unit. Most of the detectors are clustered around the thrusters on 60-cm radii (see Figures 2 and 3). Though the ion thrusters are not scheduled to be operated for up to a year after the spacecraft is in orbit, the DSS detectors are to be activated soon after launch to establish a reference data base before the thrusters are operated.

The DSSCU is about 44.5 cm long, 21.6 cm wide, 17.0 cm high, and weighs 9.4 kg. The QCM electronics unit is approximately 18.8 cm long, 17.5 cm wide, 15 cm high, and weighs 2.8 kg.

2.2.1 Ion Collectors

The ion collector detectors will measure the ions that emanate from the mercury ion thrusters. The ion collectors are also sensitive to the ambient environmental ion flux. The data received from these devices will enable us to determine the number and energy levels of arriving ions, and their location relative to the thruster. The ion collector grid potentials are selected to exclude electrons and also to reflect secondary electrons from the collecting plate. The biasing grid can be commanded to one of four voltages (0, 25, 55, and 96 V) to allow determination of the ion energy levels. The full-scale current range will automatically switch, in one decade steps, from 10^{-3} to 10^{-8} A, depending on the number of ions present.

2.2.2 Quartz Crystal Microbalance

The Quartz Crystal Microbalance (QCM) package is composed of two temperature-controlled detectors and a separate electronics unit. The QCM detectors measure the mass of condensable material that is retained at 25°C on the exposed surface of one of the two oscillating quartz crystals in each detector. The mass of the deposited material causes a shift in the beat frequency between the two crystals. The beat frequency range is from 2 to 65 kHz, which is transmitted in two 8-bit telemetry words, the least significant half (2^0 to 2^7) in one and the most significant half (2^8 to 2^{15}) in the second.

2.2.3 Potential Probe

The potential probe device will enable us to measure the electric potential of the spacecraft with respect to the surrounding plasma. The potential sensor consists of a precision current source connected to a spherical electrode that is electrically isolated from the spacecraft. The current that will flow to the probe from the surrounding plasma is commanded to be one of 16 preset values ranging from 1 to 5 mA. The voltage applied to the probe varies between -25 and +205 V as necessary to produce the commanded current. The probe is a 24.2-cm-diameter gold-plated hollow aluminum sphere mounted 26.5 cm above the -Z module surface on a fiberglass post. The surface of the probe is a minimum of 25 cm from any conductive surface.

2.2.4 Solar Cell Detectors

The solar cell detectors are devices for measuring the potential effect on satellite solar array performance caused by the efflux from mercury ion thrusters. The solar cell detectors are mounted in locations that are representative of several different regions of effluxes from the thrusters. Five of the solar cell detectors are maintained at warm temperatures (within 10°C of the spacecraft structure) by heat sinking them to the spacecraft structure. Four are maintained at cool temperatures by thermally isolating them and attaching a thermal radiator. The purpose of the temperature difference is to provide a means of determining the direct effect of mercury deposition. A portion of any mercury impinging upon a cool detector may be retained, but warm detectors are not expected to retain a significant amount of mercury. Deposition on the detectors is determined by measuring the decrease of current through a 1-Ω resistor that is in series with the output of each detector.

2.2.5 Diagnostic Subsystem Control Unit

The Diagnostic Subsystem Control Unit (DSSCU) contains the electronics for the ion collectors, solar cell detectors, and potential probe. It receives and processes the commands for the

Diagnostic Subsystem and generates all of the DSS telemetry information that is sampled by the spacecraft and either stored on a tape recorder or transmitted to the ground in real time. The DSS requires only a single serial magnitude command and eight discrete commands. The serial magnitude command selects one of sixteen potential probe current setpoints and one of four ion collector grid voltage setpoints which are common to all seven ion collectors. The discrete commands turn ON and OFF the ion collectors, solar cell detectors, potential sensor and QCMs. DSS telemetry consists of 128 eight-bit words (64 redundant pairs) sampled once every 16 sec, plus four analog and two bilevel signals which are sampled once a second.

SECTION 3

IAPS TESTS

During the course of this program, the IAPS flight units were extensively tested. Testing included in-process tests during fabrication and assembly, individual unit-qualification tests, subsystem tests, and tests conducted on the spacecraft that will carry IAPS into orbit for the flight test. The unit-level and subsystem tests are well documented in a series of individual test reports that are listed in Section 5. Figure 7 presents an overview of the test sequence of the IAPS flight hardware. The tests shown in Figure 7 are described below.

3.1 UNIT QUALIFICATION TESTS

Performance, vibration, and thermal requirements for the IAPS units were defined in a test specification for each unit. Many of the requirements in the unit-test specifications were established by the IAPS-Spacecraft interface control document (ICD), which was produced by the spacecraft contractor. Tests to verify compliance with the test specification requirements were defined in formal test procedures prepared for each unit. As assembly of each unit was completed, the unit was subjected to a standard performance accceptance test (PAT) to verify that it satisfied the performance requirements of the test specification. This initial data base was also used for comparison during the remainder of the flight qualification cycle. After each environmental test (e.g., vibration), the same PAT was repeated and the results were used to determine if the environmental exposure had altered the unit performance. The sequence of qualification tests for the TGBSU shown in Figure 8 is representative of the testing of all IAPS units. After each unit successfully completed its qualification tests, a unit test report was prepared and submitted to NASA. The test specifications, test procedures, and test reports for each IAPS unit are listed in Section 7.

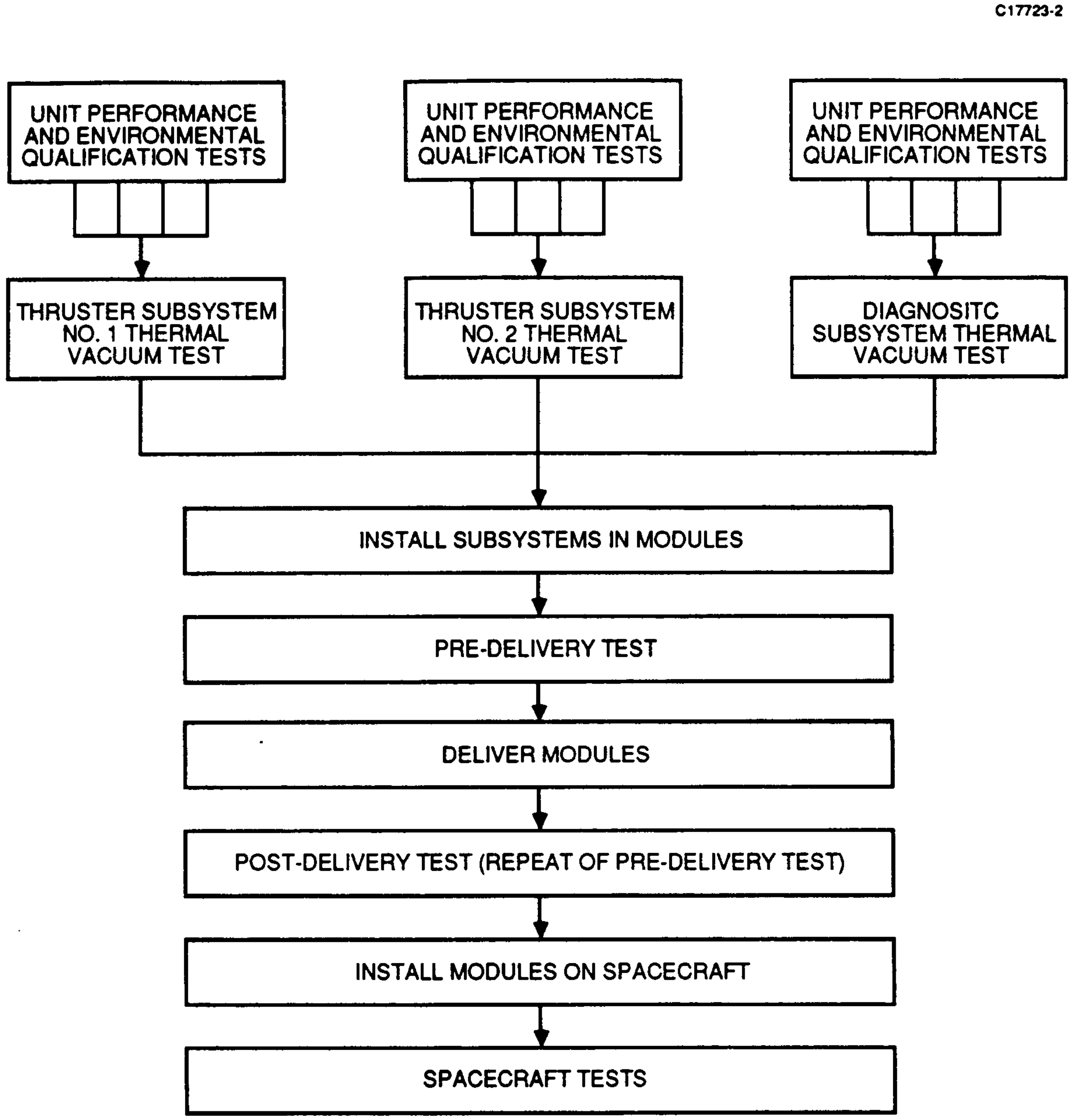

Figure 7. Overview of IAPS qualification test sequence.

