NASA/SP—2018-639

Development and Use of the SPACE Computer Code for Analyzing the Space Station Electrical Power System

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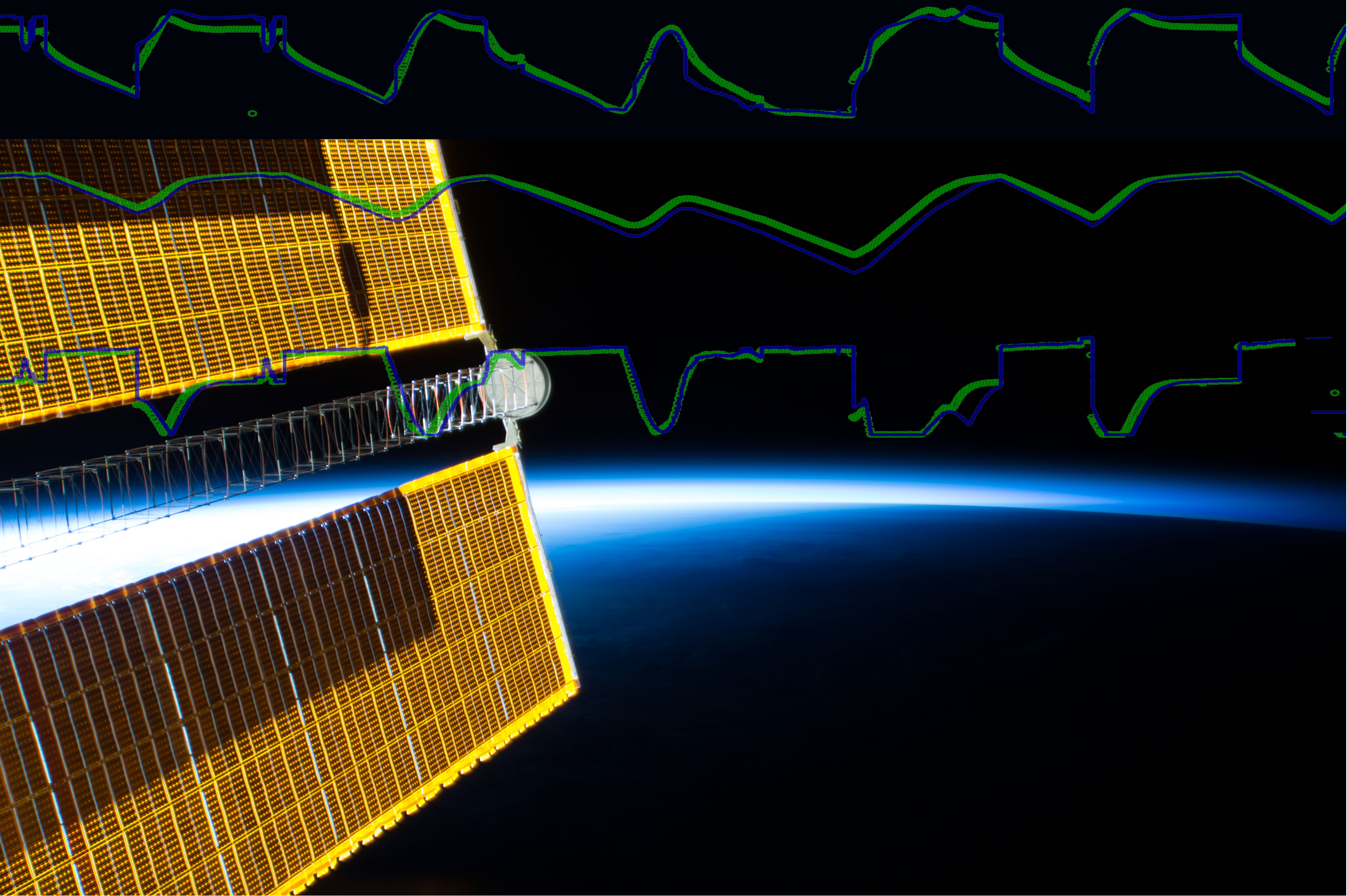
David B. McKissock
Glenn Research Center, Cleveland, Ohio



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Space Administration

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November 2018

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Suzanne Kelley and Bob Arrighi at NASA Glenn Research Center provided support in developing this report by retrieving archived files relating to Glenn's early role in the space station program. Many reviewers provided useful comments to improve this report: Ray Burns, Jeff Hojnicki, Jeff Trudell, James Fincannon, Dave Hoffman, Tom Kerslake, Penni Dalton, Ann Delleur, and Tim Propp. Tom Lavelle provided patient editorial assistance in finalizing the text and organizing the layout, with Lorie Passe helping to fine-tune the layout.

Any and all errors in this publication are the responsibility of the author.

