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Electric Power System Test and Verification Program

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FOREWORD

This report contains the plans and results for the verification activities of the Space Station Freedom Program's (SSFP) electric power system (EPS). In April 1993, following the development test phase of the program, an effort to redesign Space Station Freedom (SSF) was initiated, and at the time of this writing, plans for a newly designed space station were being completed. This paper will only address the state of the SSF verification test program prior to restructuring.

Although SSF will soon be redesigned, it will be an unmatched scientific facility orbiting high above the Earth, providing a unique research environment. Its primary goal will be to advance scientific and technological research by the year 2000. Presently, under the management of NASA Lewis Research Center, Rocketdyne is responsible for the design, development, test, and verification of the EPS.

ELECTRIC POWER SYSTEM TEST AND VERIFICATION PROGRAM

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SUMMARY

Space Station Freedom's (SSF) electric power system (EPS) hardware and software verification is performed at all levels of integration, from components to assembly and system level tests. Careful planning is essential to ensure the EPS is tested properly on the ground prior to launch. The results of the test performed on breadboard model hardware and analyses completed to date have been evaluated and used to plan for design qualification and flight acceptance test phases. These results and plans indicate the verification program for SSF's 75-kW EPS would have been successful and completed in time to support the scheduled first element launch.

INTRODUCTION

Space Station Freedom is the most complex spacecraft ever designed and consists of eight systems developed by three contractors and NASA centers and the international partnership with Japan, the European Space Agency, and Canada (figs. 1 and 2). The systems are categorized into three groups: avionics that consist of the data management system (DMS), communications and tracking (C&T), and guidance, navigation, and control (GN&C); utilities that consist of the electric power system (EPS), the thermal control system (TCS) and the environmental control and life support system (ECLSS); and the crew systems that consist of man systems (MS) and the extravehicular activity system (EVAS). Because of the system interdependencies and sequential assembly process of SSF, each successive mission essentially constitutes a new spacecraft. As such, a rigorous test and verification program must be performed according to the scheduled program milestones (fig. 3).

The NASA Lewis Research Center and the Rocketdyne Division of Rockwell International are responsible for the design, development, test, and verification of the electric power system. The tests and verification will be performed at Rocketdyne, Lewis, and other team member facilities during the five phases of verification: development, qualification, acceptance, prelaunch, and on-orbit (fig. 4). Applicable submittal standards mandate each test contain a requirements document, plan, and report. All hardware and software will be verified by analysis, test, demonstration, inspection, or a combination of these.

DEVELOPMENT

The development phase activities for SSF's EPS, which included the analysis and testing of various design requirements, was focused on the verification of the design approach. This phase also consisted of establishing a baseline for the program requirements documents and plans and lower level work package and contractor documentation. Since the organizational structure of work package–04 (WP–04) included the Photovoltaic (PV) and Electrical Systems Divisions (ESD), the development phase activities were also divided between the PV and ESD groups.

Rocketdyne's verification analysis at the orbital replacement unit (ORU), the combined assembly, launch package, and PV module levels were all managed by the PV Division. No testing was performed prior to the preliminary design review (PDR). However, following PDR, development testing was performed on breadboard and engineering model (EM) hardware, structural models, and mass and thermal acoustic models. Test objectives were to evaluate the functional and environmental compliance of the hardware and software to performance requirements.

The ESD required significantly more breadboard and EM hardware development tests. This hardware was designed and evaluated at Rocketdyne's Electronics Laboratory, with the actual breadboard development testing performed at the Space Power Electronics Laboratory (SPEL). Two phases of SPEL testing occurred: system integration and proof-of-concept. The system integration phase verified hardware and software integration, in addition to demonstrating system electrical and control functionality (i.e., fault protection, power quality, stability, and performance). The proof-of-concept phase was established to perform system level functional tests, which were used to test system and ORU level functional performance parameters.

The results from development test activities were used to validate the design, mathematical models, and analysis. If development tests had been intended for certification, the test would have been "predeclared" a qualification test prior to its start.

Qualification

Most of the design and performance requirements are formally verified in the qualification phase. Qualification represents the broadest scope of verification within design tolerances to which a component is subjected. This phase verifies that the design conforms to all requirements when subjected to environmental and life-cycle conditions. Qualification hardware and software have the same configuration and manufacturer as the flight hardware and software. Flightlike hardware and software, which is form, fit, and function, are used to resemble any interface and can be verified by analysis, test, inspection, demonstration, or a combination of these.

Following qualification testing, Rocketdyne submits reports of test results to NASA for a "closeout" of program requirements. The test report number associated with the closeout of a particular requirement is archived in the EPS data base verification module and uploaded in the program's master verification data base system (MVDS) by a transitional data base developed at Lewis. This information supports hardware and software certification activities and design reviews.

Qualification for the EPS PV hardware and software is performed at Martin Marietta for the integrated equipment assembly (IEA); at the Lewis Space Power Facility (SPF) for solar power module (SPM) testing, and at Johnson Space Center for SPM modal testing. Orbital replacement unit testing is performed at Rocketdyne and the responsible subcontractor facility. Orbital replacement unit testing consists of environmental, electromagnetic interference/electromagnetic compatibility (EMI/EMC), and electrical functional.

Electrical system hardware and software are verified during electrical system integrated test (ESIT) activities at both SPEL and the Power Systems Facility (PSF) at Lewis.

Acceptance

During the acceptance phase of the program, WP–04 determines through testing and analysis that the EPS flight-developed hardware and software meet the specified design and performance requirements.

Integrated assembly and checkout (IACO) of the PV module, the integration of all assemblies into the on-orbit assembly configuration and prepared for launch into the cargo element, is performed by WP–04 during the acceptance phase. Final hardware and software checkout also occurs at this time. After IACO is performed at the PSF, the cargo element is shipped to the NASA John F. Kennedy Space Center.

Prelaunch

Prelaunch or launch processing phase activities are performed at Kennedy and are designed to ensure that the SPM cargo element (fig. 5) is capable of performing its intended functions. After the cargo element inspection is conducted, a prelaunch test of the first two on-orbit stage configurations, including one WP–04 PV module, is performed. This stage configuration test, called the stage 2 test, is designed as a "low-power" test to verify the physical and functional interfaces of the spacecraft.

On-orbit

The on-orbit phase verifies the spacecraft's successful buildup, checkout, demonstration, performance, and operation. Data are retrieved through the use of built-in tests and actual on-orbit demonstrations to validate mathematical models, analyses, simulations, demonstrations, and test results obtained on the ground.

SPACE STATION FREEDOM PROGRAM OFFICE

The Space Station Freedom Program (SSFP) Office, located in Reston, Virginia, comprises seven divisions with verification duties. Of the seven, three have associated verification tasks: the Systems Engineering and Integration (SE&I) Office, the Utilization and Operations Office, and the Avionics Systems Office. The SE&I Office is responsible for the development of the verification requirements and implementation; however, the implementation of these requirements is managed from the Marshall Space Flight Center. The Utilization and Operations Office manages payload and ground operations integration and verification. The Avionics Systems Office manages avionics integration and verification and the software independent verification and validation (IV&V) requirements and plans (fig. 6).

Verification requirements are defined in section 12 of Space Station Program (SSP) 30000, "SSF Program Definition and Requirements Document" (PDRD). These requirements are implemented in SSP 30666, "Program Master Verification Plan" (PMVP) (fig. 7), which defines the verification of hardware and software design and performance requirements.

In addition to defining verification requirements, the SE&I Office establishes the program verification policies, goals, and objectives. To meet verification program milestones and to improve communication and integration between work packages, weekly telecons were established. The SE&I Office also administers the Program Verification Panel (PVP), a level II working group designated to resolve issues and concerns pertaining to verification. The MVDS, one of the group's main working tools for the implementation process, is used to confirm that all SSF requirements have been verified at all levels.

Distributed System Architects

Since the functional systems of SSF (e.g., EPS and DMS) are distributed, the level II end-to-end systems are independently verified by Distributed System Architects (DSA). Level II verification plans for the distributed systems are located in the architectural control documents (fig. 8). Each DSA is responsible for ensuring that required system verification information from other work packages and international partners be obtained. This information is documented in a "Verification Completion Notice" (fig. 9), uploaded into the MVDS in preparation for the Certification of Flight Readiness (CoFR) process, and documented in a separate plan for each distributed system.

Technical Disciplines

Technical disciplines (TD) are responsible for managing the tasks in figure 10. Their role is similar to the DSA's verification of level II requirements for their specific discipline, in that they must also complete verification completion notices for MVDS uploading in support of the CoFR process. Like the distributive system verification plans, there are also technical discipline verification plans.

ELECTRICAL SYSTEMS VERIFICATION

The Electrical Systems Division's ORU's are located throughout SSF and are connected to provide power to the station and its users. The ORU's are verified at the box level for different environments and interfaces and as part of the integrated end-to-end system level EPS tests. Environmental testing is conducted on each ORU during the development, qualification, and acceptance phases. EPS system level tests from the energy source to the user loads are performed in the WP–04 electrical system testbed, in SPEL and later in PSF.

The orbital replacement unit fidelity used in the development phase is both breadboard and engineering model hardware. The qualification phase uses breadboard, engineering model, and flightlike hardware, and the acceptance phase exclusively uses flight hardware. Design qualification is completed on individual ORU's with prototype hardware and is then certified for flight worthiness following the completion of acceptance phase testing. Results from the ORU and system level tests are used to validate and update verification analyses models.

Proof-of-concept breadboard testing is conducted at SPEL (see the following section). Higher fidelity hardware is integrated into SPEL/ESIT (see the Electrical System Integrated Test section) during which the EPS is qualified and flight software is validated (see the Electrical Power System Software Verifiction section). After the completion of system level qualification testing at SPEL on the SSF configuration that constitutes the first six scheduled assembly flights, the testbed is moved to the PSF at Lewis. The testing conducted at PSF is used to sustain engineering activities for space station configurations that are expected after the sixth launch.

Some power management and distribution (PMAD) ORU's are delivered to other Space Station Freedom program participants (SSFPP) to support their verification activities. Engineering model hardware is sent to support assembly level acceptance testing; only performance and functional testing is conducted on the assembly elements when the flight hardware is integrated and outfitted.

Electrical System Division Verification Results to Date

The ESD development plans for each ORU were to manufacture and test both breadboard and EM fidelity hardware. Breadboard models were produced and tested first. For most breadboard ORU's, only electrical functional tests were conducted before being taken to SPEL to be integrated into the testbed. Engineering model hardware was to have electrical and environmental tests performed. Specific environmental tests were random vibration, thermal cycle, and thermal vacuum. Finally, EMI/EMC tests were performed. An exception was a breadboard remote power controller module (RPCM) that was exposed to limited thermal testing in order to gather data for updating analyses models.

Electrical component testing also comprised a large part of the development phase. Problems or failed test requirements usually resulted from limitations in the breadboard hardware. All deficiencies were addressed by component modifications, upgraded hardware, or specification changes. Overall, the unit's performance was not affected adversely by requirement noncompliances. The noncompliances were documented and forwarded along with the hardware to SPEL for integrated system testing.

The proof-of-concept system level breadboard testing was to be conducted in a sequence of three tests spanning over 2 years beginning with the completion of PDR and concluding prior to the start of the critical design review (CDR). Test results from observing system interdependencies were used to evaluate the design and determine how to operate the system on-orbit.

The SPEL test 1 configuration (fig. 11) represented a simplified one-channel PV module architecture consisting of a solar array and two battery-energy-source simulators, a breadboard sequential shunt unit (SSU), a direct-current switching unit (DCSU), and two battery control discharge units (BCDU). Advanced development software was used in the photovoltaic controller unit (PVCU).

The SPEL test 1 evaluated power output, power quality, communications, and fault management. The power output test demonstrated successful EPS orbital performance during nominal isolation and eclipse phases. Steady-state and transient energy source control tests were conducted by operating the SSU and BCDU under various load conditions to demonstrate system response and power quality. Communications tests consisted of sending commands to the breadboard ORU's and monitoring the feedback. Minimal fault testing was performed as a result of the breadboard hardware limitations.