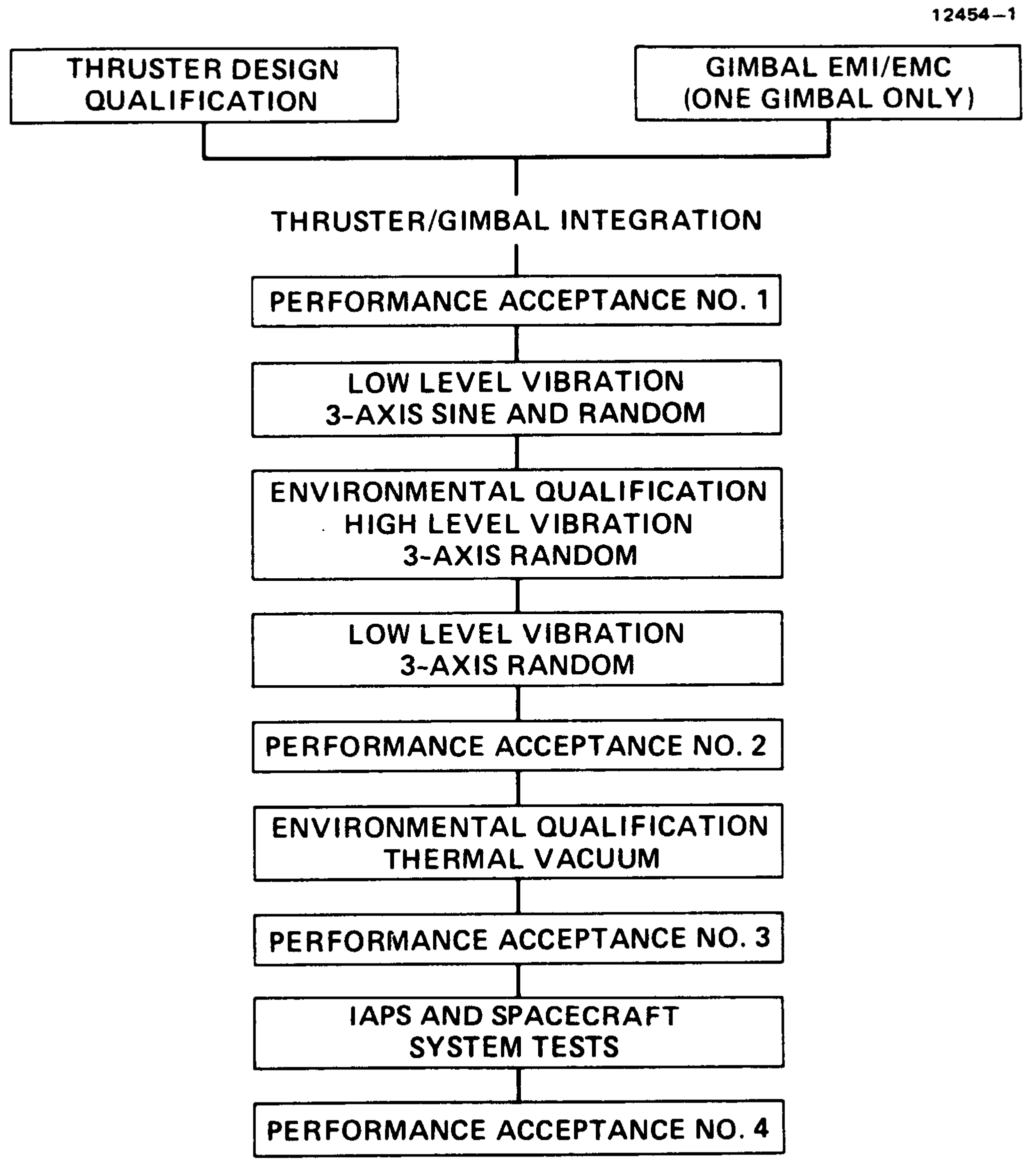

Figure 8. IAPS unit qualification test sequence.

3.1.1 Thruster-Gimbal-Beam Shield Unit Tests

The TGBSU unit test sequence description that follows is illustrative of the unit testing approach used for all of the individual IAPS units. However, the TGBSU, being a nonelectronics unit, was not subjected to thermal cycling at ambient pressure as were the IAPS electronics units. Detailed procedures and results from the TGBSU unit tests described below can be found in the FTR-100 report for each TGBSU.

The first unit test for each thruster was a design qualification test performed before the thruster was integrated with the gimbal to form a TGBSU. Testing the thruster before attachment to the gimbal permitted measurement of the individual mercury propellant flows to the discharge chamber and the neutralizer. When the thruster is integrated with the gimbal, both cathodes are fed from a common manifold. The thruster design qualification test consisted of: (1) resistance measurements to verify the electrical integrity prior to initial application of power, (2) cathode conditioning, (3) initial beam extraction followed by a 30-min operation at the nominal operating point for thermal stabilization of the feedlines, (4) electrical and propellant flow data recording every 5 min for 1 h, and (5) a scan of the beam with an ExB probe to gather data for calculating thrust loss resulting from beam divergence and doubly ionized propellant ions.

One of the gimbals was also subjected to a test before being integrated with the thruster. The initial post-production gimbal test was an EMI/EMC test using selected sections of MIL-STD-461A.

Following integration of the thruster and gimbal, the first of the standard performance acceptance tests (PAT) was performed on each TGBSU. Included in the PAT were the following test elements: (1) a gimbal test that documented the number of drive counts required to move switches from the zero position to the limit and back to return to the zero position, and that determined the angular position when the limit switches were activated;

(2) a thruster test consisting of 30 min of stable operation at the nominal operating point, 20 min of performance data at five additional operating points with specified discharge voltages above and below the nominal value, 1 h of performance data at the nominal operating point, and then a beam scan with an ExB probe.

The first PAT was followed by the vibration qualification test, the first of the environmental tests. Vibration testing included four phases, with each phase consisting of a different vibration profile being applied along the same three orthogonal axes. These four phases were (1) a low level [1g] sine sweep to determine amplification factors and resonance modes, (2) a low level random vibration [$0.001g^2/H_z$], (3) a qualification level random vibration at 3 dB above the predicted Shuttle launch vibration level (see Figure 9), and (4) a repeat of the low level random test. Data from the first and second low level random runs were compared to see if the qualification level random exposure had altered the TGBSU response to the second low level random vibration. A difference would indicate a change in the mechanical condition of the TGBSU because of the qualification level random vibration.

Vibration testing was immediately followed by the second PAT, which verified that thruster and gimbal performance had not been altered by the vibration test. The second PAT was performed with the TGBSU mounted on a test fixture with a temperature-controlled baseplate and a solar simulator so that the PAT could be followed by the thermal-vacuum test without breaking vacuum.

The thermal-vacuum test was designed to verify proper operation of the TGBSU in an environment that exceeded by 10°C the maximum and minimum temperatures specified in the IAPS-Spacecraft interface control document for on-orbit operation. Three thermal cycles were run with the thermal profiles shown in Figure 10. After the first 3 h of each hot soak, the solar simulator was turned ON. The thruster was turned ON at the end

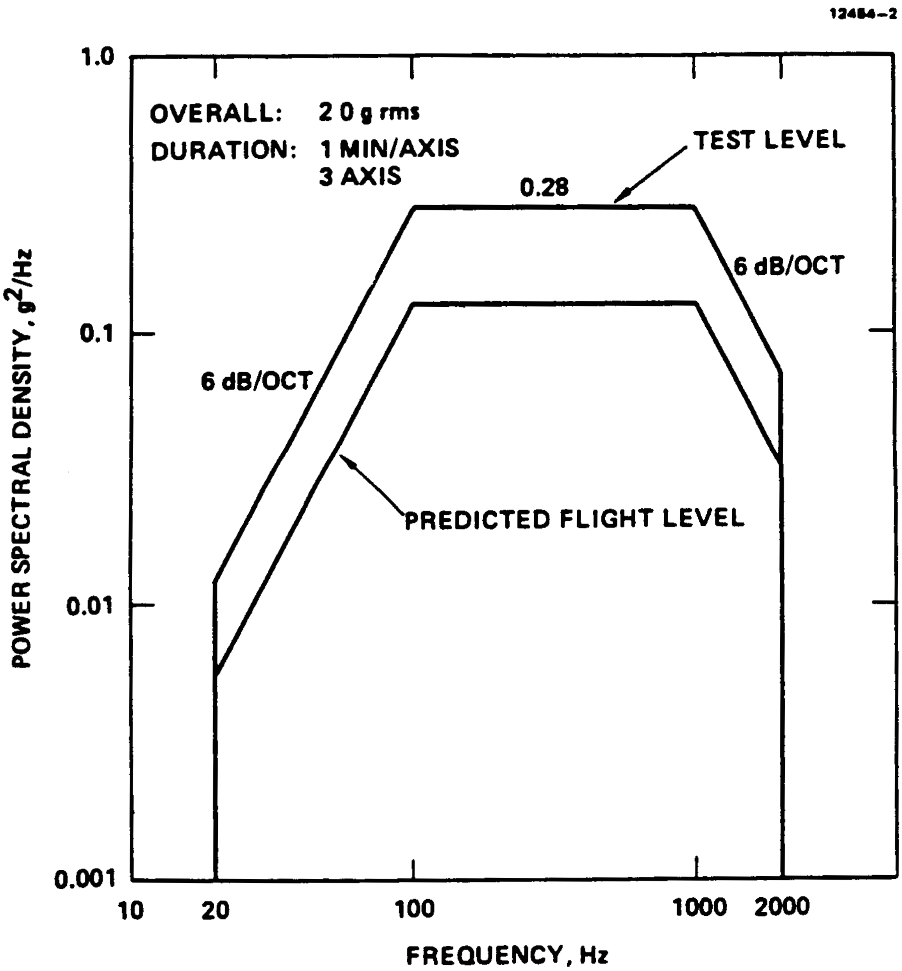

Figure 9. TGBSU qualification level random vibration profile.