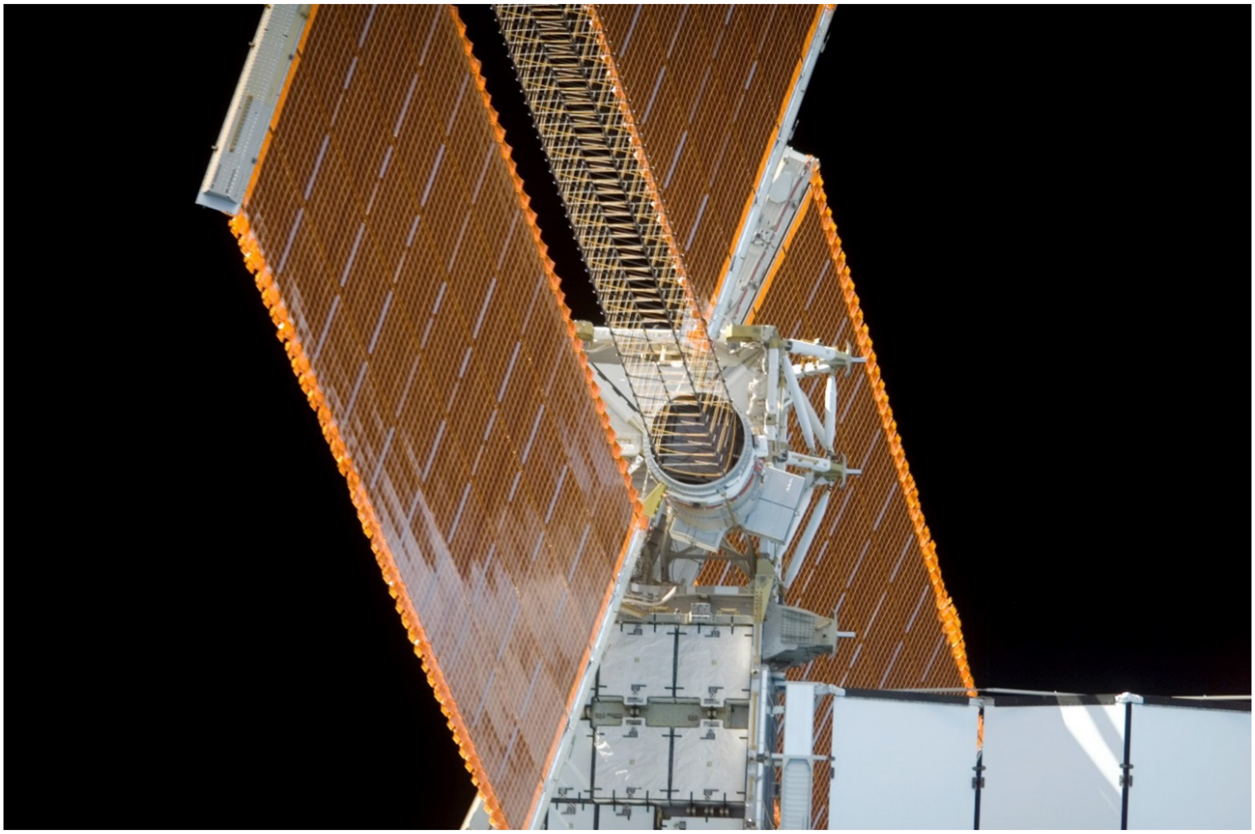

Figure 1.—ISS S4 solar array taken on Space Transportation System (STS) 120 during a flyaround after undocking (s120e009790).

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♦ Foreword ♦

This special publication tells the story of the dedicated efforts of very talented individuals to create a preeminent space electrical power system modeling and simulation tool called SPACE, short for *System Power Analysis for Capability Evaluation*. This computer model has evolved for 30 years, withstanding the test of time and obsolescence, and garnering international recognition for its ability to simulate complex space electrical power systems. The analytical results from this model have saved millions of dollars in hardware redesign, testing, and verification for NASA's International Space Station (ISS) and its European and Russian partners. SPACE has played a pivotal role in the station's design and development and continues to support its ongoing operation. It has also extended its reach beyond the ISS to other key NASA programs, where it guides the design and planned operation of NASA's Multi-Purpose Crew Vehicle Orion and simulates electric power system operation in a dusty atmosphere on Mars' surface.

The SPACE lineage was created by a core civil servant staff, supplemented by a cadre of interns and other temporary helpers. They created a tightly integrated tool that includes all phenomena that impact a solar array and battery space power system performance. SPACE is self-contained, requiring no other software modules and associated license fees. SPACE "rings true" in that is has been extensively validated with ISS on-orbit telemetry data.

This report is being released as the generation of engineers who created it are nearing retirement, passing the baton to a new generation. This next generation will carry the code into the future, no doubt further evolving it to be able to assure mission planners that newly conceived systems will successfully power NASA's next endeavors.

As a previous SPACE code developer and analyst, I have worked alongside many of the people mentioned in this report. The engineers who created the code, along with those just now learning it, are among the best and brightest at NASA. It is an honor to write this foreword as the present Branch Chief under which the legacy of SPACE continues to thrive.

David J. Hoffman
Chief, Power Architecture and Analysis Branch
NASA Glenn Research Center
July 2018

Figure 2.—Earth observation taken by Expedition 52 crew (iss052e037112).

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♦ Introduction ♦

“The International Space Station represents an unparalleled capability in human spaceflight that is increasing our knowledge of fundamental physics, biology, the Earth, and the universe.”— William Gerstenmaier, Associate Administrator for Human Exploration and Operations, NASA, Congressional Testimony, March 22, 2017

This publication tells the story of the development and use of the System Power Analysis for Capability Evaluation (SPACE) computer code, which predicts the performance of the International Space Station (ISS) Electrical Power System (EPS).

Chapter 1 provides an overview of the ISS EPS, including the architecture, geometry, key assembly flights, vehicle attitudes, and uses of the SPACE code. The timeline in Chapter 2 reviews both the history of the space station program and the SPACE code. While it is not possible to list all the individuals who have helped develop and use SPACE, the key individuals are listed in Chapter 3 (including a short description of each person’s contribution). The concluding remarks in presented in Chapter 4.

Over 50 references are listed in the References, including all papers previously published by the SPACE team. Most of the references are available online via the NASA Technical Reports Server.

As the Lewis Research Center (Lewis) was renamed to the John H. Glenn Research Center (Glenn) following John Glenn’s return to space on the space shuttle in 1999, this publication refers to Lewis prior to 1999 and Glenn thereafter in the timeline in Chapter 2.