Most SPEL test 1 results were expected with the exception of those tests performed on the BCDU. The problems associated with the BCDU were analyzed, and design modifications to the unit resulted. Other minor problems and anomalies linked to the support equipment and system-under-test hardware and software will be corrected and retested as higher fidelity hardware and software is integrated into the testbed.

The configuration for SPEL test 2 was the same as that used in test 1 with the addition of a breadboard main bus switching unit (MBSU) and direct current to direct current converter unit (DDCU) (fig. 12). A new version of the software, upgraded breadboard hardware and a prototype DMS kit were also integrated and tested in the SPEL test 2 configuration. This test examined primary power output requirements, power quality requirements, fault protection, communication functions, and it validated the recommended SPEL test 1 design modifications to the BCDU.

The power output tests measured the performance of the system during isolation, eclipse, and transition orbital phases. Specific tests focused on the operation of the DDCU, SSU, and BCDU. The array and battery source simulators were programmed for a range of steady-state and transient load conditions. The current and voltage output of the ORU's under test were monitored during nominal battery charge and discharge for the changing load conditions. Fault tests were performed to demonstrate the response of each breadboard ORU in the system under test. These tests showed the ORU's ability to detect and isolate faults, thus protecting the power system. The communications tests demonstrated EPS software- and firmware-executed commands sent by tier I through the DMS kit.

The results of SPEL test 2 revealed problems encountered during the fault tests. Some minor software problems occurred during the power output tests and these problems were corrected during the test with updated software. Power output tests showed that power quality requirements were met and system stability maintained. Approximately 90 percent of the many commands issued during the communications tests were completed successfully and all test anomalies and problems were documented. Fault tests were performed successfully on upgraded hardware during SPEL test 3 to address those problems encountered in test 2.

SPEL test 3, the SSF EPS proof-of-concept test, was originally scheduled to be completed before the WP–04 CDR but did not conclude until several months later. SPEL test 3 objectives were to evaluate primary power output, secondary power, power quality and stability, system protection, redundancy and fault tolerance, and management and control. The test configuration for SPEL test 3 consisted of the ORU's and simulators present in tests 1 and 2, and a representation of the secondary/tertiary distribution system including RPCM's (fig. 13).

Similar to SPEL test 2, the power outputs of the SSU, BCDU, and DDCU's were observed over a range of voltages and currents in the battery charge (insolation) and discharge (eclipse) phases. The two tests were then combined in a complete orbital test that continuously exercised the ORU's from insolation through transition to the eclipse phase of an orbit. The response of the system was measured during fault tests performed to analyze system protection capabilities. The power quality was maintained during orbital transition tests and requirements were met during the fault tests. Management and control capabilities were tested by sending commands to ORU's and monitoring the response.

With the exception of the fault tests on the MBSU, BCDU, and SSU, the results for SPEL test 3 were generally expected. All results were documented in summary test reports and nonconformance reports for those tests not meeting system performance requirements. Nonconformances were reviewed, appropriate changes in hardware and software requirements were made, and the tests were reconducted. Anomalies in the BCDU during power output tests were corrected, and the BCDU was successfully retested.

SPEL test 4 was an add-on proof-of-concept test that was conducted after the WP–04 CDR to determine incomplete man-tended capabilities (MTC) objectives and configurations. The tests were to be completed by the end of September 1993 followed by testing for facility preparation and integration for design qualification. The system under test built upon the SPEL test 3 configuration. A third BCDU and battery simulator were added in parallel to the previous two, in addition to a second MBSU with two internal DDCU's paralleled from each MBSU. This is the first configuration that simulates two simplified power channels.

SPEL test 4 tested three BCDU's operating in parallel, DDCU's paralleled from separate channels, and the restart of one power channel from another, and removed discrepancies from SPEL test 3. Primarily the same tests will be run in SPEL test 4 as in SPEL test 3: primary and secondary power output, power quality, system protection, redundancy and fault tolerance, and management and control.

Electrical System Integrated Test

Integrated system level verification and validation tests are supported by SPEL/ESIT. The tests are divided into major phases that span over 3 years. Besides EPS design verification and validation, the electrical interfaces and functions with other space station elements are verified. Objectives of the tests focus on verifying power performance, control, and system protection and include verifying system stability and power quality on the primary and secondary power distribution systems and validating software control operations and fault tests.

An early test phase concentrates on battery performance. The battery simulators used in early SPEL tests 1 to 4 are replaced with engineering model batteries. This phase conducts tests that were performed with the battery simulators during SPEL tests 1 to 4 and collects data to compare and correlate the performances of the battery simulators with EM batteries. Another important phase tests the EPS in each stage configuration, including tests of EPS operations: startup, shutdown, and restart. The testbed remains at Rocketdyne for testing through the MB–06 flight configuration and then moves to the Lewis PSF.

The primary testing configurations will represent two EPS channels. Testing is initiated with the flight software, containing one EM channel and one breadboard hardware channel. As the test phases progress and qualification hardware becomes available, the hardware is integrated in the testbed, replacing the breadboard hardware. The EM batteries will be available for a brief testing period before they are replaced by the battery simulators. The other energy sources (solar arrays) will be simulated. Likewise simulated loads will be used during the test with the opportunity to test actual loads from other available systems.

Secondary and tertiary power distribution architectures represent WP–01 and –02 element configurations. Early planning to test these architectures as part of the end-to-end electrical power system required that international partner switchgear controllers be integrated in the SPEL testbed. High on the priority list of tests to be performed with the switchgear hardware is fault testing to ensure that the required system protection, system stability, and power quality be maintained.

SOLAR POWER MODULE VERIFICATION

The SPM provides the hardware and software required to collect, store, convert, and distribute electric power. The starboard SPM includes two photovoltaic (PV) modules while the port SPM includes only one PV module by the permanent manned capability phase. The port SPM is scarred for "growth" to add another PV power module. The PV power module consists of two beta gimbal/photovoltaic array assemblies (BG/PVAA), two beta gimbal transition structures (BGTS), one integrated equipment assembly (IEA) and associated integration hardware. Testing for the SPM will be performed at the ORU, subsystem, and system hardware fidelity levels.

Verification Test Results to Date

Analyses to be performed for the SPM are

- Thermal models
- Reliability
- Functionality
- Space station operation
- Mass properties
- Performance
- Maintainability
- Safety
- Environmental
- Interface
- Structural

Developmental test activities are in process for the three-bay deployable and retractable mast (FASTMast), BG-bearing life cycle, and energy storage. Currently these test are all progressing according to schedule without any significant problems.

The FASTMast test verifies certain modes of failure for the test hardware. Each array is supported by a FASTMast that is approximately 110 ft long and consists of 32 bays, each 30.4 by 40.5 in. (fig. 14). The FASTMast is the primary structural member that must resist any loads imposed on the arrays. All tests performed to date on the three-bay FASTMast were configured using an eccentric axial compressive load sufficient to simulate longeron compression resulting from limit and ultimate bending moments.

The results of the axial tests show good agreement between test and analytical data that predicted longeron loads. The actual test data showed that the FASTMast sustained these loads without buckling. Measured deflection data and visual inspections gave no indication of any pin/joint damage or yielding along the critical longeron load path.

For the shear test, a shear load was applied at the top of the three-bay test mast with the axial and torsional loading devices disconnected. Displacements and strains were recorded at various locations along the mast length. In the ideal case, the applied transverse shear load is shared equally by two opposing faces of flexible battens. In summary, the mast behaved as predicted by the contractor for the linear regime of this test.

The axial-torsional test achieved an axial longeron compression load equivalent to that imposed by a 73 000 in.-lb ultimate bending moment. A superimposed 1600 in.-lb torque load did not produce system buckling in the critically loaded longeron. In addition, displacements and strains were recorded at various locations along the mast length. Overall, the mast performed as predicted for the axial, shear, and axial-torsional tests.

The BG-bearing life cycle test 1 objective was to verify a bearing life of 120 years under simulated and accelerated environmental and induced conditions. Retention of the structural and functional integrity of the bearings, without unacceptable degradation, demonstrates that the test article (fig. 15) is capable of sustaining the solar array assemblies through all anticipated and significant operational loads and environmental conditions. To date, there has only been one event during testing. The frictional torque on the horizontal unit exceeded 75 in.-lb, which was higher than the specification limit, and the units were shut down.

Toroid wedging is one of the leading theories that explain the increased frictional torque. The horizontal alignment of the beta axis means that the bearing is in a vertical plane (perpendicular to the axis of rotation). Since there is no cage in this bearing to maintain equal spacing in this orientation, gravity tends to pull the balls and toroid separators to the bottom, jamming them together where it is possible to generate higher friction.

The test was restarted by reversing the direction of rotation for a few degrees, then resuming rotation in the original direction. This redistributed the balls and toroids, returning the torques to normal. The limit of the current drive motor in the test cell was determined to be capable of 360 in.-lb. The increased torque limit is caused by the balls rolling over fresh lubricant wear debris, which is normal for a solid lubricant instead of the balls and separators jamming. To date, torque spikes near 75 in.-lb have occurred, but there has been no trend of their increasing observed. The horizontal unit has accumulated an equivalent of 23 years of beta cycles.

The BG-bearing life cycle 2 test examined the bearing subassembly for wearout and examined unanticipated failure modes associated with a mechanically moving assembly and the verification of the design against such deterioration. This test used a vertical unit and completed 37 successful weeks of testing to date.

Integrated Equipment Assembly Qualification

The IEA conditions and stores electric power collected by the PV arrays for use in SSF operations. The assembly supports on-orbit operations with either a complete or reduced energy storage subsystem complement and provides the framework to structurally, electrically, and thermally integrate the PV power module for launch and on-orbit operations.

The IEA verification program assures that all requirements on the integrated hardware are satisfied prior to flight. Verification of the IEA consists of mass thermal-acoustic model testing prior to the PDR, engineering model testing, and qualification testing including EMI/EMC, thermal vacuum, structural, and electrical functional testing following the critical design review.

The energy storage subsystem is verified at the IEA and battery levels. The subsystem consists of six Ni-H_2 batteries, each with a dedicated battery control discharge unit as shown in figure 16. Integrated equipment assembly verification is performed without two of the batteries and BCDU's in the test configuration. Because of weight considerations and low power requirements on the early stages of SSF, the batteries and BCDU's are launched later. The PV power module battery consists of 76 Ni-H_2 cells (60 plates per cell) in series to produce the 95-V dc average discharge voltage. The cells are divided into 2 assemblies of 38 for packaging in the ORU box; therefore, each battery is composed of 2 battery subassembly ORU's wired in series. During eclipse, the energy storage subsystem discharges stored energy to the dc power bus; during sunlight, it receives and stores energy collected by the solar arrays.

The verification of the thermal control system will be accomplished by a variety of analyses and tests. The ORU level heat loads are verified at its testing level and are used to verify the integrated TCS by analysis. The integrated TCS is also tested at the IEA thermal balance/vacuum qualification test. The test uses a simulator and subcontractor-conducted radiator panel thermal vacuum tests which anchor the analysis models.

Mission Simulation Test

A mission simulation test is planned at the NASA Lewis Space Power Facility in Plum Brook, Ohio. The test is designed to validate hardware and software at the PV module system level in the simulated operational environment. This thermal vacuum test is a demonstration with no pass/fail criteria applied. Data from this test will be used for PV module thermal model correlation, for comparison with the IEA thermal vacuum qualification test results and validation of software commands to the beta gimbal assembly/electronics control unit (BGA/ECU). The test will demonstrate

- PV module startup and operation after hot and cold soak
- PV module performance in simulated PMC on-orbit environmental conditions
- Shutdown and hot restart
- Beta gimbal command and control
- Thermal model calibration

The PV module is tested in a cryoshroud (approx. 46 by 22 by 80 ft), which is scheduled for completion by June 1994. The Space Power Facility provides the thermal vacuum environment for the orbital simulation testing. The temperature environment includes an array of quartz lamp fixtures and cold walls.

In addition, there is a qualification test of the PV module radiator in the cryoshroud prior to the mission simulation test. The PV radiator is an ORU consisting of a set of panels that reject waste heat to the space environment by thermal radiation. Liquid coolant conveys the heat to the radiator and circulates through channels embedded in honeycomb panels. This test demonstrates the deployment and retraction functions of the radiator in a thermal vacuum environment.