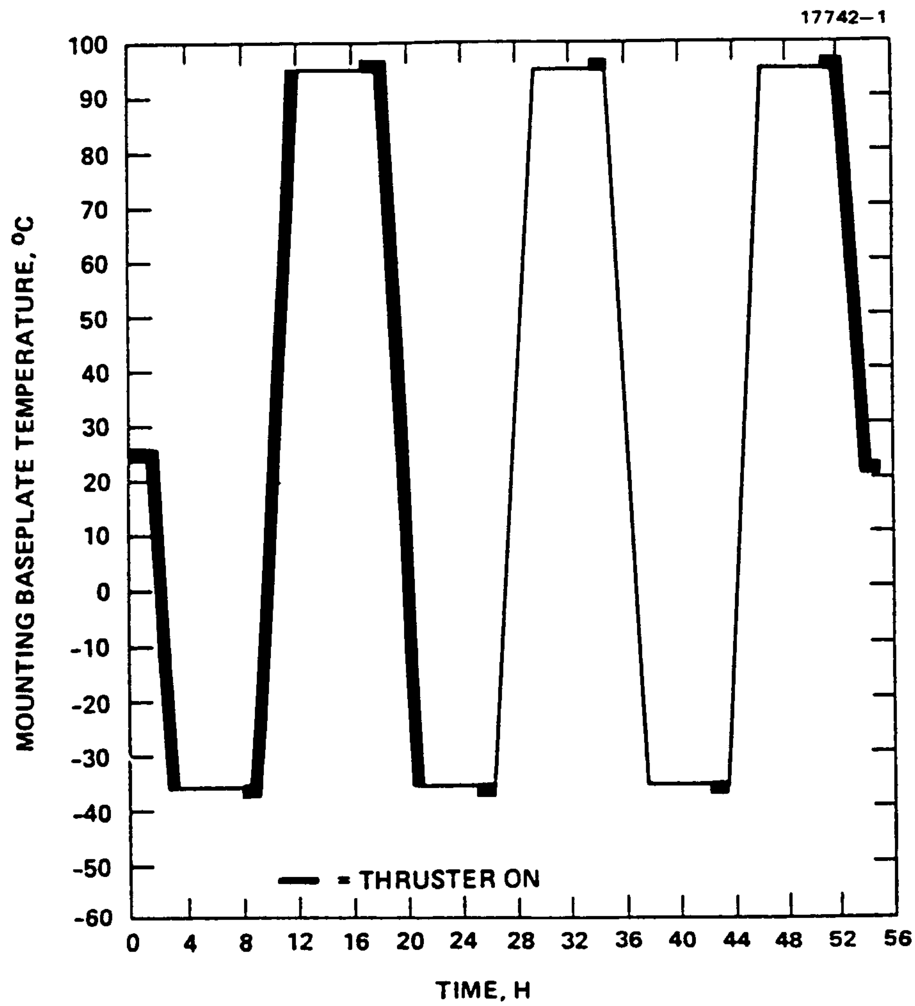

Figure 10. Thermal profile used during the TGBSU thermal-vacuum test.

of each 4 h cold and hot soak, and electrical performance and propellant usage data were taken for 1 h. Thruster performance data were also gathered during both the cold and hot transitions of the first cycle, and during the hot-to-ambient transition of the last cycle. Thruster ignition and operation were unaffected by any of the temperature variations during the thermal-vacuum test.

At the conclusion of the thermal-vacuum test, PAT No. 3 was performed without breaking vacuum. The data from PAT No. 3 confirmed that thermal-vacuum testing had not altered the performance of the thrusters.

After the third PAT, each TGBSU was combined with the designated PEU, DCIU, and PTVFU to form one of the two IAPS thruster subsystems (TSS). Each TSS was then subjected to the subsystem operational and thermal-vacuum testing described in Section 3.2. The two TGBSUs were later put through one more unit test – a performance reevaluation test conducted near the end of the IAPS-Spacecraft integration testing. This final PAT was conducted to verify the performance of the units after they had not been operated for three years. During this time they had been on the spacecraft for more than two-and-a-half years of spacecraft integration testing, including acoustic testing at 3 dB above the Shuttle launch environment. During spacecraft integration testing, operation of the TSS electronic units was periodically verified, but the thrusters could not be tested because of the test environment (atmospheric rather than vacuum). Therefore, the performance reevaluation test described in Section 3.3 was performed.

3.2 SUBSYSTEM QUALIFICATION TESTS

Subsystem qualification tests followed the unit qualification tests described in the preceding section. Each of the three subsystems (2 TSSs and the DSS) that combine to form the IAPS Flight Package were individually tested before being mounted on the modules to form a complete system.

3.2.1 Thruster Subsystem Tests

Both of the thruster subsystems were subjected to identical performance and thermal-vacuum tests at HRL. A test specification and a test procedure were written (and approved by NASA) for the TSS test. The thruster subsystem test consisted of the following segments:

(1) Electrical isolation tests to verify isolation between the various types of grounds (e.g., power returns, signal grounds, chassis ground).

(2) Gimbal tests to measure the range and repeatability of motion of the gimbal and operation of the limit switches.

(3) A command verification and telemetry calibration test. With the PEU power outputs connected to a PEU load box, command verification and telemetry calibration were achieved simultaneously. Commands were issued to step through the various PEU power supply setpoints while both the DCIU telemetry outputs and the voltages and currents at the load box test points were recorded. System response to discrete commands (e.g., Neutralizer Switch ON) and mode-transition commands (i.e., OFF to Full Beam) were also verified.

(4) The above parts of the TSS test were performed before the subsystem was placed in the vacuum chamber. Once the TSS was installed in the vacuum chamber and properly outgassed, system conditioning was initiated – which consisted of the cathode conditioning routine that is included in the DCIU firmware – followed by 20 h in the system maintenance mode. Operational testing under vacuum conditions included four phases: a performance acceptance test, a three-cycle thermal-vacuum test, a repeat of the PAT, and a performance parameter mapping test. Each of these test phases is described briefly below.

(a) The performance acceptance test began with 1 h of full beam operation at nominal bus voltage to establish a set of baseline performance parameters for comparison with later data taken during the TSS test. This was followed by operation at full beam with the neutralizer switch closed, and at high and low bus voltages. Performance data for each of these bus voltage conditions were verified to agree within 5% of the original baseline data.

(b) The thermal-vacuum test consisted of three cycles having identical thermal profiles. Figure 11 shows the temperature profiles and bus voltage values for the thermal-vacuum test. Each cycle included a 4-h nonoperating cold soak and a 4-h nonoperating hot soak. Each hot soak was followed by 2 h at the hot operating temperature, with a solar simulator illuminating the thruster. To increase the number of operating conditions tested, system operation was varied from cycle to cycle. Operating conditions for each sequence event of the three thermal cycles are given in Table 1. During the last cold-to-hot transition and the last hot-to-cold transition, the 37 operating mode transitions shown in Table 2 were performed. (Descriptions of each of the modes listed in the operating mode transition table are given in Table 3.) The first set of operating mode transitions were performed with valid temperature feedback from the thruster vaporizer temperature sensors; during the second transitions the DCIU firmware was commanded to operate with "failed vaporizer temperature sensors." During the thermal-vacuum testing, there was no evidence of adverse effects on the performance of either TSS.

(c) Following the post-thermal-vacuum PAT, system performance was documented, as several electrical parameters were varied. These parameters and their range of variation are presented in Table 4.

The Thruster Subsystem tests described above will be the last time the TSS units will be tested together as a complete subsystem prior to operation in orbit. During spacecraft integration testing, the electronic units were tested numerous times, as described in Section 4. However, during all spacecraft testing the thrusters were disconnected from the PEU power outputs and resistive load boxes were substituted. The thrusters were performance-tested one time after the TSS testing (during the thruster reevaluation test described in Section 3.3).

3.2.2 Diagnostic Subsystem Tests

The Diagnostic Subsystem underwent a series of tests similiar to those conducted on the two Thruster Subsystems. Two additional tests were performed on the DSS that were not

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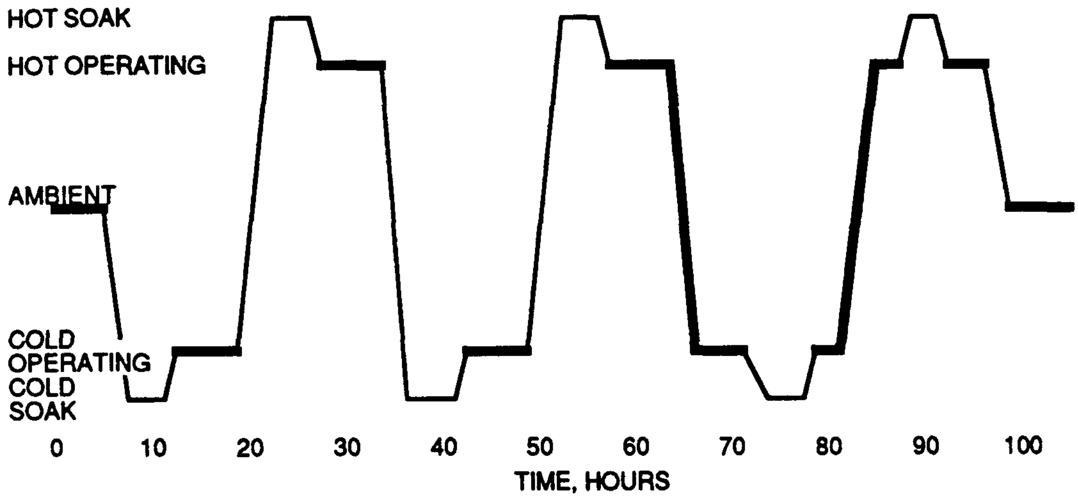

BUS VOLTAGES		
	28 V BUS	70 V BUS
HIGH	34	90
NOM	28	70
LOW	22	52

TEMPERATURE, °C					
UNIT	SOAK		OPERATION		
	COLD	HOT	COLD	AMB.	HOT
TGBSU	-36	95	-36	23	95
PEU/DCIU	-50	80	-30	23	60
PTVFU	-36	80	-36	23	70

NOTES:

SOAK TIMES ARE 4 HOURS MINIMUM.

HOT AND COLD OPERATING TEMPERATURES ARE MAINTAINED FOR 2 HOURS AFTER SOAK PERIODS BEFORE TURNING ON THE PEU OR DCIU.

THE SUN SIMULATOR IS TURNED ON 2 HOURS BEFORE STARTING THE THRUSTER FOR HOT OPERATION.

HEAVY LINES INDICATE SYSTEM OPERATING.

Figure 11. Thermal profile used during the Thruster Subsystem thermal-vacuum test.