Figure 4.—Astronaut Cady Coleman playing a flute during free time in March 2011 in Japanese Kibo laboratory module.

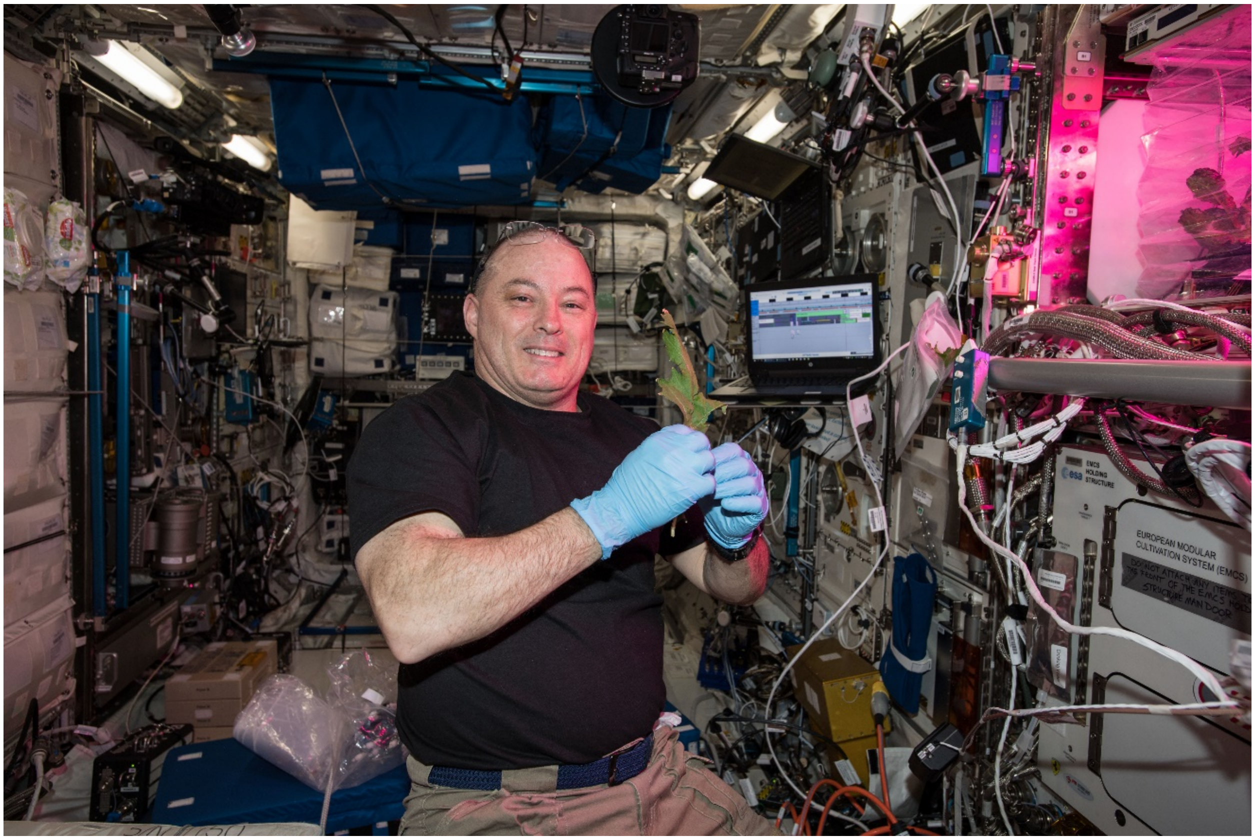

Figure 5.—Scott Tingle harvesting mizuna and red romaine lettuce March 2018 in Columbus European Laboratory Module (iss055e001186).

Figure 6.—The ISS passes over South America showing Argentina and the Southern Andes, taken by the crew of Expedition 50 (iss050e030665).

♦ Chapter 1 ♦

International Space Station (ISS) Electrical Power System (EPS) Architecture Overview

The ISS EPS final architecture for a single channel is shown in Figure 7 for the U.S. segment. The elements inside the dashed box are physically located in a photovoltaic module (PVM). Each PVM is delivered to the ISS on a dedicated space shuttle assembly flight, with each PVM containing two power channels. The eight power channels on the ISS are located in four PVMs launched on four shuttle flights.

During insolation periods, power from the solar array flows to the sequential shunt unit (SSU). Four hundred solar cells connected in series form on string on a solar array wing (SAW), and each SAW contains 82 strings. The SSU shunts unneeded solar array strings to regulate the primary bus voltage. Power then flows through the Beta Gimbal Assembly (BGA), which rotates the solar array to adjust for the seasonal solar beta angle. Solar array power then enters the DC Switching Unit (DCSU) and can either flow into the battery charge discharge unit (BCDU) to charge batteries, or flow downstream to the solar alpha rotary joint (SARJ) and the main bus switching unit (MBSU). Power from the MBSU then flows to either the DC-to-DC converter units (DDCU), or the Russian side of the space station via the American-Russian Converter Unit (ARCU). DDCUs are either installed inside pressurized modules (DDCU-I) or located on the truss (DDCU-E). The DDCUs convert from the primary bus voltage (nominally 160 Vdc) to the secondary distribution voltage (nominally 120 Vdc).

During the eclipse portion of an orbit, the nickel-hydrogen (NiH_2) batteries discharge with the power flowing through the BCDU. The BCDU raises the battery voltage to the primary bus voltage. There are three BCDUs on each channel, with each BCDU fed by two NiH_2 battery orbital replacement units (ORUs) in series. Two NiH_2 battery ORUs together make one ISS battery. The power then flows through the DCSU to the SARJ and into the MBSU. A small amount of power flows from the DCSU back through the BGA to provide keep-alive power to the SSU.