ELECTRICAL POWER SYSTEM SOFTWARE VERIFICATION

All EPS flight software verification activities are performed in the Central Test Facilities (CTF), located in Houston, Texas and in WP–04 test facilities. Following testing at the CTF, the verified software is delivered to a WP–04 facility for validation in a hardware and software integration test. Central Test Facilities provided software and DMS kits while WP–04 provided simulations to be used in the verification testing of the EPS flight software. Flight software validation at the WP–04 test facilities will use government-furnished equipment (GFE), CTF software, a DMS kit, the WP–04 simulations, and system hardware. The software verification tests are a series of interrelated tests that build on each other starting from the smallest unit, a computer software configuration item (CSCI), and culminate in a test with the entire EPS at SPEL/ESIT.

The EPS flight software and control system is a hierarchical set of communicating processors and embedded controllers that manage and control the EPS. The highest level of control, tier I, issues commands including those received from the ground and crew. Tier II, which contains the highest level of EPS software, receives commands from and transmits data to tier I to other tier II systems, and to the two subordinate EPS tiers below tier II. The EPS tier II software application, power management controller application (PMCA), resides on a standard data processor. The PMCA controls two tier III applications: the photovoltaic controller application (PVCA) and the main bus controller application (MBCA). These applications primarily interface with the

PMCA and the tier IV firmware controllers internal to the EPS ORU's. The PVCA controls all the ORU's associated with the same PV module whereas the MBCA controls the primary power distribution network, including all EPS ORU's not located on the PV module.

As such, verification testing for those requirements applicable to software commands written by WP–04 for tiers III, IV, and some of II can be performed at WP–04 facilities. Tier II requirements that pertain to the communications between the EPS and other SSF systems are verified at the CTF where all SSF systems software will be present. All WP–04 flight software is developed, modified, updated, and recorded at the Rocketdyne Software Production Facility (SWPF). The PMCA, PVCA, and MBCA are each made up of computer software configuration items (CSCI). Like an ORU, each CSCI is individually verified and acceptance tested. Verification tests are performed in the SWPF where specific tests show that the software correctly receives, transmits, and provides valid commands, collects data, and detects out-of-operational limits.

Once the CSCI's have been individually verified, they are verified as a system. This EPS software verification is conducted at the CTF. Here, the software and hardware required to support the testing are validated prior to WP–04 system software verification. The tier IV WP–04 firmware controllers are simulated. Many subtests are run where the management and control of EPS functions such as PV module temperature control, PV module fluid leak, and primary power voltage regulations are monitored through simulated sensor data. Upon receiving an expected output such as a voltage, current, pressure, temperature, or an on/off status indication in response to a test input, the operation is considered to be verified.

The verified flight software from the CTF is then integrated in WP–04 system verification tests with the EM and qualification hardware at SPEL/ESIT. This testing validates that the hardware is compatible with the software while the system performance is verified. Pump and flow control subassembly and beta gimbal electronics control unit (BGECU) functions are simulated at SPEL/ESIT because this hardware is not part of the EPS testbed. Photovoltaic control unit to pump and flow control subassembly (PFCS) control functions are validated during IEA qualification tests which are part of the PV tests. During the mission simulation certification test at the SPF, the PVCU-to-BGECU functions are validated. The software verification tests are a series of interrelated tests that build on each other starting from the smallest CSCI unit and culminate in a test with the entire EPS at SPEL/ESIT.

In an almost parallel effort to the software verification and validation activities, independent verification and validation of the EPS application software is conducted. The IV&V process ensures that the software has been properly implemented and complies with requirements during the verification phases. Through a series of independent test plans and scenarios, IV&V testing is performed on the same software and at the same facilities as the formal software verification activities. Independent verification and validation of the stand-alone PVCA and MBCA CSCI's is conducted at the SWPF. The software is then moved to the CTF where the PMCA and the combined EPS CSCI's are tested. EPS flight software and hardware integrated IV&V testing is completed at SPEL.

Verification Activities to Date

To date, no software verification has occurred. The establishment of a consolidated set of system software requirements occurred several months before the CDR. Test plans and procedures have been generated for each CSCI.

The EPS simulation support software used at CSF is currently being developed. When complete, this software will be tested at Rocketdyne's Simlab to detect any errors before being sent to the CSF. Software errors will be logged in discrepancy reports and the source code will be modified, requiring a rerunning of the affected test case.

The testing will demonstrate compliance with requirements (functional tests), coding the software in accordance with applicable standards, and ensuring that unit decision outcome produces the desired results. These objectives will be accomplished through fault detection and recovery, erroneous input tests, timing tests, software interface tests, and transmitting or receiving proper commands.

Central Test Facilities

From lessons learned and steering groups/study teams, it was recommended that a test system for program level integration and certification be established to model the Shuttle Avionics Integration Laboratory (SAIL). As a result, the CTF's were approved and combine all of the systems together in a simulation to perform software verification and system-to-system horizontal integration. This type of integration conducts limited station level functional and performance verifications, end-to-end software and avionics functionality, and interface verification. Certification of the CTF's and the support hardware and software are completed prior to any formal testing.

The Central Software and Central Avionics Facilities will remain in place to support on-orbit anomaly resolution for the life of the program and will be used to support the stage verification of the integrated flight software. The CAF verifies the interaction of flight software and avionics prior to flight such as the CSF on a stage-by-stage configuration level. This facility will provide a high-fidelity representation of SSF avionics using a combination of flightlike components and simulations.

Work package–04 representatives on the CTF teams participate in planning and implementing a verification program that ensures EPS software test activities be completed. Work package–04 will use the CSF for flight software verification. The EPS flight software developed at Rocketdyne is transferred to the CSF facility for integrated EPS software verification and system-to-system verification. Errors encountered during testing are corrected by the accountable developer. The EPS tier IV firmware controllers are located in the CAF and therefore are simulated in CSF with software applications that accept and respond to commands. In addition to the EPS software provided to the CTF's, WP–04 provides primary power distribution simulations and firmware controllers, which will be contained in the BCDU, PFCS, and BGECU. As discussed in the Electrical Power System Software Verification section, each of these applications is validated at different WP–04 test facilities.

ELECTRICAL POWER SYSTEM OPERATIONS VERIFICATION

Electrical power system operations verification is performed during the prelaunch and on-orbit phases. Verification consists of ensuring the hardware and software has a final ground inspection, installation into the shuttle for launch, initial activation and checkout on-orbit, and continual support including monitoring and maintenance.

All SSFP elements are processed through Kennedy's facilities to be configured for orbit delivery; the cargo element's capability to function and interface with other assembly elements is verified. Photovoltaic modules and space trusses are delivered directly to Kennedy to be prepared for assembly launches aboard the shuttle. Before arriving at Kennedy, all other WP–04 hardware including DDCU's, RPCM's, MBSU's, uninterruptible power supplies (UPS), and plasma contactors are outfitted and integrated in the elements that they will be launched with at other facilities.

Upon arrival, the hardware receives an inspection on the PV module to ensure that no damage occurred during transportation. This includes a visual inspection and a sniff test of the environment around the NiH_2

batteries and ammonia coolant components. Instrumentation on board the cargo transportation system is checked and data outputs are verified to be within allowable transportation limits. The acceptance data package that accompanies the PV modules is reviewed for completeness, and any remaining open-work items are finished at Kennedy.

Postdelivery verification (PDV) tests check the element's functionality in a stand-alone configuration before integration with other elements. Ground support equipment (GSE) is used to power up hardware with controller components to verify that stand-alone testing of the PV module has ensured successful activation. Likewise, distributed WP–04 hardware outfitted and integrated in other elements is functionally checked during the assembly element PDV tests. Work package–04 GSE, includes handling, packaging, transportation, servicing, and checkout equipment that is verified and certified before use with the flight hardware. This equipment must meet physical interface, load, pressure, mechanical functional, and electrical functional SSF support equipment requirements.

Following PDV tests, integration testing with other available elements is performed. Current plans are to test the flight hardware and software that constitute the first two assembly launches. Following this test, a test will be conducted to combine flight hardware and software for assembly flights 3 to 6 with simulators for assembly flights 1 and 2. This combination will represent the first SSF full system level test for the man-tended configuration. The verification objectives for these tests are more thoroughly discussed in the Integrated Flight Elements Testing section.

The PV module that is launched as part of the first cargo element is mated electrically and mechanically to the WP–02 portion of the cargo element. After all connections have been made, an interface verification test is performed to verify the newly mated interfaces. The test power is applied by the GSE to the WP–02 portion of the cargo element that flows through the cables and connectors to the PV module. When powered up, the PV module sends commands to the GSE where successful activation is verified. Additionally, electrical continuity checks are performed on the PV power cabling to verify expected performance characteristics.

Last, before launch, a cargo element-to-orbiter interface verification test is performed. This test verifies the functionality between the cargo element and orbiter. The PV cargo element has no electrical interfaces with the orbiter nor does any other WP–04 hardware launched as part of other cargo elements; therefore, WP–04 involvement in this test is minimal. A visual test is performed to verify that no portion of the cargo element extend further than the allowable orbiter payload envelope.

Electrical power system startup and stage-by-stage on-orbit operation are verified prior to launch at SPEL and Kennedy with the flight hardware. The purpose of this testing is to ensure that the system is operating as designed by verifying that the hardware correctly accepts and carries out commands sent by the on-board crew or ground controllers. The Electrical System Division Verification Results to Date and Integrated Flight Element Testing sections provide information about the SPEL and Kennedy verification processes. Overall EPS performance assessments are made frequently with data received from monitoring ORU's and are available through the Engineering Support Center (ESC). Electrical power system startup is verified by monitoring selected parameters (e.g., voltage and current) as each ORU is activated and its functionality examined. Plans to verify the power capability requirements of the EPS with on-orbit tests are currently being worked out. Sustaining engineering and on-orbit anomaly resolution is supported by the ESC and the electrical testbed at the Lewis PSF.

Verification Activities to Date

Maintenance tasks and neutral buoyancy tests of the PV module EVA assembly were performed and completed at Johnson and Marshall during the development phase (fig. 17). The test subjects were astronauts, WP–02 engineers responsible for providing EVA support equipment and WP–04 engineers responsible for developing task operation procedures (fig. 18). The primary emphasis of the tests was to assess the CDR design by evaluating and demonstrating PV module assembly tasks and ORU removal and reinstallation activities. Different methods of removal and reinstallation were performed to determine optimum operations. Feedback received from the test focused on human-factor-related features. For example, positioning test subjects to facilitate performance of a given task included locating handholds for crew translation around the PV module and portable foot restraint (PFR) positioning for crew and tool access to the ORU work area. Recommendations for design enhancements were directed toward visual and/or tactual cues or displays to identify the work area, to align the ORU's, and to signal completion or status of a task. Other comments were received on fastener selection and tools designed to aid in the removal of the WP–04 ORU's.

The test team was confident that all procedures could be performed successfully. Any recommendations and problems encountered during the tests were reviewed by the test team at the completion of each run. The results were presented to ORU design teams and, in some cases, were carried forward as part of the WP–04 ORU CDR's.

In addition to the EVA tests conducted to support the evaluation of the CDR design, several WP–04 robotic ORU removal and replacement tests were performed (fig. 19). These tests simulated the proposed capabilities of the Canadian robot used to changeout SSF ORU's in the zero-g environment. The tests focused on the mating and demating of ORU's with the associated alignment guides and status indications. Since results indicate optimal camera views and cues are crucial to the success of the changeout tasks, the tests also investigated the occurrence any constraining camera views of assembly activities. Like the EVA tests, all of the robotic tests were successful and provided data on the removal and replacement procedures for ORU's.

Current verification plans for PV module and EPS ORU assembly and maintenance tasks are to perform a combination of computer graphic analyses and simulations, 1-g, robotic, and neutral buoyancy tests and/or demonstrations. These verification activities are performed in accordance with established assembly and maintenance procedures derived during the development phase. Certification of the on-orbit assembly and maintenance tasks is complete when all established procedures have been successfully verified.