TABLE 1. **Test Sequence Used During the Thruster Subsystem (TSS) Test.**

Sequence Event No.	Test Description	Temperature	Bus Voltage	Remarks
1	Electrical Isolation Tests, Ambient Conditions	Ambient	Off	Document Separation of Grounds
2	Gimbal Test, Ambient Conditions	Ambient	Nominal	Document Operation of Gimbals (part of PAT)
3	Command Verification Tests, Ambient Conditions	Ambient	Nominal	Document Operation of All Supplies and TLM Calibration
4	OFBF, Good RTDs, Nominal Bus	Ambient	Nominal	Document Nominal Start-up and Operaiton (part of PAT)
5	Neutralizer Switch Test	Ambient	Nominal	Document Operation of Neutralizer Switch (part of PAT)
6	OFBF, Good RTDs, High Bus	Ambient	High	Document Startup and Operation (part of PAT)
7	OFBF, Good RTDs, Low Bus	Ambient	Low	Document Startup and Operation (part of PAT)
8	Cold Transition	Ambient to Cold Soak	Off	Start of First Thermal Cycle
9	Cold Soak	Cold Soak	Off	Nonoperating 4 h Cold Soak
10	OFBF, Good RTDs, BF for 2 h	Cold	Nominal	Document Start and Operation
11	OFBF, Good RTDs	Cold	Nominal	Document Startup and Operation After 1 h Off
12	Hot Transition	Cold to Hot Soak	Off	
13	Hot Soak	Hot Soak	Off	Nonoperating 4 h Hot Soak
14	OFBF, Good RTDs, BF for 2 h	Hot	Nominal	Document Startup and Operation
15	OFBF, Good RTDs	Hot	Nominal	Document Startup and Operation After 1 h Off

(continued on next page)

Sequence Event No.	Test Description	Temperature	Bus Voltage	Remarks
16	Cold Transition	Hot to Cold Soak	Off	
17	Cold Soak	Cold Soak	Off	Nonoperating 4 h Cold Soak
18	OFBF, Failed RTDs, BF for 2 h	Cold	High	Document Startup and Operation
19	OFBF, Failed RTDs	Cold	High	Document Startup and Operation After 1 h Off
20	Hot Transition, Thruster Off	Cold to Hot Soak	Off	
21	Hot Soak	Hot Soak	Off	Nonoperating 4 h Hot Soak
22	OFBF, Failed RTDs, BF for 2 h	Hot	Low	Document Startup and Operation
23	OFBF, Failed RTDs	Hot	Low	Document Startup and Operation After 1 h Off
24	Cold Transition, Failed RTDs Transitions of Table 2	Hot to Cold	Low	Document Operational Stability During Transition
25	Cold Soak	Cold Soak	Off	Nonoperating 4 h Cold Soak
26	OFSM, Good RTDs	Cold	High	Document Transition
27	SMSS, Good RTDs	Cold	High	Document Transition
28	SSBF, Good RTDs	Cold	High	Document Transition
29	Hot Transition, Good RTDs, Transitions of Table 2	Cold to Hot	High	Document Operational Stability During Transition
30	Hot Soak	Hot Soak	Off	Nonoperating 4 h Hot Soak
31	OFSM, Good RTDs	Hot	Low	Document Transition
32	SMSS, Good RTDs	Hot	Low	Document Transition

(continued on next page)

Sequence Event No.	Test Description	Temperature	Bus Voltage	Remarks
33	SSBF, Good RTDs	Hot	Low	Document Transition
34	Ambient Transition	Hot to Ambient	Off	
35	OFBF, Good RTDs, Nominal Bus	Ambient	Nominal	Document Nominal Startup and Operation (part of PAT)
36	Neutralizer Switch Test	Ambient	Nominal	Document Operation of Neutralizer Switch (part of PAT)
37	OFBF, Good RTDs High Bus	Ambient	High	Document Startup and Operation (part of PAT)
38	OFBF, Good RTDs Low Bus	Ambient	Low	Document Startup and Operation (part of PAT)
39	Performance Map	Ambient	Nominal	Baseline Data for In Orbit Tests
40	Gimbal Tests, Ambient Conditions	Ambient	Nominal	Document Operation of Gimbals (part of PAT)

TABLE 2. Operating Mode Transitions Used During the Thruster Subsystem Thermal-Vacuum Test.

Step	Transition[1] (From-To)	Command (Hexidecimal)
1	OFDM	1305
2	DMOF	1300
3	OFNM	1306
4	NMOF	1300
5	OFSM	1304
6	SMSS	1301
7	SSBF	1302
8	BFSS	1301
9	SSBR	1303
10	BRSS	1301
11	SSSM	1304
12	SMBF	1302
13	BFBR	1303
14	BRBF	1302
15	BFSM	1304
16	SMBR	1303
17	BRSM	1304
18	SMDM	1305
19	DMBF	1302
20	BFDM	1305
21	DMBR	1303
22	BRDM	1305
23	DMSM	1304
24	SMNM	1306
25	NMBF	1302
26	BFNM	1306
27	NMBR	1303
28	BRNM	1306
29	NMSM	1304
30	SMBF	1302
31	BFMS	1307
32	MSSS	1301
33	SSMS	1307
34	MSBR	1303
35	BRMS	1307
36	MSBF	1302
37	BFOF	1300

[1]See Table 3 for a description of these operating modes.

TABLE 3. Thruster Subsystem Operating Modes Provided by the DCIU Firmware.

Mode	Description
Beam Full (BF)	The normal full-thrust (5-mN) operating mode
Beam Reduced (BR)	A reduced-thrust (4.3-mN) mode which is used to conserve power
Steady-State Standby (SS)	A discharge-on, neutralizer-on, beam-off mode for rapid transition to a thrusting mode
Minimum Standby (MS)	A minimum-power, discharge-on, neutralizer-on standby mode
System Maintenance (SM)	Only the discharge and neutralizer cathodes are ignited
Discharge Maintenance (DM)	Only the discharge cathode is ignited
Neutralizer Maintenance (NM)	Only the neutralizer cathode is ignited
System Conditioning (SC)	Power is applied to the two cathode tip heaters to condition the hollow cathodes
Neutralizer Off (NO)	An experimental mode to investigate full beam operation with the neutralizer off
Anti-Freeze (AF)	A low level of power is applied to both vaporizers to keep the mercury in them and the feedlines from freezing
Off (OF)	All power to the thruster is off

TABLE 4. Parameter Performance Mapping at Conclusion of Thruster Subsystem Thermal-Vacuum Test.

Step	Mode	Parameter	Value
1	Beam Full	V_δ (Discharge Voltage minus Discharge Keeper Voltage)	26.4 V
2			26.8 V
3			27.2 V
4			26.4 V
5			25.6 V
6			25.2 V
7			24.8 V
8			25.6 V
9			26.0 V
10	Beam Full	Beam Current	75 mA
11			72 mA
12			67 mA
13			63 mA
14			59 mA
15			63 mA
16			67 mA
17			72 mA
18	Beam Full	Neutralizer Keeper Voltage	15.7 V
19			15.2 V
20			16.2 V
21			17.3 V
22			18.3 V
23			17.3 V
24			16.2 V
25	Beam Full	Neutralizer Keeper Current	425 mA
26			500 mA
27			600 mA
28			500 mA
29	Beam Full	Discharge Keeper Current	120 mA
30			360 mA
31			120 mA
32			60 mA
33	System Maintenance	Discharge Vaporizer Current	1.26 A
34			1.54 A
35			1.78 A
36			1.99 A
37			1.78 A
38			1.54 A
39	System Maintenance	Discharge Keeper Current	500 mA
40			120 mA
41			360 mA

performed on the TSSs because the electronic units of the TSSs had already been tested separately. These two tests were nine thermal cycles at ambient pressure and an EMI/EMC test. The first and last thermal cycles were subsystem operational tests conducted at +50 and -20°C. The other seven cycles were run at +70 and -40°C with the DSS not operating.

3.2.3 Other Subsystem Tests

As part of the IAPS development effort, several other qualification tests were performed that involved units from more than one subsystem. These tests included flight software qualification tests, integration testing of the DSS with a thruster subsystem, and two preliminary integration tests of a flight thruster, flight PEU, and flight software. As described below, these tests were conducted with combinations of flight and engineering model units.

The software qualification tests were conducted to demonstrate the functional operation of the flight software developed under this program. The thruster subsystem for these tests consisted of a flight model DCIU and nonflight models of the TGBSU and PEU, which were functionally equivalent to the IAPS flight units. A sufficient number of mode transitions and operating modes, under software control and simulated thermal, electrical, and vacuum environments, were successfully demonstrated to qualify the DCIU software for flight use and to establish its reliability.

Another important system integration test was the Thruster Subsystem/Diagnostic Subsystem compatibility test, conducted to demonstrate performance compatability of both subsystems during simultaneous operation over a simulated mission operating profile. The test configuration consisted of an engineering model TGBSU and PEU mounted on a test fixture with a diagnostic subsystem. The diagnostic subsystem consisted of nonflight electronic units and one of each of the different types of DSS sensors. (Two ion collectors were included; one was bagged to eliminate the effect of electrons from the plasma in the vacuum chamber.) The sensors were positioned to duplicate their locations on the IAPS Flight Package within the constraints imposed by the vacuum test chamber. To prevent mercury contamination, the electronic boxes and the DSS sensors, with the exception of one ion collector, were individually covered with polyethylene. TSS control and telemetry functions were provided by the breadboard DCIU, operated externally to the vacuum chamber.

Operational compatibility of the TSS and DSS was demonstrated by monitoring telemetry outputs from both subsystems during the following operational sequences:

(1) With the DSS on (all sensors operating), the TSS was stepped through the various power switching events and an OFF-to-Full-Beam transition, as shown in Table 5.

(2) With the TSS operating in the full beam mode and the DSSCU ON, the DSS sensors were switched between the following modes:

   (a) each sensor ON individually,
   (b) ion collectors and solar cell ON,
   (c) ion collectors, solar cell, and potential sensor ON (only QCM OFF),
   (d) all sensors ON.