All of the electrical boxes in the EPS are collectively referred to as the Power Management and Distribution (PMAD) hardware.

The ISS is shown in Figure 8 with all eight U.S. power channels installed. The ISS channel name is shown in white text next to each solar array, while the truss segments are labeled in red. This picture was taken in May 2011, slightly more than 2 years after the last power module was launched in March 2009. The channel 2A solar array is oriented with the backside pointing toward the Sun.

The key ISS assembly and logistics flights (from the perspective of the EPS) are described in Table I. The shuttle flight designation is shown in the first column and the ISS program designation in the second column.

More details of the ISS EPS architecture for both the U.S. and Russian segments can be found in Reference 1.

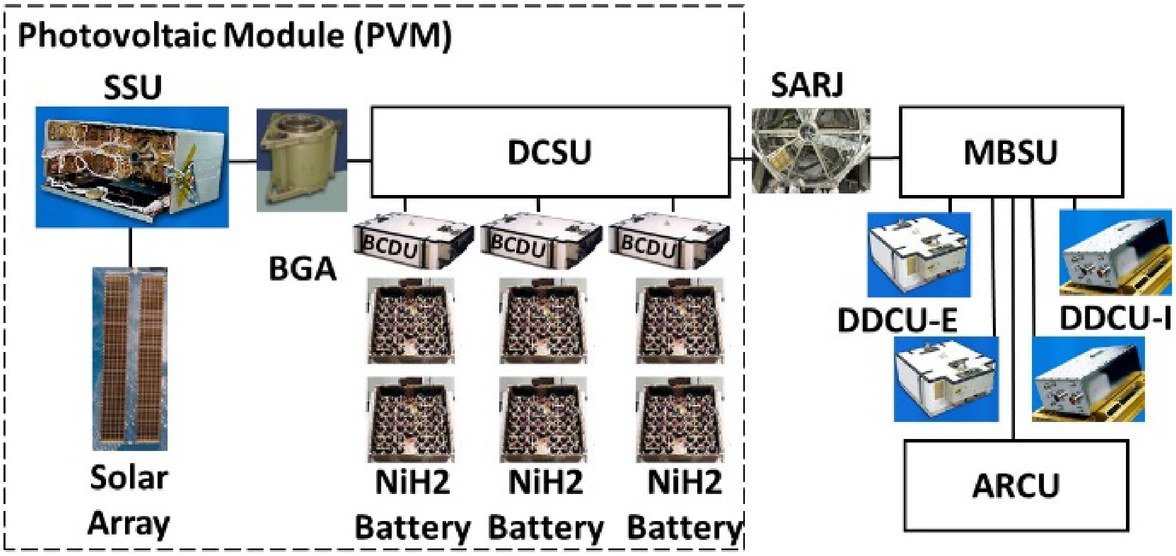

Figure 7.—International Space Station Electrical Power System channel architecture.