Integrated Flight Elements Testing

Successful interface and functional verification testing proves that discrete flight elements have been integrated. The first two assembly launches in a stage 2 test and assembly flight elements 3 to 6 tested in the mantended configuration (both at Kennedy) indicate that these flight elements are available for integrated testing.

The stage 2 test is the only time when the flight PV module interfaces with another flight element on the ground. This test verifies the functionality of the systems present on each element, the continuity tests of the interfaces, and simulation of the activation and startup operation. The initial station activation of all equipment on both flight elements is performed on the ground with the exception of PV module deployments and full battery charging.

Ground support equipment is used to send power and data commands to the PV module to initialize and power up its controller (the PVCA); the ORU boxes are then checked out sequentially for channel 1. The PV TCS is activated and checked out during channel 1 operations. The TCS continues to operate circulating ammonia for the remainder of the test through the undeployed radiator to provide ORU box cooling. At the completion of channel 1 initialization and checkout, the same steps are repeated for channel 3. Other systems and elements that are functionally tested during the stage 2 test include the GN&C, C&T, and the mobile transporter.

The incremental launch schedule was adjusted to furnish an interval at Kennedy that will provide for a test of the man-tended configuration. The test will include flight hardware and software for assembly flights 3 to 6 and dedicated test articles (DTA's) representing flights 1 and 2. This test hard mates the flight-to-flight hardware to ensure interface verification. Additionally, this is the only test where verification of functional paths for station-critical systems including orbiter-to-station simulations is accomplished.

The PV DTA is delivered to Kennedy following structural test activities at Johnson. Engineering model ORU's are outfitted on the PV DTA in support of the integrated flight tests. Work package–04 flight hardware on assembly flight elements 3 to 6 includes DDCU's, MBSU's, RPCM's, UPS's, and plasma contactors. These are tested as part of the functional path test at partial power to acceptance test levels. This work package testing of the EPS to demonstrate and verify end-to-end power hardware integration and performance through the MTC configuration is accomplished during SPEL/ESIT as described in the Electrical System Integrated Test section.

CONCLUSION

The Electrical Power System's verification program was defined and documented in the electrical power system's Master Verification Plan. Verification activities were conducted as scheduled in the development phase of the program, and the results were as predicted. These tests were performed primarily on breadboard hardware to provide the necessary proof-of-concept information prior to flight hardware fabrication.

In conclusion, the electrical power system Critical Design Review was held in February 1993 and the majority of the review item discrepancies reports related to verification have already been completed and incorporated into a revised version of the Master Verification Plan. The electrical power system verification program is ready for the qualification of the hardware and software, which is the next phase of the program.

LIST OF ACRONYMS

ACD	architectural control document
BCDU	battery control discharge unit
BG	beta gimbal
BGA	beta gimbal assembly
BGECU	beta gimbal electronics control unit
BGTS	beta gimbal transition structure
C&T	communications and tracking
CAF	Central Avionics Facility
CDR	critical design review
CIL	critical items list
CoFR	Certification of Flight Readiness
CSA	Canadian Space Agency
CSCI	computer software configuration item
CSD	contract sign date
CSF	Central Software Facility
CTF	Central Test Facilities
DCR	design certification review
DCSU	direct-current switching unit
DDCU	direct current to direct current converter unit
DMS	data management system
DSA	Distributed System Architects
DTA	dedicated test article
ECLSS	environmental control and life support system
ECU	electronics control unit
EM	engineering model
EMC	electromagnetic compatibility
EMI	electromagnetic interference
EPS	electric power system
ESA	European Space Agency
ESC	Engineering Support Center
ESD	Electrical Systems Division
ESIT	electrical system integrated test

EVA	extravehicular activity
EVAS	extravehicular activity system
FEL	first elements launch
FMEA	failure modes and effects analysis
FSE	flight support equipment
GAO	Government Accounting Office
GFE	government-furnished equipment
GN&C	guidance, navigation, and control
GSE	ground support equipment
IACO	integrated assembly and checkout
IEA	integrated equipment assembly
IG	Inspector General
IV&V	independent verification and validation
MBCA	main bus controller application
MBSU	main bus switching unit
MOPO	Mission Operations Planning Office
MS	man systems
MTC	man-tended capabilities
MVDS	master verification data base system
MVP	master verification plan
NASDA	National Space Development Agency of Japan
NSTS	National Space Transportation System
OPS	operations
ORU	orbital replacement unit
OSE	orbital support equipment
PDR	preliminary design review
PDRD	Program Definition and Requirements Document
PDV	postdelivery verification
PFCS	pump and flow control subassembly
PFR	portable foot restraint
PIP	payload integration plan
PMAD	power management and distribution
PMC	permanent manned capability
PMCA	power management controller application

PMVP	Program Master Verification Plan
PSF	Power Systems Facility
PV	photovoltaic
PVAA	photovoltaic array assembly
PVCA	photovoltaic controller application
PVCU	photovoltaic controller unit
PVP	Program Verification Panel
RID	review item discrepancy
RPCM	remote power controller module
SAIL	Shuttle Avionics Integration Laboratory
SE&I	Systems Engineering and Integration
SPEL	Space Power Electronics Laboratory
SPF	Space Power Facility
SPM	solar power module
SSF	Space Station Freedom
SSFP	Space Station Freedom Program
SSFPP	Space Station Freedom Program participants
SSP	Space Station Program
SSU	sequential shunt unit
SWPF	Software Production Facility (Rocketdyne)
TCS	thermal control system
TD	technical discipline
TMIS	technical and management information system
TSE	test support equipment
UPS	uninterruptible power supplies
WETF	Weightless Environment Test Facility
WP	work package

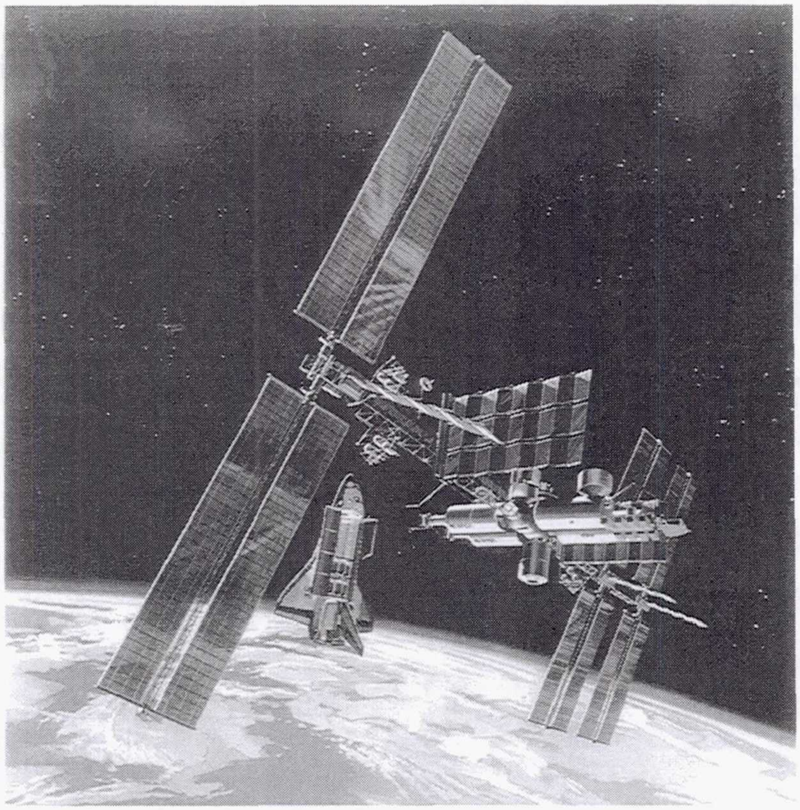

Figure 1.—Space Station Freedom.

Figure 2.—U.S. laboratory mockup.

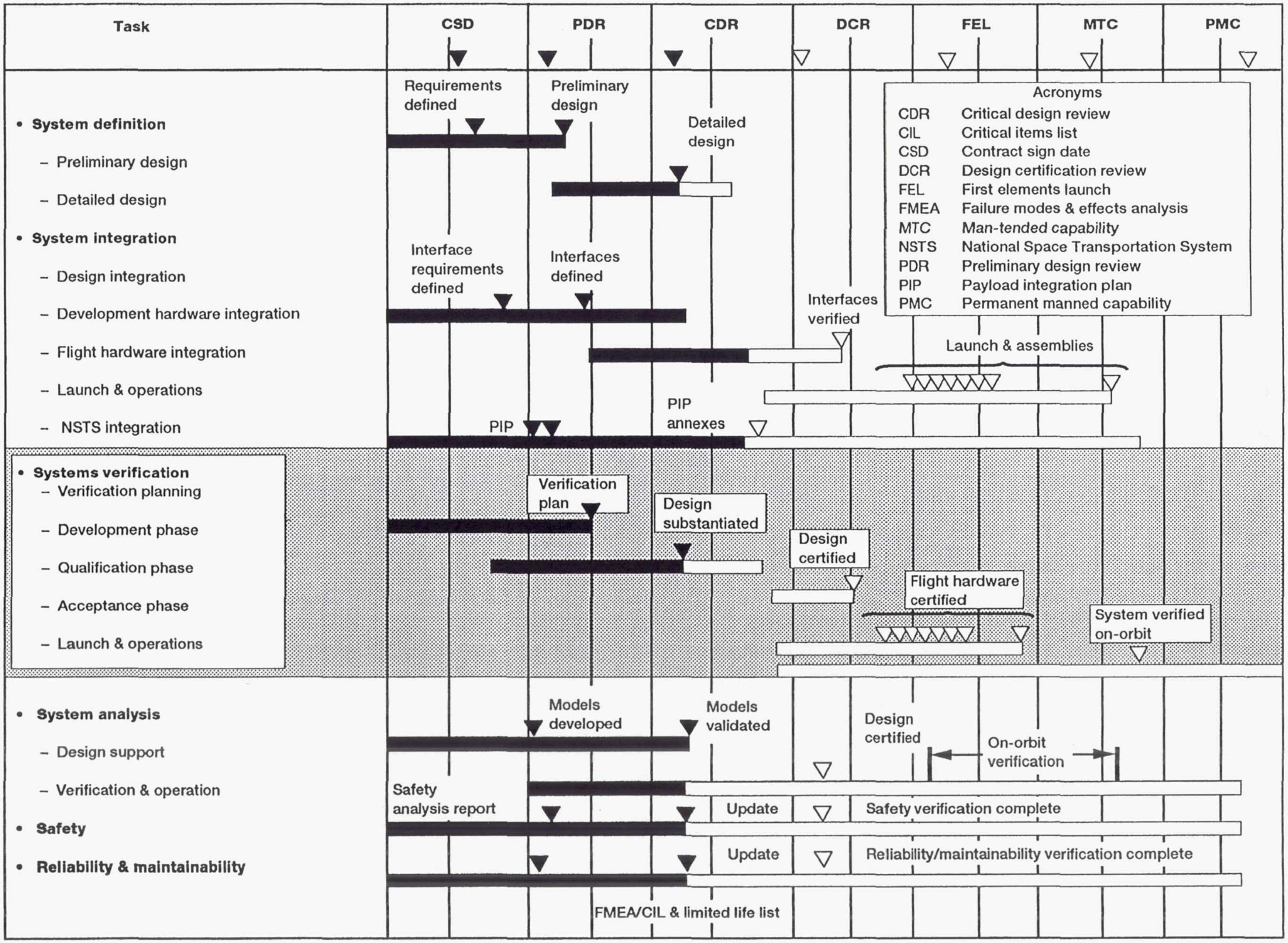

Figure 3.—Verification program summary.