Two preliminary integration tests of a flight TGBSU, flight PEU, and flight software were conducted prior to the TSS subsystem testing phase of the IAPS program. These tests were performed to improve the probability of success during the TSS tests by an early demonstration of interunit compatibility. By conducting these tests with the flight software loaded into the DCIU Breadboard, system compatability was verified before the flight software was committed to firmware in the flight DCIU PROMs. The flight equipment used for the first of these integration tests consisted of TGBSU S/N 909, PEU F1, and Software FLT 001.018. This combination of TGBSU and PEU is on

TABLE 5. **Test Sequence for Diagnostic Subsystem/Thruster Subsystem Compatibility Test.**

Step	Mode/Operation
1	Command DSS ON. (All sensors ON)
2	Start recording DSS and TSS telemetry continuously.
3	Operate gimbals.
4	Command neutralizer heater power ON, wait >64 sec, command neutralizer heater OFF.
5	Command discharge heater power ON, wait >64 sec, command discharge heater OFF.
6	Command Neutralizer Maintenance, wait >64 sec after neutralizer ignites, command Thruster Subsystem OFF.
7	Command Discharge Maintenance, wait >64 sec after discharge cathode ignites, command Thruster Subsystem OFF.
8	Command Steady State Standby, wait >64 sec after discharge ignites.
9	Command Full Beam, wait >64 sec after beam current reaches 72 mA.
10	Command Neutralizer Switch to close, wait >64 sec.
11	Command Neutralizer switch to open, wait >64 sec.
12	Command Thruster Subsystem OFF.
13	Command Full Beam, wait >15 min.
14	Command all DSS sensors and DSSCU OFF, wait >2 min.
15	Command DSSCU ON (sensors still OFF), wait >2 min.
16	Command Ion Collectors ON, wait >2 min, command ICs OFF.

(continued on next page)

Step	Mode/Operation
17	Command Solar Cell detectors ON, wait >2 min, command SCs OFF.
18	Command Potential Sensor ON, wait >2 min, command PS OFF.
19	Command Quartz Crystal Microbalance ON, wait >2 min, command QCM OFF.
20	Command Ion Collectors and Solar Cell Detectors ON, wait >2 min.
21	Command Potential Sensor ON, wait >2 min.
22	Command Quartz Crystal Microbalance ON, wait >2 min.
23	Command DSSCU and all sensors OFF.
24	Command Thruster Subsystem OFF.

the -X IAPS module. The second test was performed with the units of the -Z module, TGBSU S/N 908 and PEU F2, plus FLT 001.018 Software. The matrix of tests performed during the integration tests is shown in Table 6. The results of these tests confirmed the wisdom of performing such integration tests prior to the flight TSS subsytem tests and prior to burning the flight PROMs. Desireable software changes and a PEU wiring error were identified as a result of these tests. These software changes resulted in FLT 001.019 as the final flight version software.

3.3 TGBSU PERFORMANCE REEVALUATION TEST

During the various IAPS-Spacecraft tests, the IAPS thrusters were not operated because all tests except the thermal-vacuum test were conducted in air. During the spacecraft thermal-vacuum test, the flight TGBSUs were replaced with thermal simulators. This replacement served two purposes: (1) the thermal simulators provided the required thermal load to the spacecraft during the thermal-vacuum test, and (2) the TGBSUs were made available for a final prelaunch performance test to verify that the various spacecraft environmental tests had not altered the thruster performance. The TGBSU performance reevaluation test was an expanded version of the standard PAT used throughout the unit qualification testing. The number of operational data points was increased from 6 to 39 to expand the performance envelope data base. Table 7 identifies the additional operating points used during the performance reevaluation test.

Three years elapsed between the TSS Subsystem Tests and the TGBSU Performance Reevaluation Tests, during which time the TGBSUs were not operated and were not stored in an inert environment. (For most of the three years, the TGBSUs had been on the IAPS modules attached to the spacecraft.) It is important to note after such an extended dormant period that (1) the thruster cathodes ignited quickly using the standard ignition procedure, and (2) both thrusters operated very well. Proper

TABLE 6. Test Matrix for Preliminary Thruster Subsystem Integration Tests.

Test	Temperature		RTDs[1]		Transition (OFBF = OF to BF[2])	Input Line	Comment
	Thruster	PEU	Good	Failed			
1	Ambient	Amb	X		OFBF	70 V	Run for 1 h
2	Ambient	Amb	X		BFSS	70 V	Run for 1 h
3	-30°C	Amb	X		OFBF	90 V	
4	-30°C	Amb	X		BFSM	90 V	Run for 1 h
5	+60°C	Amb	X		OFBF	55 V	
6	-30°C	Amb		X	OFBF	55 V	
7	+60°C	Amb		X	OFBF	90 V	
8	+60°C	Amb	X		OFBF	70 V	Fixed point disch. vap. operation
9	+60°C	Amb		X	OFBF	70 V	Fixed point disch. vap. operation
10	Ambient	Amb	X		OFBF	70 V	

1. RTDs are the vaporizer temperature sensors. "Failed" means DCIU flags have been set to simulate failed RTDs.

2. See Table 3 for description of operating modes.

TABLE 7. Operating Points for TGBSU Performance Reverification Test (PAT No. 4).

Data Point	Mode	Principal Parameter Variation: Parameter	Principal Parameter Variation: Value	Other Variations from Nominal	Additional Measurements
1	BF	None		None	$\dot{m}_T$, $\tilde{I}_D$, $\tilde{I}_{DK}$
2		V_δ	27.0 V		
3			27.8 V		
4			25.4 V		
5			24.6 V		
6		I_{DK}	140 mA		
7		I_{DK}	380 mA		
8		I_{DH}	1.64 A		$\dot{m}_T$,
9		V_{NK}	15.1 V		$\tilde{I}_{NK}$
10		V_{NK}	17.7 V		
11		I_{NK}	450 mA	Adj. V_{NK} for nom. T_{NV}	
12		I_{NK}	600 mA		
13		I_{NH}	1.69 A		
14	BR	None		None	$\dot{m}_T$, $\tilde{I}_D$, $\tilde{I}_{DK}$
15	BF	I_B	69 mA		
16	BF	I_B	75 mA		
17	DM	None			$\dot{m}_D$
18		I_{DH}	1.16 A	Adj. I_{DV} for nom. T_{DV}	
19		I_{DH}	1.64 A	Adj. I_{DV} for nom. T_{DV}	
20		I_{DV}	0.885 A	I_{DH} = 1.64 A	
21			1.54 A		
22			1.99 A		
23			2.20 A		
24			2.32 A		
25	NM	None			$\dot{m}_n$, $\tilde{I}_{NK}$
26		I_{NH}	1.30 A	None	
27		I_{NH}	1.97 A		
28		I_{NK}	330 mA		$\tilde{I}_{NK}$
29			450 mA		
30			600 mA		
31		V_{NK}	16.1 V	I_{NH} = 1.30 A	$\dot{m}_N$
32			15.6 V		
33			15.1 V		
34			16.9 V		
35			17.7 V		
36			19.3 V		
37		I_{NV}	0.867 A		
38			1.10 A		
39			1.30 A		

Symbols used in Table 7 are defined in the list below.

Symbol	Defintion of Symbols Parameters
V_δ	Discharge voltage - Discharge Keeper voltage
I_{DK}	Discharge Keeper current
I_{DH}	Discharge Heater current
V_{NK}	Neutralizer Keeper voltage
I_{NK}	Neutralizer Keeper current
I_{NH}	Neutralizer Heater current
I_B	Beam current
I_{DV}	Discharge Vaporizer current
I_{NV}	Neutralizer Vaporizer temperature
T_{DV}	Discharge Vaporizer temperature
T_{NV}	Neutralizer Vaporizer temperature

operation of the thruster gimbals was also confirmed during the final prelaunch PAT. The same test equipment and test chamber were used for this test as had been used during the earlier TGBSU PATs. Data for several important thruster operating parameters for all of the TGBSU PATs are presented for both thrusters in Table 8. At the end of this test, which was the last thruster operation before actual flight, the flight thrusters had each accumulated approximately 140 h of high voltage ON time.

TABLE 8. Thruster Performance Data from Design Qualification and Performance Acceptance Tests.

Test and TGBSU S/N	Parameter			
	Thrust (mN)	Specific Impulse (sec)	Electrical Efficiency (%)	Total Efficiency (%)
Design Qualification				
S/N 908	5.14	2483	67.1	47.6
S/N 909	5.14	2542	67.5	48.0
PAT No. 1				
S/N 908	5.10	2604	67.0	50.2
S/N 909	5.10	2507	67.0	48.4
PAT No. 2				
S/N 908	5.10	2536	66.8	48.7
S/N 909	5.10	2511	66.9	48.4
PAT No. 3				
S/N 908	5.10	2469	66.8	47.4
S/N 909	5.09	2609	66.9	50.3
PAT No. 4[a]				
S/N 908	5.14	2608	66.0	49.4
S/N 909	5.10	2579	66.1	49.0
Mean				
S/N 908	5.12	2540	66.7	48.7
S/N 909	5.11	2550	66.9	48.8
Combined	5.11	2545	66.8	48.7

a. PAT No. 4 was an expanded performance reevaluation test, performed 3 years after the previous operation of the TGBSUs.

SECTION 4

SPACECRAFT-INTEGRATION TESTS

After completion of the unit and subsystem qualification tests, the units were mounted on modules provided by the spacecraft contractor (see Figures 2 and 3) and prepared for delivery to the spacecraft. Before delivering the modules, a predelivery functional test of the system was performed. The same test was repeated after delivery to the spacecraft contractor, but before the modules were mounted on the spacecraft. After the Postdelivery test verified that the system was operating properly, the modules were installed on the spacecraft and a series of IAPS-Spacecraft tests was conducted. The Predelivery, Postdelivery, and IAPS-Spacecraft tests are discussed in the following sections. More details of the IAPS-Spacecraft integration test effort are provided in document FM-1000, IAPS Handling, Installation, and Test.

4.1 PREDELIVERY AND POSTDELIVERY TESTS

Identical Predelivery and Postdelivery tests were designed to verify that installation of the units on the modules and delivery of the modules to the spacecraft contractor had not altered system performance. Therefore, the procedure written for these tests was derived from the TSS and DSS subsystem test procedures. An early part of the TSS Subsystem Test was a check of the TSS electronics with resistive loads (PEU Load Box) substituted for the thruster. The steps from this section were incorporated directly into the Pre/Postdelivery Test Procedure. Further commonality was ensured by using the same equipment to conduct all of the tests. Thus, the results of the Predelivery and Postdelivery tests could be compared step for step with the results from the earlier subsystem tests.