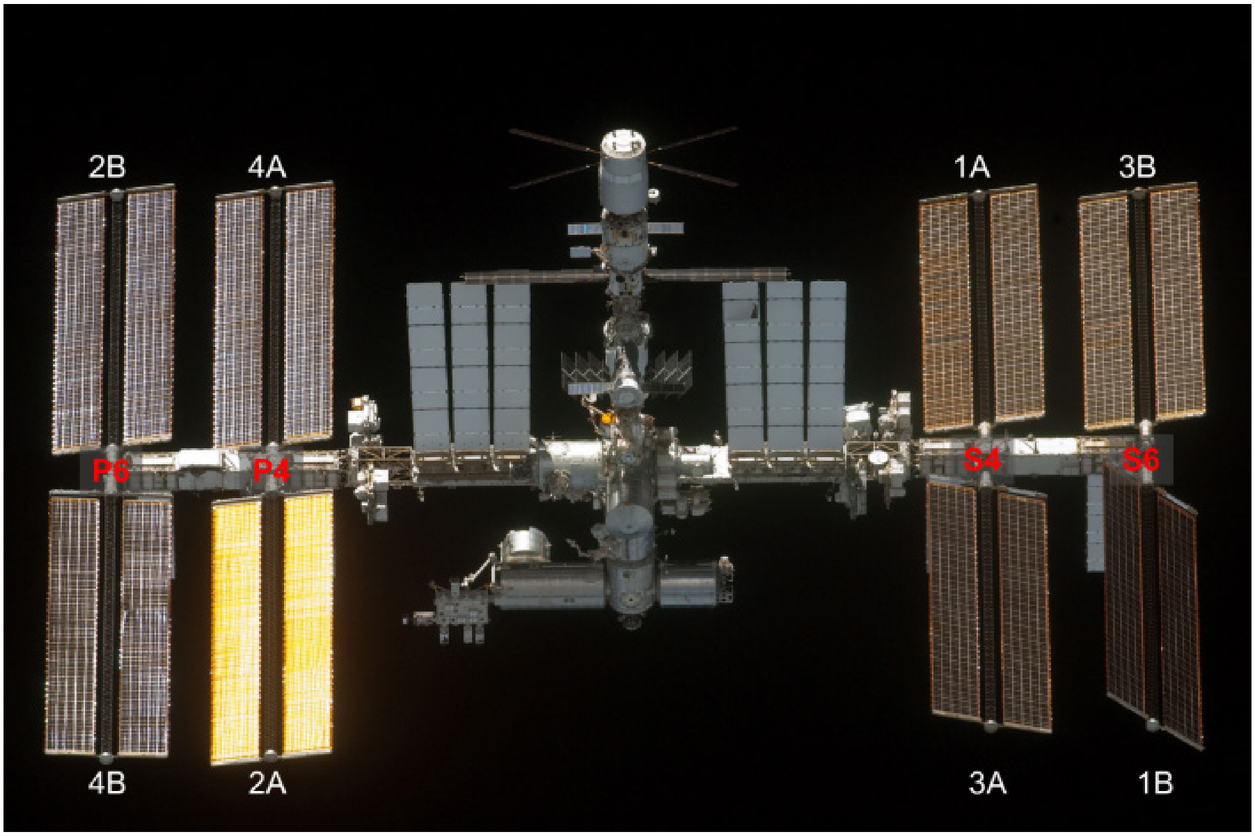

Figure 8.—International Space Station (ISS) Electrical Power System channels and truss segments photographed on May 29, 2011, by an STS–134 crew member on Space Shuttle Endeavour after ISS and shuttle began post-undocking relative separation (S134-E-011548).

TABLE I.—KEY INTERNATIONAL SPACE STATION (ISS) FLIGHTS AND EVENTS

Shuttle Flight	ISS Flight	Date	Description
------------	1A/R	November 1998	Zarya (Functional Cargo Block) launched on Proton
STS–97	4A	December 2000	P6 (2B and 4B) launched and installed on Z1 truss segment
STS–98	5A	February 2001	U.S. Destiny Laboratory added to ISS with six internal DC-to-DC converter units (DDCUs)
STS–110	8A	April 2002	S0 truss structure installed with the Main Bus Switching Unit (MBSU) and four external DDCUs. MBSUs were dormant until Electrical Power System (EPS) reconfiguration in 2006
STS–115	12A	September 2006	P4 (2A and 4A) launched
STS–116	12A.1	December 2006	EPS reconfigured to utilize MBSUs and 4B solar array retracted
STS–117	13A	June 2007	S4 (1A and 3A) launched and 2B solar array retracted
STS–120	10A	October 2007	Eight DDCUs launched with Node 2 (Harmony) to power European Space Agency (ESA) Columbus lab and Kibo lab from Japan Aerospace Exploration Agency (JAXA). Redeployed 2B and 4B solar arrays
STS–119	15A	March 2009	S6 (1B and 3B) launched
STS–127	2J/A	July 2009	2B NiH_2 battery replaced
STS–132	ULF4	May 2010	4B NiH_2 battery replaced
-----------	HTV6	December 2016	NiH_2 batteries on 1A and 3A replaced with lithium-ion (Li-ion)

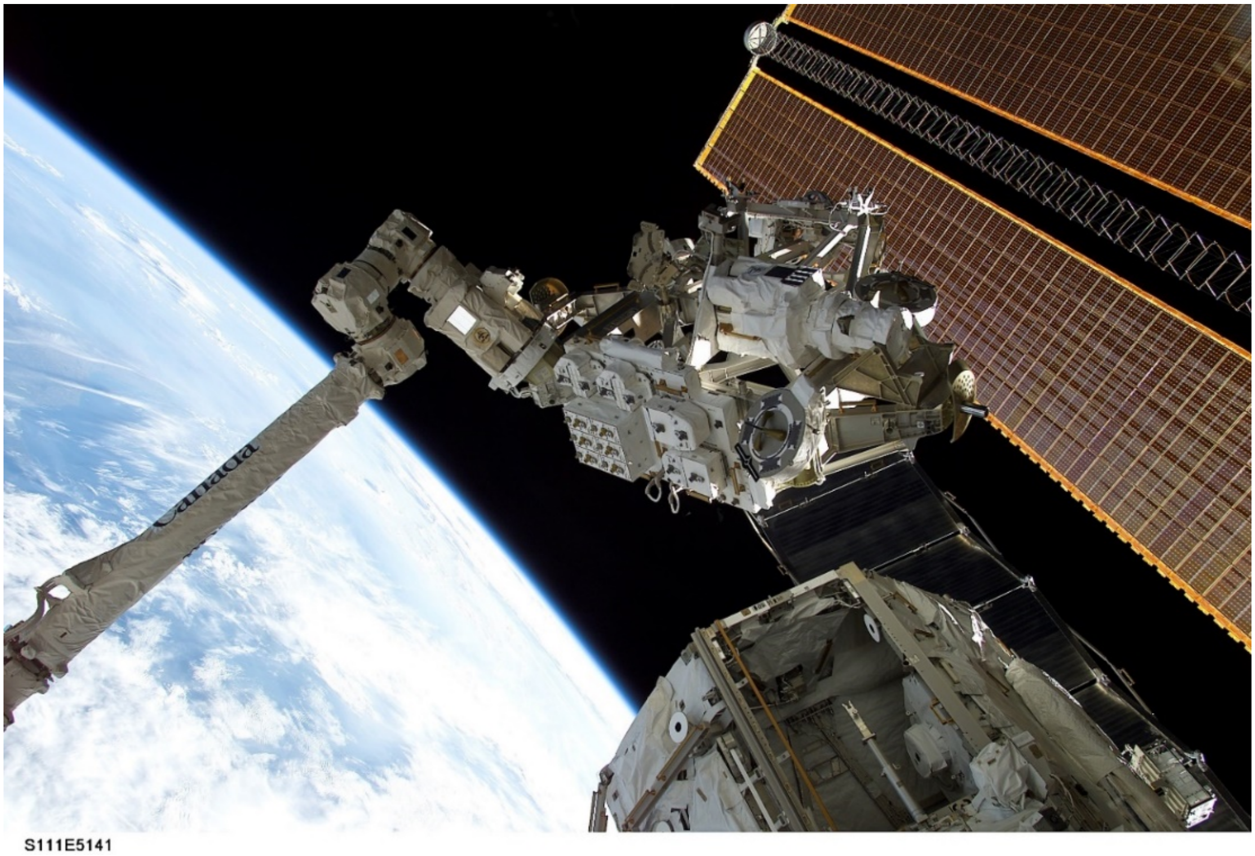

Figure 9.—Mobile Base System grappled to Canadarm2 Space Station Remote Manipulator System during STS–111 in June 2002.