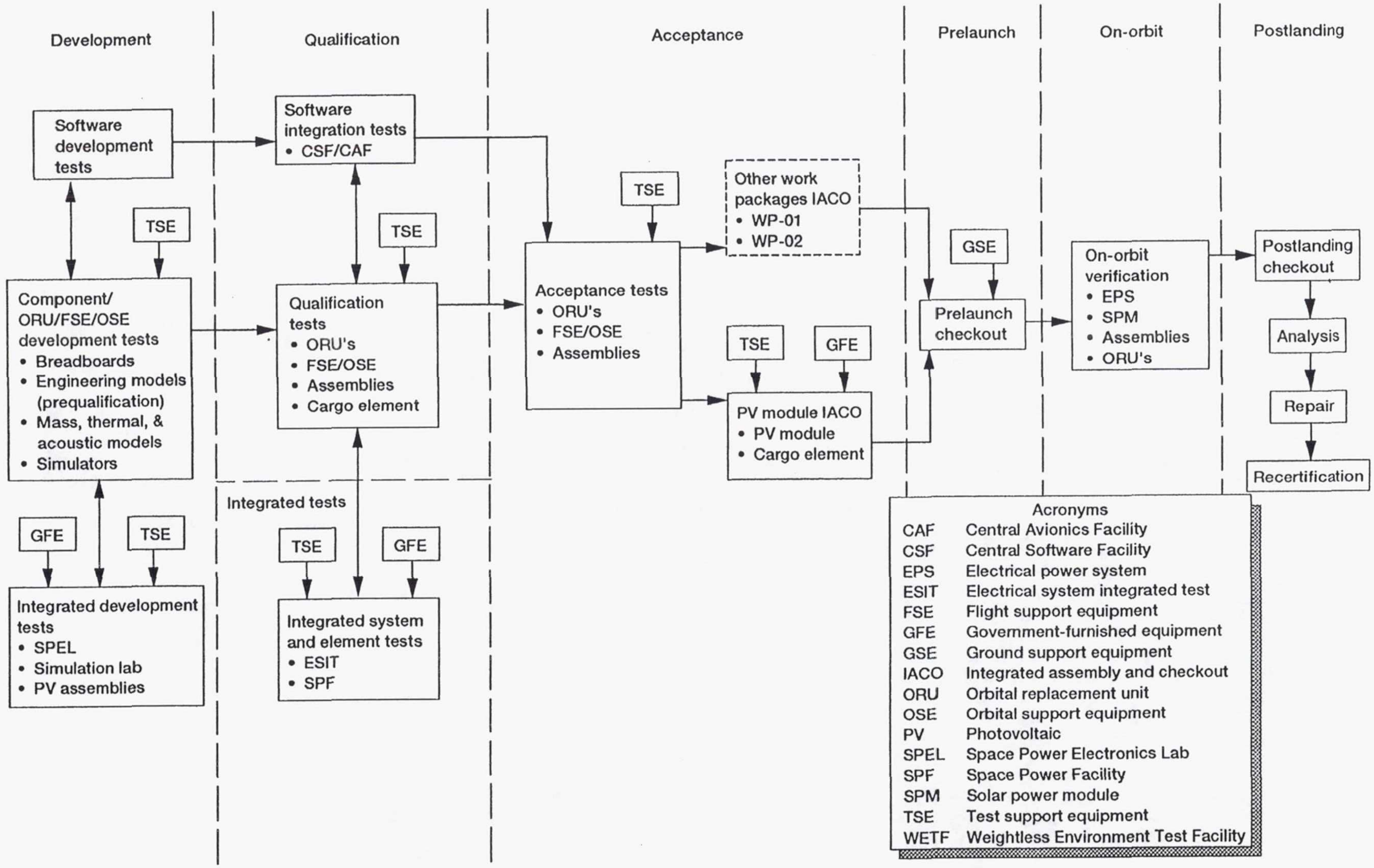

Figure 4.—Electrical power system verification process overview and work package-02 cargo.

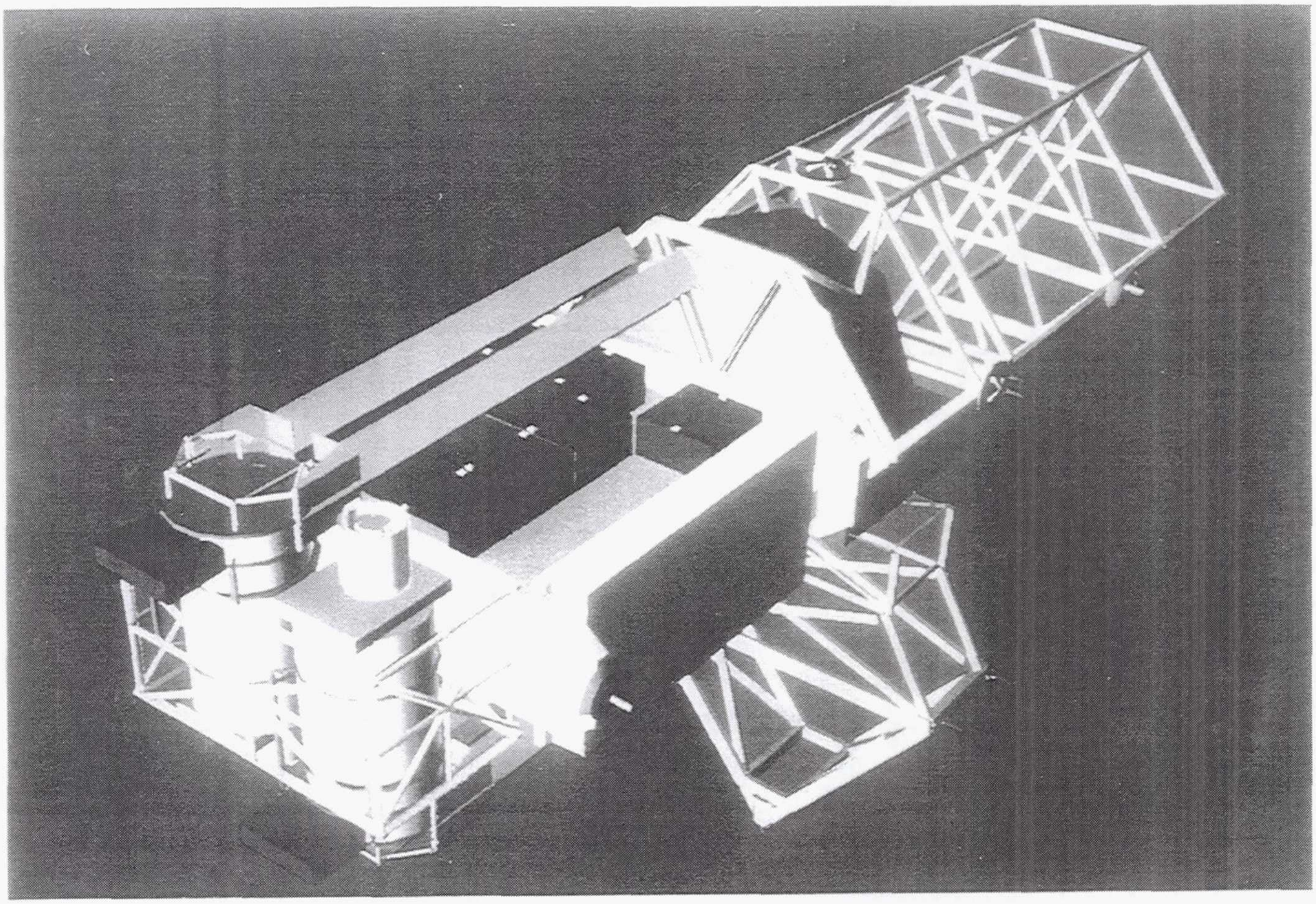

Figure 5.—Solar power model and work package-02 cargo element.

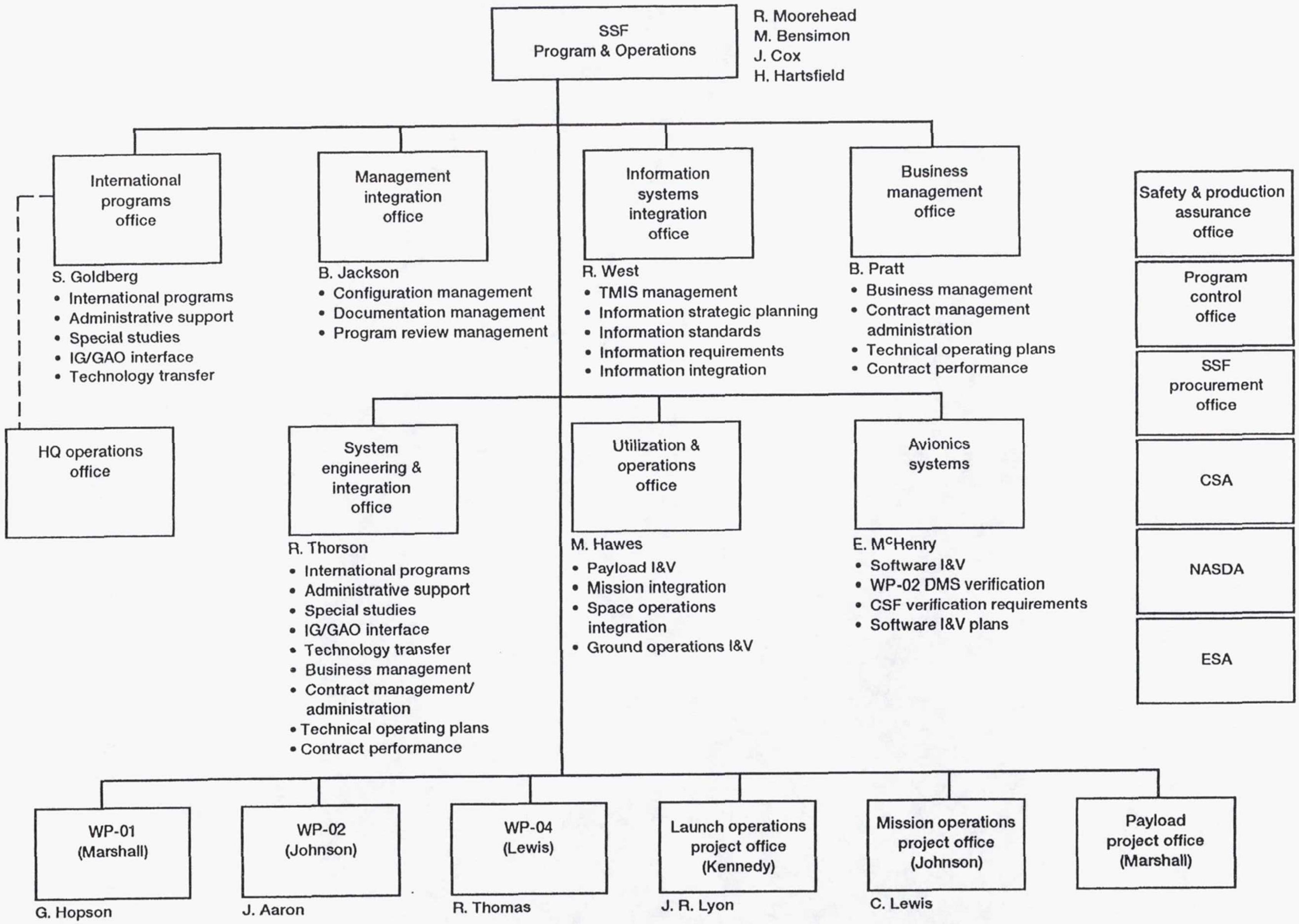

Figure 6.—Space Station Freedom program organization.