The Predelivery test confirmed that installation of the units and cables on the modules had not altered system performance; the Postdelivery test results duplicated the results from the Predelivery test. The data presented in Table 9 illustrate the excellent correlation of results from the Subsystem tests, Predelivery tests, and Postdelivery tests.

4.2 IAPS TESTS ON THE SPACECRAFT

The initial step in establishing compatibility between the IAPS Flight Package and the host spacecraft was to verify power, command, and telemetry interfaces. Verification was obtained by connecting a DCIU simulator and a DSS simulator to the IAPS-Spacecraft cables before connecting the IAPS Flight Package to those cables. The simulator output and input circuits duplicated the corresponding IAPS Flight Package circuits. This configuration permitted a check of impedances, loads, and functions across all electrical interfaces without risking damage to the IAPS Flight Package and with minimum risk to the spacecraft. Following the successful simulator-spacecraft electrical interface verification, the IAPS Flight Package was connected to the spacecraft and the series of integration tests described below were performed.

Tests conducted with the IAPS Flight Package installed on the spacecraft served two main purposes: they demonstrated the operational compatibility of the IAPS-Spacecraft combination, and they verified proper IAPS Flight Package operation during or after certain environmental exposures (e.g., thermal-vacuum and acoustic). Table 10 shows the sequence of tests performed while the IAPS Flight Package was on the spacecraft. (All currently scheduled tests have been completed; however, additional pre-launch tests will be scheduled after a new Shuttle mission launch date is established.)

For most spacecraft tests, IAPS was configured in the flight ready mode, with the following exceptions: (1) the power input cables to the TGBSUs were connected to PEU load boxes rather than to the TGBSU, (2) a rubber diaphragm was installed in the propellant feedline connector on both thrusters to prevent

TABLE 9. Test Data from TSS Subsystem Tests, Predelivery Tests, and Postdelivery Tests.

	-X Module Tests			-Z Module Tests		
Parameter	TSS Sub-System	Pre-delivery	Post-delivery	TSS Sub-System	Pre-delivery	Post-delivery
I_{DH}						
SP5	3.02 A	3.05 A	3.04 A	3.00 A	2.99 A	2.98 A
Tlm (Hex)	E1	E1	E0	E1	E1	E1
I_{NH}						
SP4	2.75 A	2.74 A	2.74 A	2.70 A	2.75 A	2.75 A
Tlm (Hex)	D7	D7	D7	D6	D6	D6
I_{DV}						
SP6	2.30 A	2.32 A	2.33 A	2.38 A	2.32 A	2.32 A
Tlm (Hex)	N/A	N/A	N/A	N/A	N/A	N/A
I_{NV}						
SP3	1.34 A	1.30 A	1.31 A	1.34 A	1.33 A	1.33 A
Tlm (Hex)	N/A	N/A	N/A	N/A	N/A	N/A
I_{DK}						
SP0	63.8 mA	64.9 mA	65.6 mA	65.0 mA	63.6 mA	64.1 mA
Tlm (Hex)	27	27	27	26	26	26
I_{NK}						
SP2	525 mA	522 mA	523 mA	533 mA	534 mA	534 mA
Tlm (Hex)	E3	E3	E3	E8	E8	E9
I_D						
$SP=20_H$	439 mA	435 mA	435 mA	437 mA	439 mA	439 mA
Tlm (Hex)	68	68	68	68	68	68
V_A	-301 V	-301 V	-301 V	-310 V	-310 V	-310 V
Tlm (Hex)	96	96	96	9B	9C	9B
V_S	+1198 V	+1196 V	+1195 V	+1199 V	+1198 V	+1197 V
Tlm (Hex)	FE	FD	FD	FD	FC	FC

TABLE 10. Spacecraft Tests That Involved IAPS.

Test	Date
IAPS Integration and Functional	12/82 - 1/83
Combined Systems Test (CST) (Expanded version)	3/83
Early Satellite Control Facility Compatibility Test	12/83
Combined Systems Test (CST) (Expanded version)	2/84
Electromagnetic Compatibility Test	
First Phase	10/84
Second Phase	2/85
Pre-Acoustic Test CST (Basic version)	3/85
Acoustic Test	3/85
Post-Acoustic Test CST (Basic version)	4/85
(TGBSU Thermal Simulators installed)	4/85
Pre-Thermal-Vacuum Test CST (Basic version)	5/85
Thermal-Vacuum/Thermal-Balance Test	6/85 - 8/85
(Flight TGBSU's reinstalled)	9/85
Combined Systems Test (Expanded version)	2/86
Integrated Systems Test (IST)	4/86

accidental mercury flow, and (3) a valve-command test connector was installed in both modules to prevent the "valve open" command from reaching the propellant valve and to short out the valve opening solenoid.

Commands to IAPS during spacecraft tests originated in a test control computer and were routed through the spacecraft command system, as they will be when in orbit. IAPS performance data were obtained from the spacecraft telemetry system and from ground support equipment meters (e.g., PEU load box).

4.2.1 Installation Functional Test

The Installation Functional test was the first operational test of the IAPS Flight Package after installation on the spacecraft. The objectives of this test were (1) to check all IAPS-Spacecraft electrical interfaces (power, command, and telemetry), and (2) to verify normal operation of the TSS electronics and the DSS electronics and sensors. The electrical interface check was run with IAPS connected to the spacecraft through breakout boxes so that turn-on transients on the spacecraft bus could be measured. Undervoltage load shed was also checked.

The TSS functional test consisted of checking or verifying the following functions: Bus Power, Command, Telemetry, and PEU Output; "Off-to-Beam Full" Transition and Full Beam Operation at High and Low Bus Voltage; Recycle/Shutdown; Antifreeze Mode; Valve Commands and Resistance; and Boost Voltage Converter Cross-Strapping. Many of these same test elements were included in the spacecraft Combined Systems Test (CST). The spacecraft CST served the same purpose as the IAPS PATs: to verify proper operation before and after an environmental exposure.

Included in the DSS functional test were the following elements: Bus Power, Command, and Telemetry Verification; Solar Cell Detector Test; Potential Sensor Test; Ion Collector Test; and Quartz Crystal Microbalance Test. Many of the steps in this test are also included in the DSS portion of the CST (see Table 11).

TABLE 11. Comparison of Installation Functional Test, Basic Combined Systems Test (CST), and Expanded Combined Systems Test.

Test Element	Installation Functional	Basic CST	Expanded CST
TSS			
1. Bus Pwr, Cmds, Tlm & PEU Output	5 Power Supp. Power Level Combinations	2 Power Supp. Power Level Combinations	5 Power Supp. Power Level Combinations
2. OFF to Beam Full Trans.	Yes	Yes	Yes
3. High & Low Bus Volt.	Yes	Yes	Yes
4. Recycle-Shutdown	4 of 4	3 of 4	4 of 4
5. Antifreeze Mode	Yes	Yes	Yes
6. Neutralizer	Yes	No	Yes
7. Valve Cmds & Coil Resistance	Yes	Cmds only	Yes
8. BVC Cross-Strapping & Dual TSS Operation	Yes	No	No
DSS			
1. Bus Pwr, Cmds & Tlm	2 Pot. Sens. IC Setpoint Combinations	1 Pot. Sens. IC Setpoint Combinations	2 Pot. Sens. IC Setpoint Combinations
2. Solar Cell	Yes	Yes	Yes
3. Potential Sensor	6 Ranges	1 Range	6 Ranges
4. Ion Collector	3 Ranges	1 Range	3 Ranges

4.2.2 Combined Systems Test

There were two versions of the spacecraft Combined System Test (CST): a Basic CST and an Expanded CST. These two tests and the Installation Functional Test use many of the same procedures. Table 11 lists and compares the contents of these three tests. The objective of the basic CST was rapid evaluation of spacecraft/experiment performance before or after a spacecraft environmental test or following a spacecraft move. The objective of the expanded CST was to verify all spacecraft/experiment performance parameters within the constraints imposed by a ground test environment. The expanded CST was performed twice, once following the Installation Functional Test and once following the thermal-vacuum test. Table 10 shows where each of the two versions of the CST was used in the spacecraft test sequence.

4.2.3 Integrated System Test

The Integrated System Test (IST) provided testing of the spacecraft subsystems and experiments within the constraints of the mission sequences, where practical. Each subsystem was tested in operational modes dictated by the launch, parking orbit, orbit injection, and in-orbit operation mission sequences. During the actual mission, IAPS will be unpowered until the spacecraft is in orbit. Therefore, the IAPS portion of the IST consisted of only an in-orbit sequence.

IAPS test operations during the IST consisted only of sending commands to the IAPS Flight Package and verifying reception of the commands by reading the DSS and TSS command word telemetry channels. Operation of IAPS, in response to the commands sent, was not verified. Only 28-V power was applied; the 70-V bus was not turned ON. Serial magnitude commands to change the operating points of the potential sensor and ion collectors were sent to the DSS and verified. Serial magnitude commands to set the operating points of the cathode heaters, vaporizer heaters, both keepers, and the discharge current were sent to both thruster subsystems and verified.

4.2.4 Electromagnetic Compatibility Test

The purpose of the spacecraft Electromagnetic Compatibility (EMC) Test was twofold: (1) to demonstrate EMC at the spacecraft subsystem interfaces and at the interfaces between the spacecraft and the experiments, such as IAPS, and (2) to verify that a 6-dB electromagnetic interference safety margin (EMISM) existed between the measured noise level and the susceptibility threshold of certain critical circuits.

IAPS involvement in the EMC test consisted of: (1) being in the full power mode (all sensors of the DSS ON and both TSSs in the "Beam Full" mode) while EMC measurements were being made on other subsystems, and (2) having EMISM verified on certain "critical" IAPS circuits. The critical IAPS circuits were defined to be the 70-V bus lines to the thruster subsystems, and telemetry output D815, DSSCU Clock Frequency. Another measurement used to verify EMC compatibility was the bit error rate (BER) of the spacecraft telemetry tape recorders. (It should be noted that throughout the many spacecraft tests involving IAPS operation, there was never an indication of any EMI between IAPS and the spacecraft.)