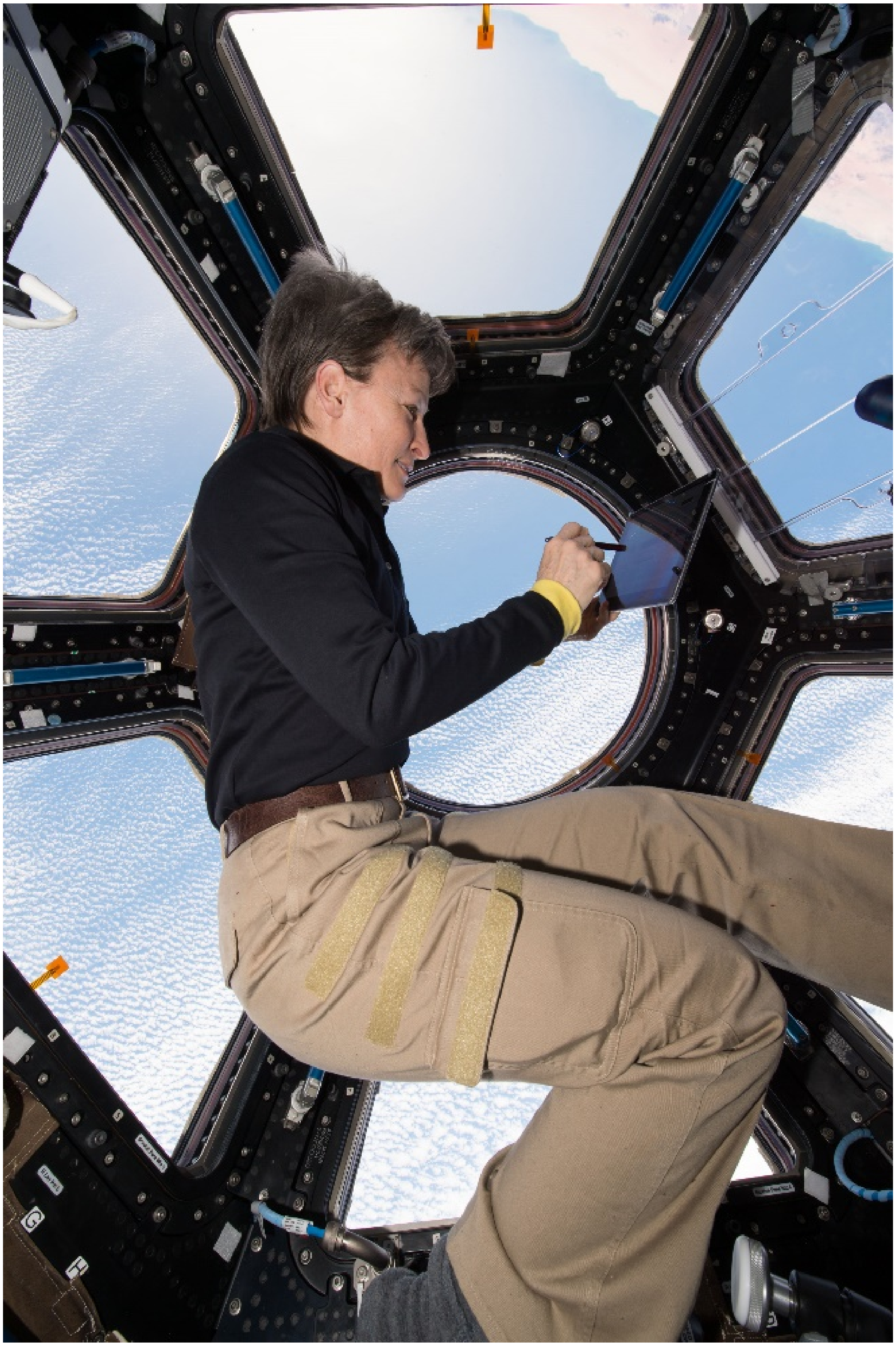

Figure 10.—Astronaut Peggy Whitson in Cupola in July 2017 (iss052e016179).

♦ Chapter 2 ♦

Space Station and the SPACE Code History

Overview

On January 25, 1984, many NASA employees were watching on television as President Ronald Reagan delivered his State of the Union address. It was rumored that the President might mention the space station program. That evening, the President said:

> *"Our progress in space, taking giant steps for all mankind, is a tribute to American teamwork and excellence. Our finest minds in government, industry and academia have all pulled together. … America has always been greatest when we dared to be great. We can reach for greatness again. We can follow our dreams to distant stars, living and working in space for peaceful, economic, and scientific gain. Tonight, I am directing NASA to develop a permanently manned space station and to do it within a decade. …NASA will invite other countries to participate so we can strengthen peace, build prosperity, and expand freedom for all who share our goals."*

With these words, NASA officially began development of a space station. The following subsections review the development history of the space station EPS and key developments and analyses performed by Glenn staff using the SPACE computer code, from 1984 to the present.

The 240 SPACE and 67 ECAPS (SPACE spelled backward) analyses conducted throughout the ISS development and operations are shown in Figure 11. The label ECAPS in Figure 11 refers to time-phased analyses for a Design Analysis Cycle or Verification Analysis Cycle. These analyses cover multiple days in an ISS mission, usually during key assembly operations such as vehicle docking and undocking, installation of new elements, Extravehicular Activities (EVAs) (particularly involving the power modules such that the solar array gimbals must be locked), and space shuttle waste water dumps (which required a unique ISS attitude and locked solar array gimbals).