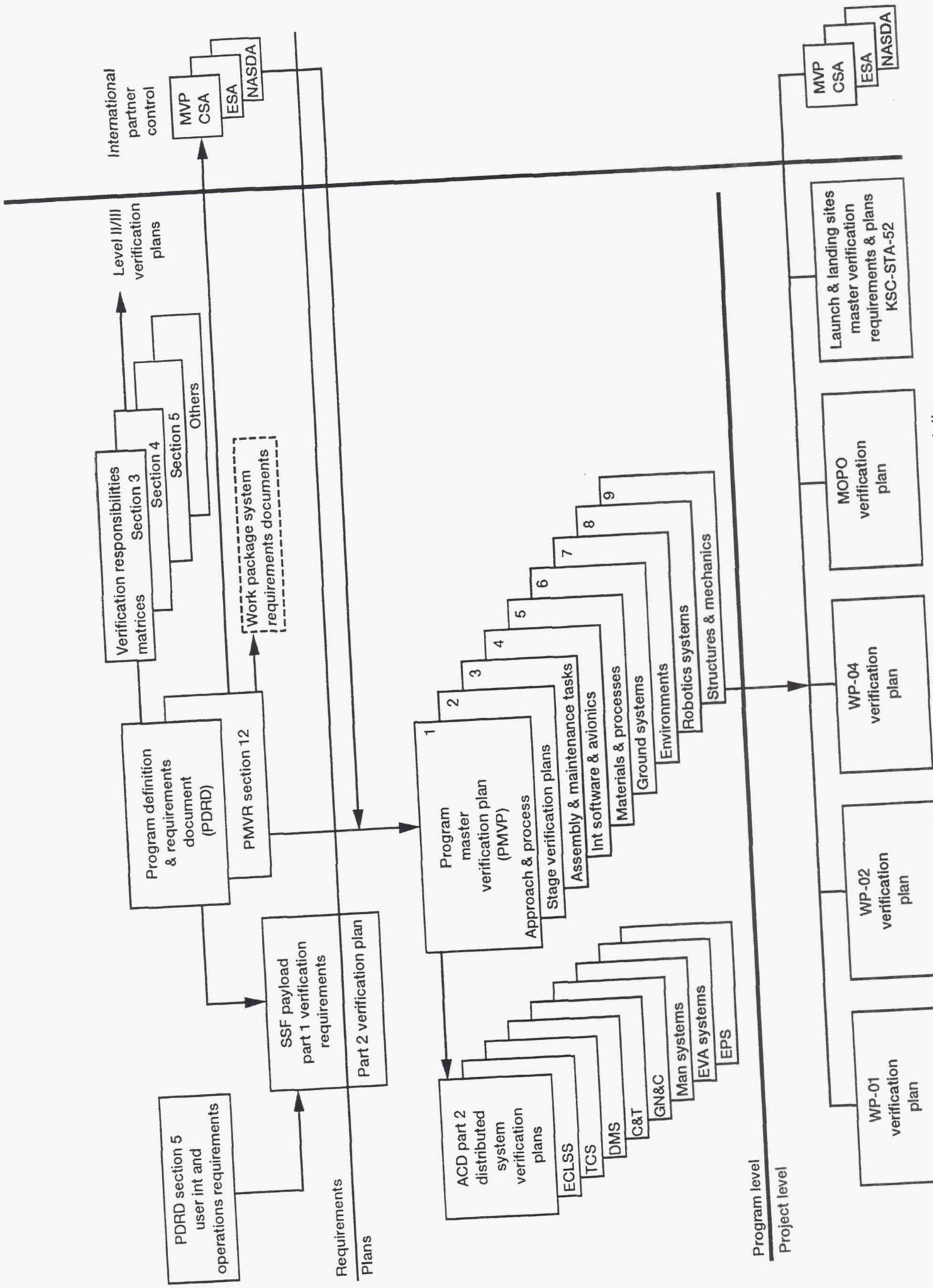

Figure 7.—Space Station Freedom program verification documentation.

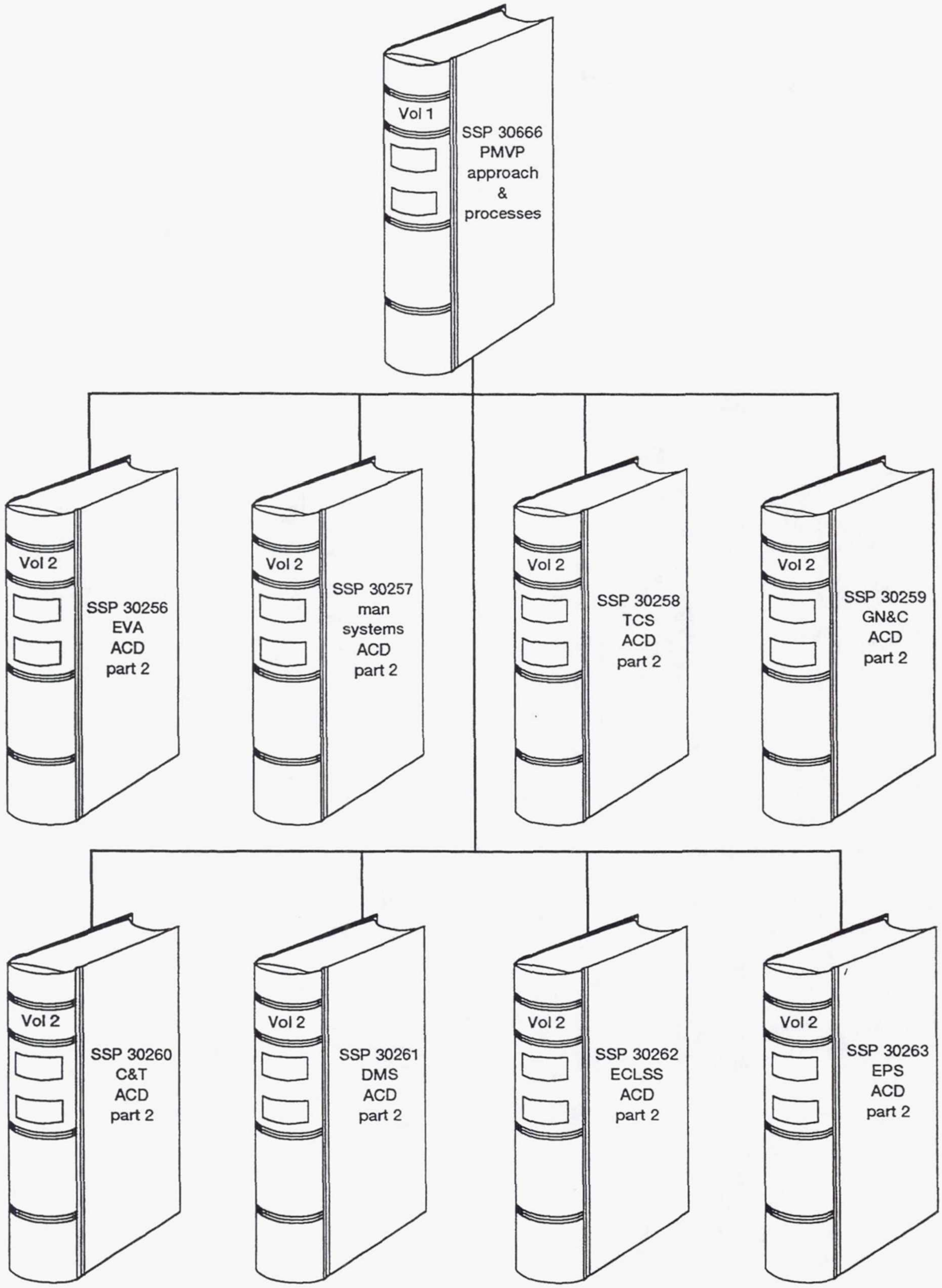

Figure 8.—Space Station Freedom distributed system verification plans.

NASA

SPACE STATION FREEDOM
VERIFICATION COMPLETION NOTICE

VCN NO. ______________________

STAGE NO. ______________________

DATE ______________________

ASSOCIATED CLOSEOUT PRODUCT (REPORT) NO. ______________

REQUIREMENTS VERIFIED:

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APPROVALS

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QA Approval: ______________	NASA QA Approval: ______________
Project Manager: ______________	NASA Program Manager: ______________

Figure 9.—Verification completion notice.

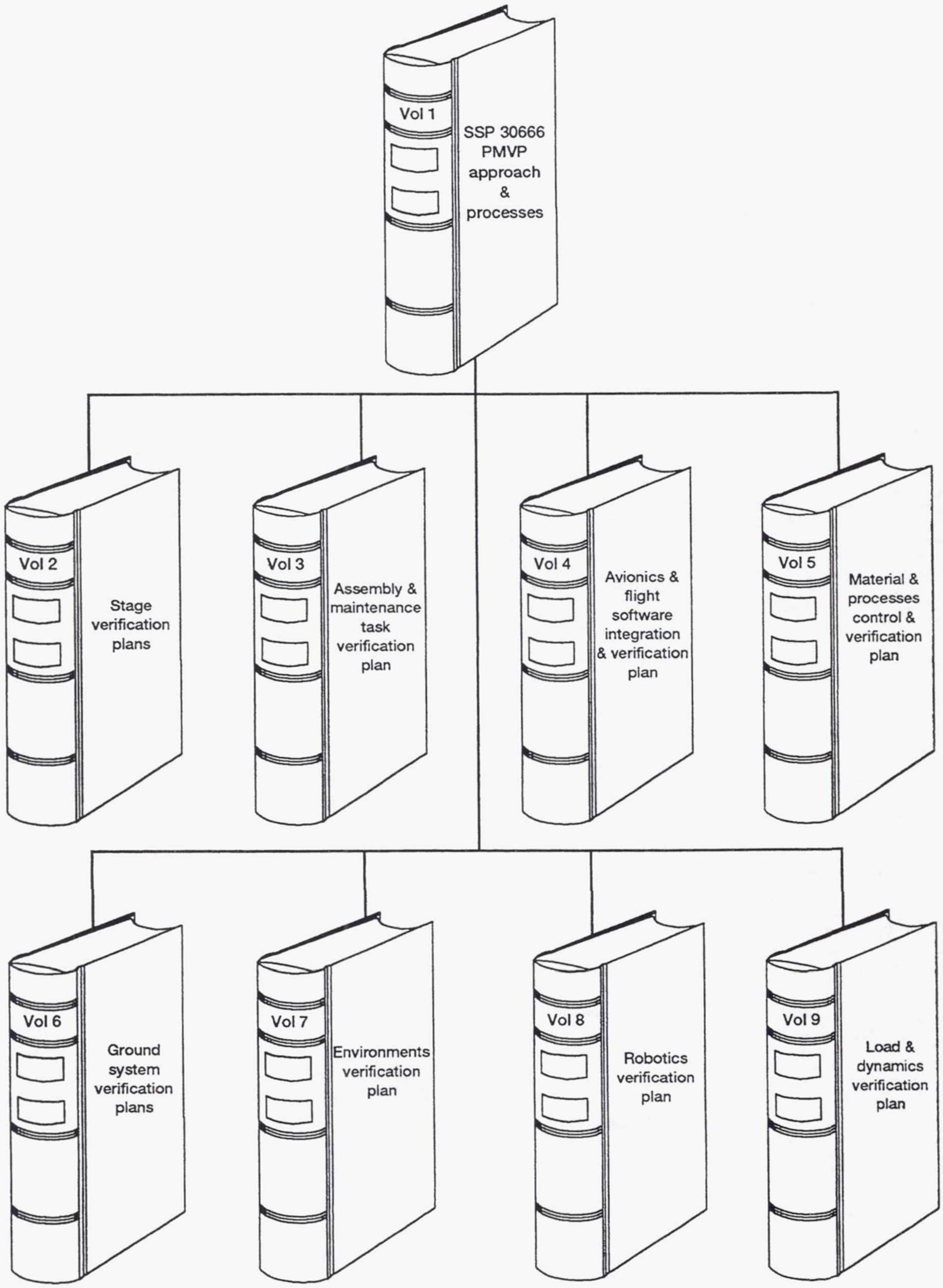

Figure 10.—Space Station Freedom program master verification plan.

Figure 11.—Space power electronics laboratory SPEL test 1 configuration.