4.2.5 Acoustic Test

The spacecraft, with experiments installed and energized, was subjected to a qualification/acceptance acoustic test. The maximum acoustic exposure was 3 dB above the flight launch environment. This test consisted of the four acoustic exposures described below:

(1) Low level test: 40 sec at 6-dB below flight level, DSS ON and TSS-1 28-V and 70-V power ON.

(2) Flight level test: 40 sec at flight level, DSS ON and TSS-1 28-V and 70-V power ON.

(3) High level test: 32 sec at 3-dB above flight level, DSS ON and TSS-2 28-V and 70-V power ON.

(4) Second high level test: 32 sec at 3-dB above flight level, DSS ON and TSS-1 and TSS-2 28-V and 70-V power ON.

After each acoustic exposure, a walk-around inspection was performed to verify that no damage had occurred and that it was safe to proceed. The final acoustic run was followed by a CST, which verified that the performance of the TSS electronics and the DSS had not been affected by the acoustic test. After the Acoustic Test the Thruster-Gimbal-Beam Shield Units were removed from the IAPS modules and taken to Hughes Aircraft for the performance reevaluation test described earlier in Section 3.3.

4.2.6 Thermal-Vacuum/Thermal-Balance Test

The purpose of the Thermal-Vacuum/Thermal-Balance test was to test the spacecraft and experiments under conditions that simulate the worst-case thermal-vacuum environments that will be experienced during the parking/transfer orbit and the operational orbit. Objectives of this test included: (1) detection of any material, process, or workmanship defects that would manifest themselves under thermal-vacuum conditions, (2) demonstration that the spacecraft would perform properly under thermal-vacuum conditions representative of those predicted for flight, plus a margin of safety, and (3) demonstration of spacecraft thermal balance using maximum and minimum thermal environmental conditions.

After the spacecraft Acoustic Test and before the Thermal-Vacuum Test, both TGBSUs were removed from the IAPS modules and replaced with TGBSU thermal simulators. The thermal simulators were installed so that a heat load representative of an operating thruster could be provided to the spacecraft during the thermal-balance test. Removing the TGBSUs made them available for the performance reevaluation test previously described.

IAPS testing during the spacecraft Thermal-Vacuum Test consisted of three operational phases. These were: (1) a 20-h IAPS mission test, (2) a cold low-line-voltage Combined Systems Test (CST), and (3) a hot low-line-voltage CST.

The IAPS mission test was divided into two 10-h segments. During the first segment, two OFF-to-Beam Full-to-OFF cycles were performed with TSS 1. During the first 10-h segment, the electrical output of the solar array simulator was periodically adjusted to simulate the spacecraft going in and out of eclipse. During the second 10-h segment, first TSS 1 was transitioned from OFF-to-Beam Full, and then TSS 2 was transitioned from OFF-to-Beam Full. At the end of the 10 h both TSSs were transitioned from Beam Full-to-Off. Eclipse was not simulated during the second 10-h segment. The IAPS Diagnostic Subsystem was turned ON at the beginning of the IAPS mission test and left ON until the end of the test.

During the thermal-vacuum testing, the TGBSU thermal simulator heater power was turned ON when the discharge supply was ON. In this way, the thermal load of an operating thruster was simulated for the spacecraft thermal control system.

The two Combined Systems Tests performed during the thermal-vacuum test were both modified basic CSTs. Two major differences from the standard CST were: (1) addition of a gimbal command test, made possible by the presence of the TGBSU simulators, and (2) the absence of external stimulation to the DSS sensors, because of the size of the vacuum chamber. The first CST was performed with the spacecraft at the acceptance level "cold soak" temperature and the bus voltage at "low-line" [5~(24.5 V)]. The second CST was a hot, low-line-voltage test performed at the acceptance level "hot soak" temperature.

4.2.7 Summary Of Spacecraft-Integration Testing

IAPS testing associated with spacecraft integration was conducted over a time span of 45 months and at five locations: Hughes Aircraft, El Segundo and Malibu, CA; Rockwell, Seal Beach, CA; Vandenberg AFB, Vandenberg, CA; and McDonnell Douglas, Huntington Beach, CA. IAPS-Spacecraft tests were conducted using formal test procedures. These procedures were prepared by the spacecraft contractor; inputs for the tests that required operation of IAPS were supplied by Hughes Aircraft. A sample from one of these procedures is shown in Figure 12. As Figure 12

SEQ	STA	CMD/MEAS	LIMITS/DESCRIP/INSTRUCTIONS		VERIFY
61.09700					
	TTY	E489	ON	(IAPS BVC C.O. RELAY NORMAL)	
		4536		(IAPS BOOST CONV B ON)	
		E449	ON	(IAPS BVC NO.2 PWR ON)	
		4540		(IAPS DCIU PWR B ON)	
		E455	ON	(IAPS DCIU NO.2 PWR ON)	
		DELY	0640	DELAY TEST	
		P504	68. TO 90.	VDC (TSS 2 70V BUS VOLTAGE)	
		P502	0.3 TO 0.5	ADC (TSS 2 70V BUS CURRENT)	
		9920		(VTCW TRANSFER)	
		DELY	0100	DELAY TEST	
		REMK	CMD 4584 TAKES 48	SEC TO EXECUTE	
		4584		(16 VAC ON -X)	
		DELY	1120	DELAY TEST	
		P502	0.5 TO 0.6	ADC (TSS 2 70V BUS CURRENT)	
		DUMP	TLM SPM		
		HOLD			
61.09800					
	TTY	9920		(VTCW TRANSFER)	
		DELY	0100	DELAY TEST	
		REMK	CMD 4570 TAKES 288	SEC TO EXECUTE	
		4570		(HEATRS AND KEEPERS ON X)	
		DELY	2880	DELAY TEST	
		DELY	0640	DELAY TEST	
		EU		SELECT ENGINEERING UNITS	
		P506	0. TO 50.	VDC (TSS 2 SCREEN VOLTAGE)	
		P510	0. TO -50.	VDC (TSS 2 ACCELERATOR VOLTAGE)	
		P516	0. TO 10.	VDC (TSS 2 DISCH VOLTAGE)	
		P518	0. TO 75.	MADC (TSS 2 DISCH CURRENT)	
		P522	40. TO 80.	MADC (TSS 2 DISCH KEEPER CURRENT)	
		P524	1.0 TO 1.4	AAC (TSS 2 DISCH HEATER CURRENT)	
		P528	300. TO 360.	MADC (TSS 2 NEUT KEEPER CUR)	
		P532	1.1 TO 1.5	AAC (TSS 2 NEUT CATHODE HEAT CUR)	
		P102	20. TO 30.	DEGC (TSS 2 PROP TANK TEMP)	
		P108	20. TO 60.	DEGC (TSS 2 END BELL TEMP (P108))	
		P202	28. TO 50.	PSIA (TSS 2 PROP TANK PRESS)	
		P514	4.8 TO 5.2	VDC (TSS 2 DCIU 5V SUPPLY)	
		P104	340. TO 410.	DEGC (TSS 2 DISCHARGE VAPOR TEMP)	
		P106	340. TO 410.	DEGC (TSS 2 NEUT VAPOR TEMP)	
		P704	00. TO 00.	MIN (TSS 2 BEAM ON TIMER LSH)	
		CU		SELECT DECIMAL COUNTS UNIT	
		P806	94 TO 94	HEX (TSS 2 CMD REGISTER MSB)	
		P808	3F TO 3F	HEX (TSS 2 CMD REGISTER LSB)	
		EU		SELECT ENGINEERING UNITS	
		HOLD			

Figure 12. Page from spacecraft test procedure used during IAPS portion of Combined Systems Test (Expanded version).

shows, most test steps did not result in data being recorded (except on magnetic tape for later printout, if needed). During the tests, telemetry outputs were compared to preset limits and if the data were within limits, the test proceeded. Test results throughout this series of tests were uniformly excellent. During the IAPS-Spacecraft integration testing, IAPS performance was repeatable and no performance or installation incompatibilities with the spacecraft were detected. At the conclusion of the IAPS-Spacecraft integration effort, all scheduled tests had been successfully completed.

SECTION 5

RELIABILITY AND QUALITY ASSURANCE

An effective and timely quality program was implemented for the IAPS Flight Package to satisfy all contract requirements and produce a reliable product. The quality assurance system that was in effect during the building and testing of the IAPS Flight Package is defined in the IAPS Reliability and Quality Assurance Plan, Revision C. This quality system assured that defects or other unsatisfactory conditions were discovered and corrected at the earliest practical moment. The system included provisions for ascertaining and controlling equipment quality from the time material and components were procured for fabrication, through fabrication, unit testing, subsystem testing, and integration testing on the spacecraft. Recorded evidence of the IAPS Flight Package quality effort was documented in the form of inspection and test results. Program activities addressed by the R & QA plan included: reliability; procurement source control; material control; inspection and test; process control; configuration control; material identification, handling, and storage; preservation, packaging, and shipping; nonconforming articles; failure reporting; inspection, measurement, and test equipment control; inspection status indication; equipment logs; parts selection; parts derating; and cleanliness control.

The order of precedence for selection of parts for the IAPS Flight Package was:

(1) Parts listed in MIL-STD 975 or NASA/GSFC PPL-13

(2) Parts defined by Hughes Aircraft Company Specification Control Drawings (900XXX) and Military Specifications

(3) Commercial Hi-Rel parts

(4) Commercial parts upgraded by burn-in, X-ray (two views), fine and gross leak tests, PIN tests, DPA sample, and acceptance tests.

NASA LeRC approval was obtained for parts in categories (2), (3) and (4) above. Procurement was controlled by QA screening to assure that parts were obtained from approved vendors, and pre-cap and/or source inspection provisions were included.