ECAPS assessments are generally a multimonth activity, and include receiving time-phased load demand files and solar array gimbal strategies from NASA Johnson Space Center as well as executing ECAPS to compute battery state of charge (SOC) levels. If battery SOC levels are below the target values, Johnson and Glenn collaborate on developing solutions. These solutions can include one or more of the following: adjusting DDCU proportionality constants to shift loads from power-rich channels to power-constrained channels, turning off discretionary loads (such as shell heaters), reducing payload power, and using alternate vehicle attitudes and/or alternate solar array gimbal positioning strategies. Proposed solutions are assessed by rerunning ECAPS for the revised scenario.

The SPACE label in Figure 11 refers to power generation assessments using the SPACE code. These analyses report the maximum continuous power that the EPS can deliver to the ISS without violating any constraints and can generally be performed in hours or days (depending on the complexity of the analyses).

The Johnson team that provides Lewis with time-phased load demands is currently referred to as Spacecraft Time-phased Electrical Loads Analysis and Resources (STELAR). They have a long history of working with power systems for crewed spacecraft, spanning the Gemini through the shuttle eras. In the shuttle era, the team was in the Consumables Analysis Section of the Mission Planning and Analysis Division. For the ISS, they compute the total load demand on each DDCU during a mission by combining their detailed database of all electrical loads on the ISS with mission operational plans and their knowledge of how these loads are scheduled.[2]

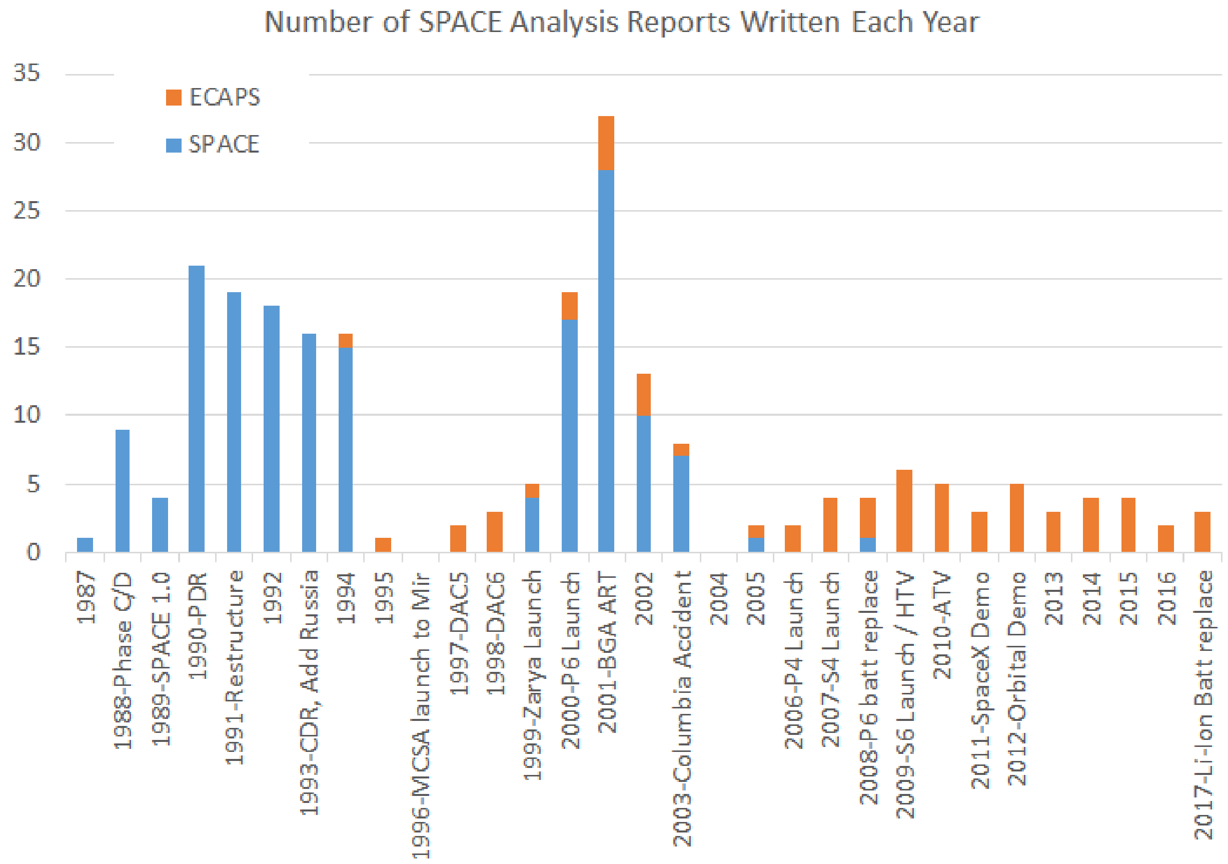

Figure 11.—SPACE analysis history.

Rather than trying to summarize each analysis listed in Figure 11, this report provides examples of the types of analyses performed with the SPACE code throughout the life of the program.

Pre-Space Station Lewis Space Power Activities

In his thorough summary of the history of Lewis,[3] Arrighi notes that the researchers who developed the solar cells for Vanguard (the world's first solar-powered satellite) joined Lewis in 1961. The researchers went on to develop a new type of radiation-resistant silicon solar cell, which became an industry standard. Lewis was also involved with dynamic power systems, such SNAP–8 (a nuclear reactor with a Rankine conversion system) and Brayton system life testing to verify mission goals.