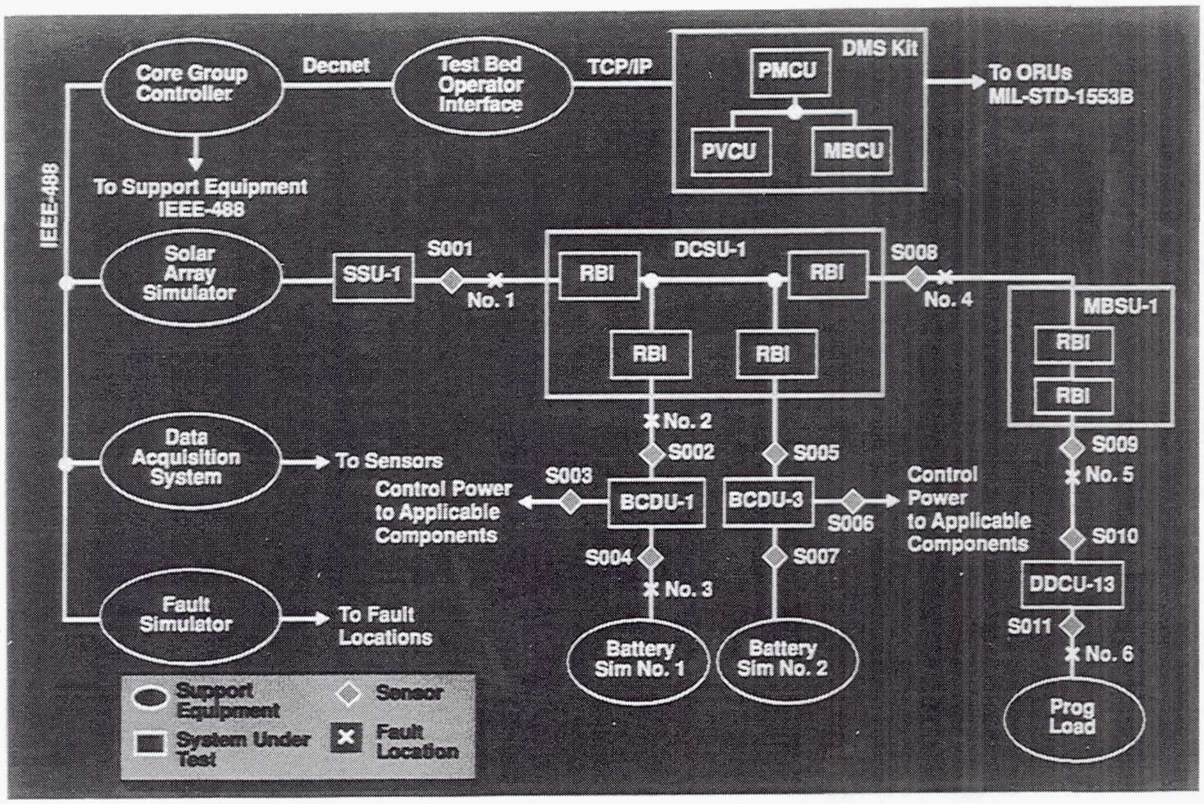

Figure 12.—Space power electronics laboratory SPEL test 2 configuration.

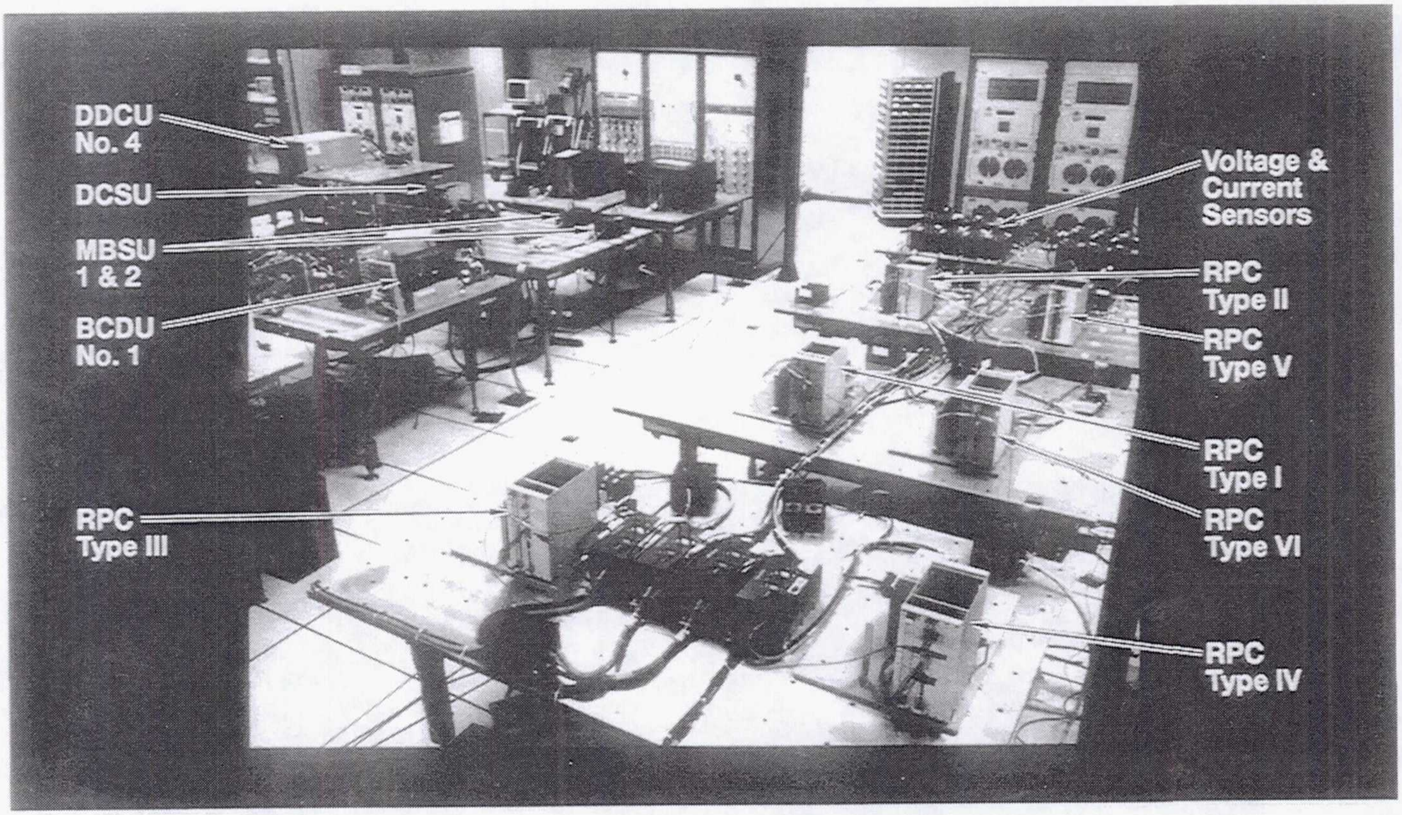

Figure 13.—Space power electronics laboratory SPEL test 3 configuration.

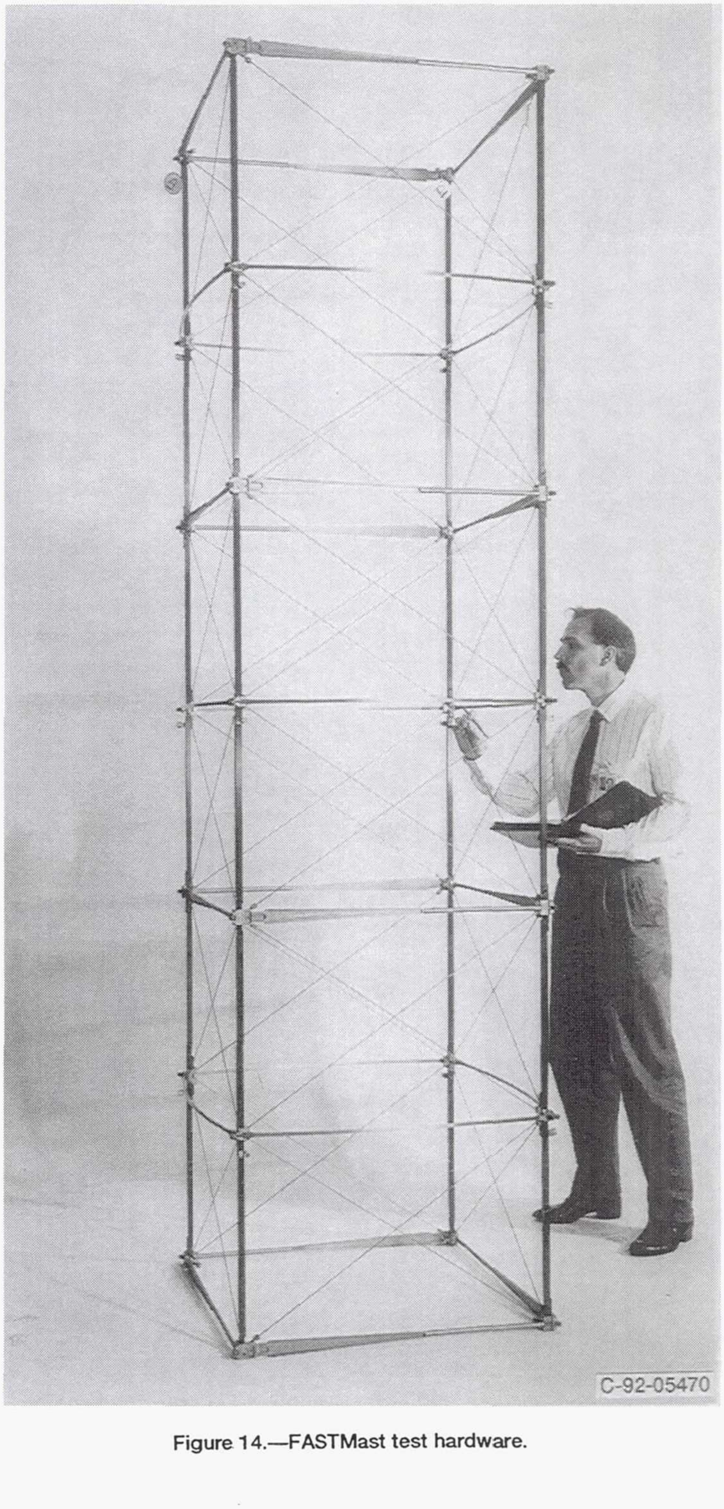

Figure 14.—FASTMast test hardware.

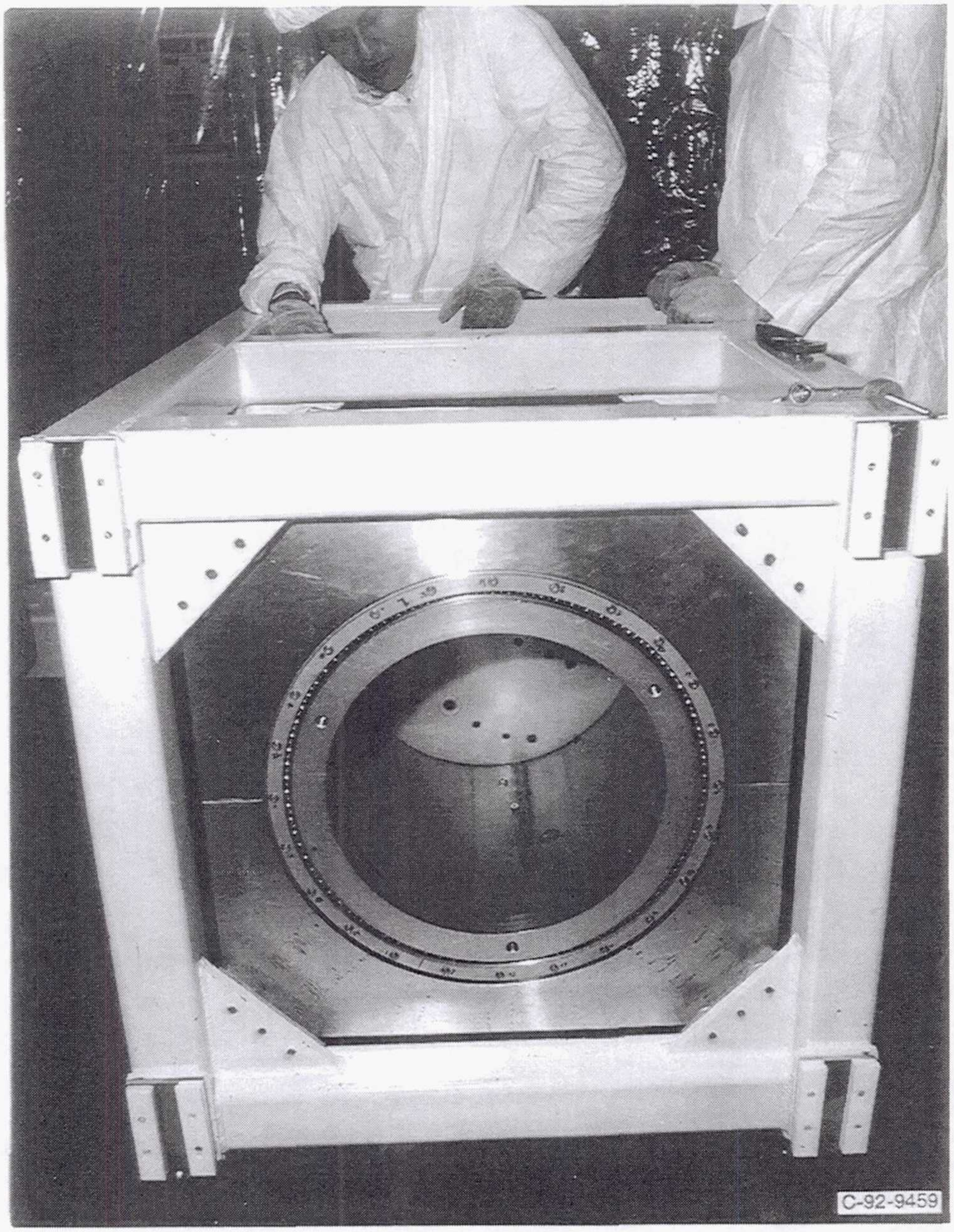

Figure 15.—Beta gimbal test hardware.