IAPS electronics parts were listed in an Approved Parts List (APL). Prior to a part being added to the APL, the Parts Manager reviewed the request to be certain that every effort had been made to obtain the most reliable part available compatible with schedule requirements. The Parts Manager, after consulting with parts experts, ordered any required screening and/or tests. Electronic parts were derated in accordance with contract requirements. Design derating factors were 0.50 (min.) for voltage and current and 0.25 (min.) for power.

Hughes has an effective parts management and control system whereby any government or industrial component or part "ALERT" is immediately called to the attention of all program offices and responsible engineering organizations. The IAPS program office received several such alerts. In each case, action was taken to purge the program of disappproved or suspect conponents, or to implement the required corrective measures to comply with all R & QA requirements. Examples include: Picofuses 988244 and AVX capacitors 908502.

All IAPS Flight Package units and subsystems were qualification tested and acceptance tested in compliance with contractually established and approved plans and to approved procedures. Results were documented in formal reports and accepted by NASA LeRC as evidence of compliance with test and performance requirements. The IAPS Flight Package qualification/acceptance test specifications (FTS), test procedures (FTP) and test reports (FTR) are listed in Section 5 of this report.

A record was kept of each anomaly or failure that occurred for each flight unit or subsystem beginning with the start of the qualification phase of the program, i.e., after completion of unit fabrication and assembly. Failure reports, as defined in the IAPS Reliability and Quality Assurance Plan, were used to report and control the disposition of all such test anomalies and hardware failures. The following approval signatures were required for the final closure of each failure report: Responsible Engineer, Hughes Quality Assurance and IAPS Program Manager or Deputy Program Manager. Failure reports were first submitted to NASA LeRC within 24 hours of the event and again when the failure report was closed out. The failure reporting system remained active during the spacecraft-integration testing phase of the program.

SECTION 6

SAFETY

Because of the planned launch of the IAPS Flight Package on a Shuttle, safety was a significant factor throughout the program. There are two major aspects of IAPS safety: (1) safety while IAPS is on board the Shuttle and (2) safety during ground test operations. The IAPS Flight Package was designed and built to be physically, operationally, and environmentally safe. Design features incorporated in the IAPS Flight Package assure that no potential for personal injury or equipment/experiment damage exists when the system is handled or operated in accordance with prescribed procedures. Examples of how the design features and prescribed procedures combine to assure that IAPS does not present any safety hazards are presented below.

The subject of IAPS safety was addressed early (and repeatedly) in this program. An Accident Risk Assessment Report (ARAR) was prepared and submitted to NASA LeRC and the spacecraft contractor during the first year of the program. The ARAR was revised as the IAPS design solidified and additional safety reviews were held. Ultimately a total of 30 potential hazards that might exist while the IAPS Flight Package was undergoing spacecraft-integration testing or was in the Shuttle bay were identified and addressed. Adequate safeguards were provided for each of the identified potential hazards either within the design of the IAPS Flight Package or by implementing the appropriate handling and test procedures. The IAPS hazard analyses were reviewed and accepted at the spacecraft safety reviews held for the Air Force and NASA by the spacecraft contractor.

Some safety items meriting special note are:

(1) Two positive closures are provided in series in the mercury line to prevent escape of the mercury propellant into the Shuttle bay. (Until late in the

spacecraft-integration testing effort a third closure was provided by a rubber diaphragm in the feedline between the propellant reservoir and the thruster.)

(2) The calculated burst pressure of the propellant feed assembly is greater than 13.5 times the maximum working pressure.

(3) Both Propellant Tank, Valve and Feedline Units were vibrated to 1.5 times expected flight loads while loaded and pressurized.

(4) Shorting plugs were in place during spacecraft-integration testing to prevent opening of the propellant valves.

(5) All high voltage cables are shielded and grounded and the output connectors are socket (female) type.

(6) No power will be applied to the IAPS Flight Package while it is in the Shuttle bay.

(7) Operation of the thrusters during spacecraft-integration testing was prevented by never connecting the PEU output power cables to the thrusters. The power cables will be connected to the thrusters at the last access opportunity prior to launch.

SECTION 7

DOCUMENTATION

The program that resulted in the production of IAPS as a flight qualified system was well documented. Design, performance, and interface requirements were defined in formal test specifications; test requirements were set forth in program-released test procedures; and test results were reported in a separate test report for each major element of the test program. The resulting documents bear an alphanumeric identifier based on the system described below. Following the description of the document identifiers, the documents are listed in numerical order.

FTS = Flight Hardware Test Specification
FTP = Flight Hardware Test Procedure
FTR = Flight Hardware Test Report

100 = Thruster-Gimbal-Beam Shield
200 = Power Electronics Unit
300 = Propellant Tankage, Valves and Feed Unit
6xx = Digital Controller and Interface Unit
7xx = Diagnostic Subsystem
8xx = Thruster Subsystem

<u>Thruster-Gimbal-Beam Shield Unit</u>

FTS-100 Rev. A	Flight Hardware Test Specification, TGBSU
FTP-100 Rev. A	Flight Hardware Test Procedure, TGBSU
FTR-100-908	Flight Hardware Test Report, TGBSU, S/N 908
FTR-100-909	Flight Hardware Test Report, TGBSU, S/N 909

<u>Power Electronics Unit</u>

FTS-200 Rev. A	Test Specification, PEU, 8-cm Mercury Ion Thruster System
FTP-200 Rev. B	Test Procedure, PEU, 8-cm Mercury Ion Thruster System

-	Final Qualification Test, 8 Centimeter Ion Engine Power Electronics Unit

Propellant Tankage, Valves and Feed Unit

FTS-300	Test Specification, Propellant Tankage, Valves and Feed Unit (PTVFU)
FTP-300	Test Procedure, Propellant Tankage, Valves and Feed Unit (PTVFU)
FTR-300-(-X)	Final Test Report, Propellant Tankage, Valves and Feed Unit, -X Module
FTR-300-(-Z)	Final Test Report, Propellant Tankage, Valves and Feed Unit, -Z Module

Digital Controller and Interface Unit

FTS-600	Test Specification, Digital Controller and Interface Unit
FTP-600 Rev. A	Test Procedure, Digital Controller and Interface Unit
FTR-600-001	Test Report, Digital Controller and Interface Unit, S/N 001
FTR-600-002	Test Report, Digital controller and Interface Unit, S/N 002
FTP-610	Test Procedure, DCIU EMI Tests
FTR-610	Test Report, DCIU/PEU EMI Tests
STP-610 Rev. A	IAPS Software Prequalification Plan
SPTR-610	IAPS Software Prequalification Report
SQTP-601 Rev. A	IAPS Software Flight Qualification Test Plan
SQTP-602	IAPS Software Qualification Test Procedure
SQTR-600	IAPS Flight Software Qualification Tests Report

Diagnostic Subsystem

FTS-700	Test Specification, Flight Diagnostic Subsystem (DSS)

FTP-700	Test Procedure, Diagnostic Subsystem (DSS)
FTP-700 Supplement Rev. B	Test Procedure, Diagnostic Subsystem (DSS), Supplementry Thermal Vacuum and Vibration Test Procedure for Solar Cell Detectors and Potential Sensor Probe
FTP-700	Test Procedure, Diagnostic Subsystem (DSS), Supplementry Vibration Test Procedure for TQCM Electronics
FTR-700	Test Report, Diagnostic Subsystem (DSS)
FTP-710	Test Procedure, Diagnostic Subsystem (DSS) EMI Tests
FTR-710	Test Report, IAPS Diagnostic Subsystem Control Unit, EMI Tests

<u>Diagnostic Subsystem Integration with Thruster Subsystem</u>

FTS-790 Rev. A	Test Specification, Diagnostic Subsystem (DSS) Integration with Mercury Ion Thruster Subsystem (MITS)
FTP-790	Test Procedure, Diagnostic Subsystem (DSS) Integration with Mercury Ion Thruster Subsystem
FTR-790	Test Report, Diagnostic Subsystem (DSS) Integration with Mercury Ion Thruster Subsystem (MITS)

<u>Thruster Subsystem</u>

FTS-800	Test Specification, Test Flight Mercury Ion Thruster Subsystem
FTP-800	Test Procedure, Test Flight Mercury Ion Thruster Subsystem
FTR-800-X	Test Report, Test Flight Mercury Ion Thruster Subsystem, -X Module
FTR-800-Z	Test Report, Test Flight Mercury Ion Thruster Subsystem, -Z Module
FTS-850	Test Specification - Preliminary Integration Test of a Flight Thruster, Power Processor, and Software

FTP-850	Test Procedure - Preliminary Integration Test of a Flight Thruster, Power Processor, and Software
FTR-850	Test Report - Preliminary Integration Test of a Flight Thruster, Power Processor, and Software

System Integration With The Spacecraft

FM-1000	IAPS Handling, Installation and Test

SECTION 8

CONCLUSIONS

The goal of this program, as defined in the contract scope of work, was "to provide the Flight Package integrated with the spacecraft and readied for launch." That goal was accomplished. The IAPS Flight Package was fully integrated on the host spacecraft and all spacecraft-integration testing was successfully completed. Integration on the spacecraft was preceded by unit and subsystem tests that qualified the IAPS Flight Package for flight. Conclusions that can be drawn from the development, flight qualification, and spacecraft integration of the IAPS Flight Package include the following:

1. Testing of the IAPS thrusters, over a time span of 55 months, produced repeatable performance and consistently easy cathode ignition, even after a period of 37 months atmospheric exposure between tests while the IAPS Flight Package was undergoing spacecraft integration.

2. The control logic that was developed and built into the Digital Controller and Interface Unit (DCIU) is capable of automatically controlling startup and operation of the ion thrusters over the specified range of temperature variations. The anomaly detection and recovery routines contained within the DCIU firmware provide increased confidence for utilizing the IAPS Flight Package in a flight test mission that will be out of contact with ground control approximately 75% of the time.

3. The regulated power outputs of the PEU produce stable thruster operation over the specified range of line voltage and temperature variations.

4. Integration of the IAPS Flight Package on the spacecraft did not require any modifications to the IAPS Flight Package and concluded with a fully operational system without any known operational incompatabilities or anomalies.