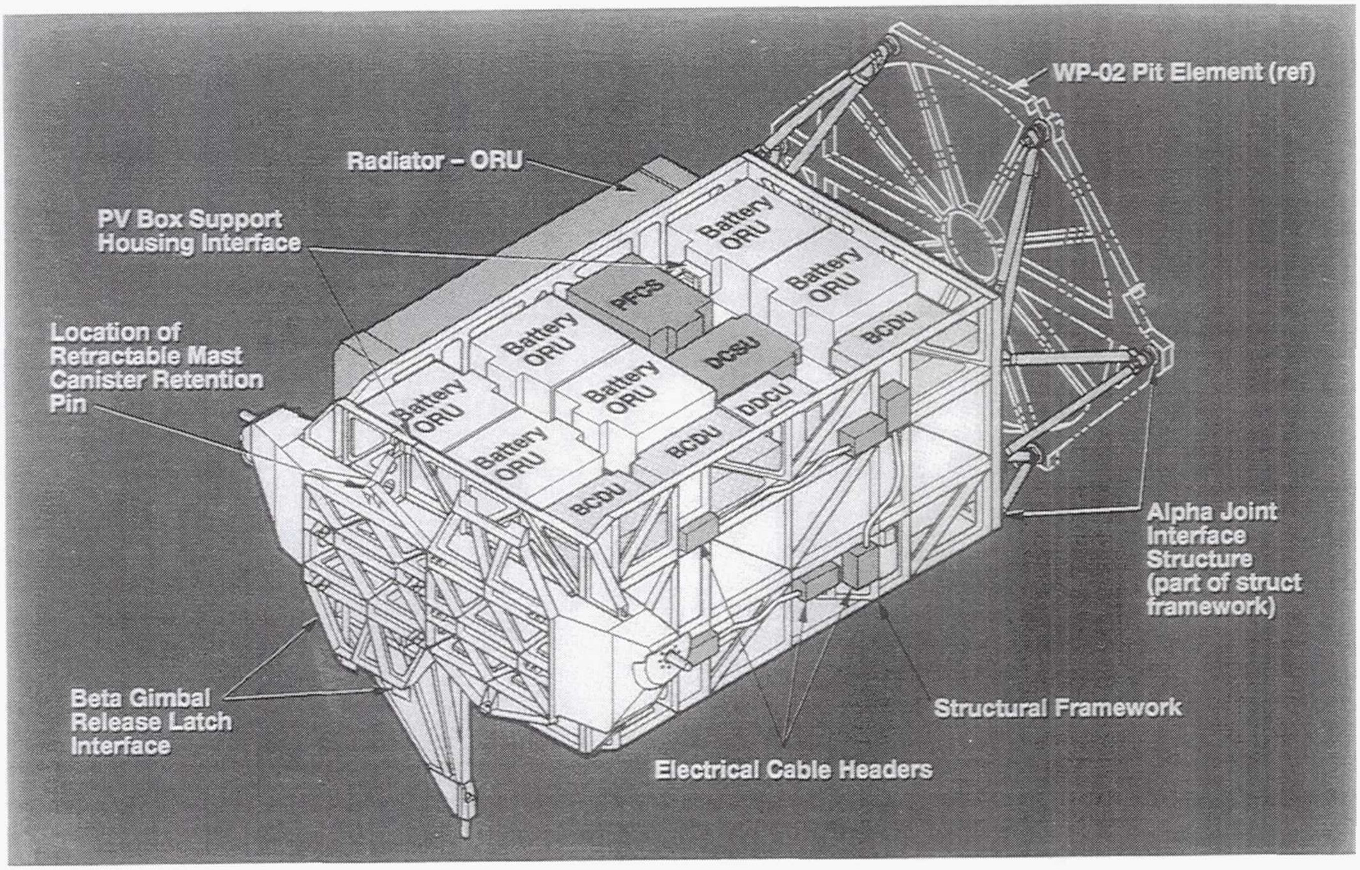

Figure 16.—Integrated equipment assembly.

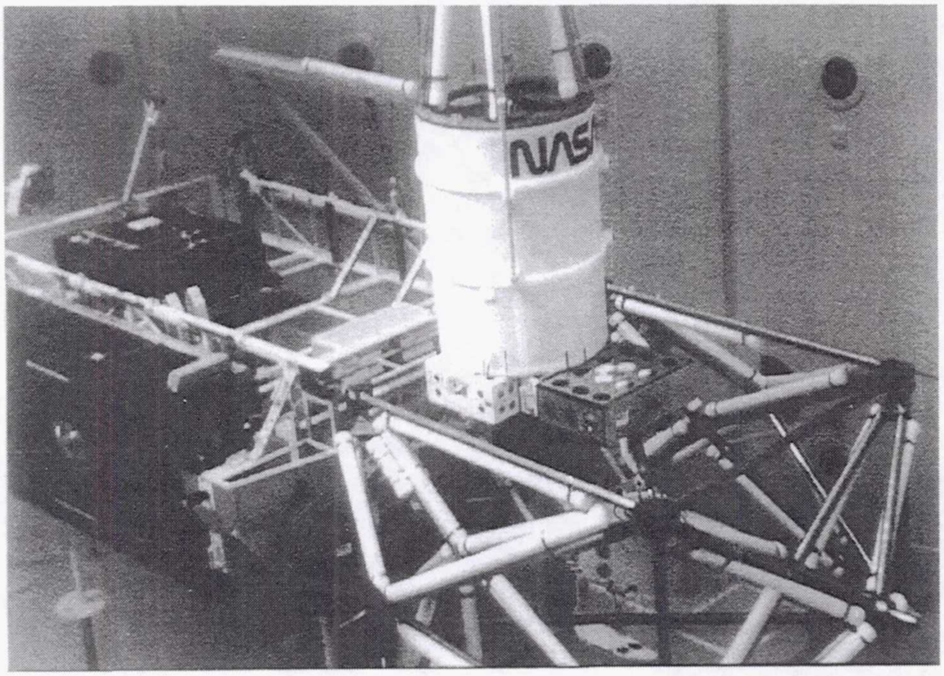

Figure 17.—Neutral buoyancy photovoltaic module mockup.

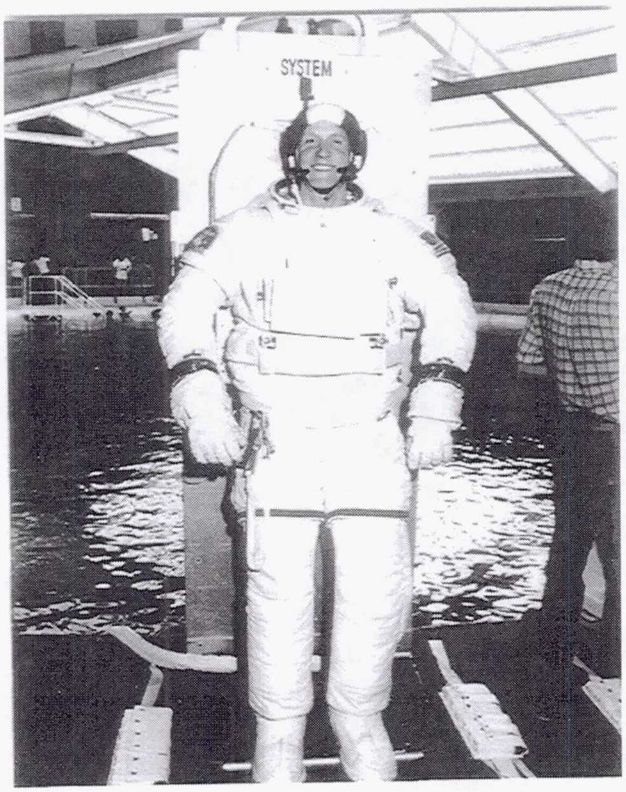

Figure 18.—Neutral buoyancy test subject.

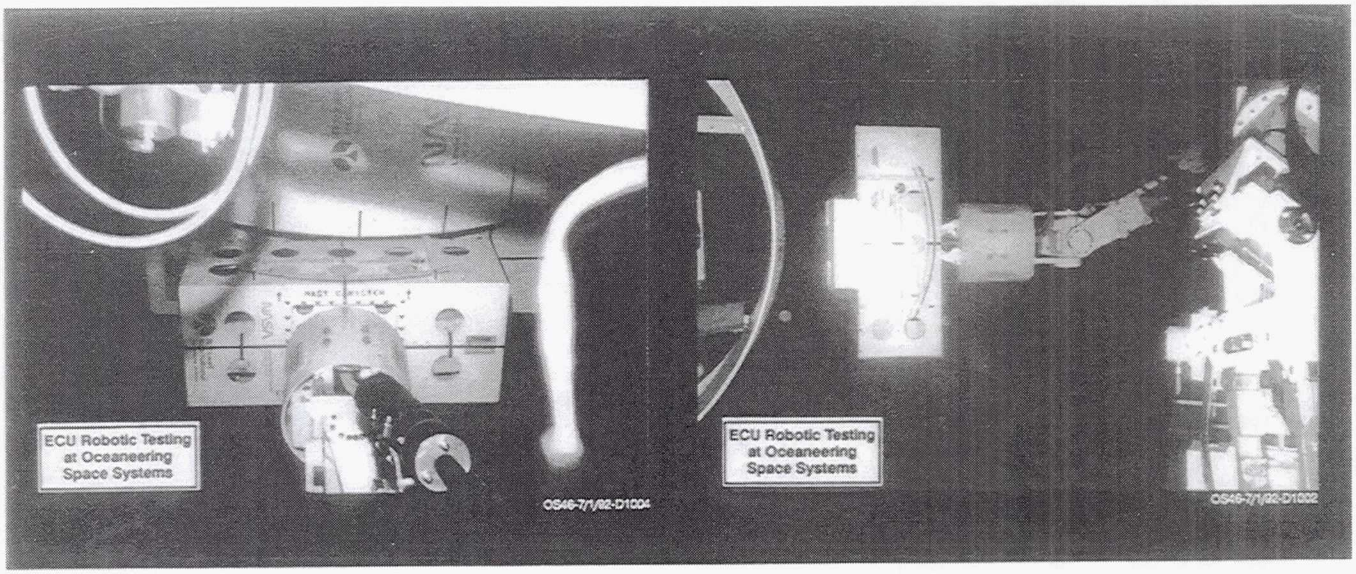

Figure 19.—Orbital replacement unit robotic testing.

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13. ABSTRACT *(Maximum 200 words)*

Space Station Freedom's (SSF) electric power system (EPS) hardware and software verification is performed at all levels of integration, from components to assembly and system level tests. Careful planning is essential to ensure the EPS is tested properly on the ground prior to launch. The results of the test performed on breadboard model hardware and analyses completed to date have been evaluated and used to plan for design qualification and flight acceptance test phases. These results and plans indicate the verification program for SSF's 75-kW EPS would have been successful and completed in time to support the scheduled first element launch.

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