Figure 12.—Coreen Rawlings and Ray Burns with Brayton Cycle Unit in test cell (C-1969-1622).

In the 1970s, Arrighi reports[4] that the Lewis director "spearheaded an effort to transform Lewis into the Agency's lead energy conversion center." Lewis initiated collaborations with the Energy Research and Development Administration (ERDA), the predecessor of the Department of Energy (DOE). Lewis and ERDA jointly sponsored a Terrestrial Photovoltaic Measurements Workshop in 1975, attended by almost 100 individuals from the solar cell community.[5] The issues addressed in the workshop regarding intensity and spectral distribution for solar simulation were important for both terrestrial and space power systems.

Figure 13.—Fred Teren, Tom Labus, Dick Donovan, and Ray Burns at a center picnic (left to right) (GRC-1989-C0464).

Lewis conducted the Energy Conversion Alternatives Study (ECAS) in 1977 under sponsorship of the ERDA, the National Science Foundation, and NASA.[6] ECAS investigated advanced energy conversion techniques for terrestrial electric utilities using coal or coal-derived fuels. Phase 1 consisted of parametric studies performed by two contractors. From these results, 11 concepts were selected for further study in Phase 2. During each phase, NASA analyzed the contractors' results to reconcile differences and to compare the systems. Many Lewis personnel involved in the ECAS study soon became leaders in the Lewis space station organization, including Jerry Barna (deputy chief of the space station directorate), Ray Burns (branch chief of the space station power system analysis group), and Dick Donovan (deputy branch chief of the space station power system analysis group). Five analysts in the ECAS study became analysts in the Lewis space station organization: Yung Choo, John Klann, Joseph Nainiger, Bob Stochl, and Jerry Winter.

Figure 14.—Jerry Barna (C-2001-1709).

Three years later, the DOE requested Lewis to perform another study to establish research and development funding priorities for coal-fueled advanced energy conversion systems for industrial cogeneration.[7] Lewis performed independent analyses and prepared a comparative evaluation of the studies performed by two contractors. Over 6,000 cases were calculated for the various combinations of energy conversion systems, configurations, fuels, matching strategies, and industrial process plants.

A Lewis-sponsored symposium was held in Cleveland in May 1978, "Future Orbital Power Systems Technology Requirements."[8,9] This joint government-industry conference was attended by over 450 people representing 33 industrial organizations, 5 non-NASA government installations, and 3 universities. NASA participation included Lewis, Goddard Space Flight Center, NASA Headquarters, Johnson, Marshall Space Flight Center, and the Jet Propulsion Laboratory (JPL). A JPL assessment showed the cumulative total space solar power production for about 200 missions launched by NASA was approximately 90 kW. Future spacecraft power needs were projected to rapidly increase, necessitating power technology advances in energy storage, life, power conditioning, power management, physical size, and cost. All of these parameters soon became critical for designing the ISS power system.

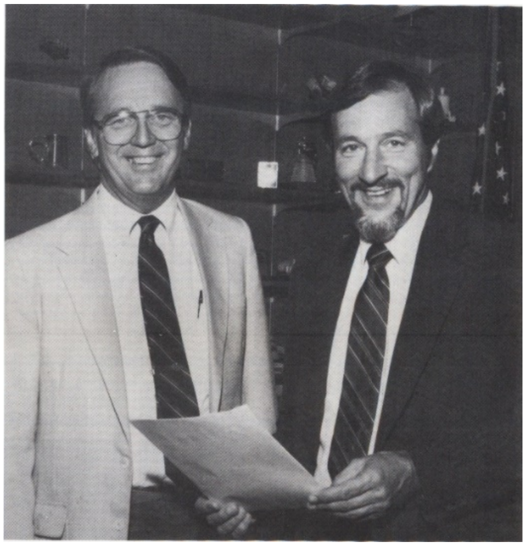
Figure 15.—Ron Thomas (left) and Andrew Stofan (Lewis Center Director).

Lewis also managed the large wind turbine program for the DOE. This goal of this technology development program was a safe, reliable, environmentally acceptable large wind turbine to generate electricity at costs competitive with conventional electric generation systems. In a 1982 status report by Ron Thomas (soon to be head of the Lewis space station organization), he noted that

- Four 200-kW turbines operated for over 36,000 hours
- Three 2,500-kW units had been installed with acceptance testing in progress
- Two contractors were designing 7,000-kW units[10]

Although not mentioned in Thomas's report, the large wind turbines developed under the Lewis effort set several world records for diameter and power output.[11]


Figure 16.—Expedition 4 crew: Yury Onufriyenko, Daniel Bursch, and Carl Walz (clockwise from the bottom).

Phase A Studies, Lewis Code Development (Early 1980s)

In August of 1982, NASA signed contracts for eight space station Phase A studies focusing on space station needs, attributes, and architectural options. As an example, results from the contract with McDonnell-Douglas Corporation are shown below in Figure 17.[12] The power requirements are for users only; space station housekeeping loads are excluded. The initial user power of 25 kW is designated as “modest,” rapidly building to over 70 kW.

In this timeframe, under the direction of Ron Thomas (chief of the Space Systems Office in the Space Technology Directorate) and Ray Burns (branch chief of the Power and Propulsion Analysis Office under Thomas), Lewis staff began to develop and utilize new computer codes to analyze aspects of interest to the space station EPS. Peter Staiger developed most of the key codes and Table II contains a list of his products.

Initial analyses results generated from these computer codes were recorded in Preliminary Information Reports (PIRs), which unfortunately are no longer available. However, two simple samples are shown below in Figure 18 and Figure 19.

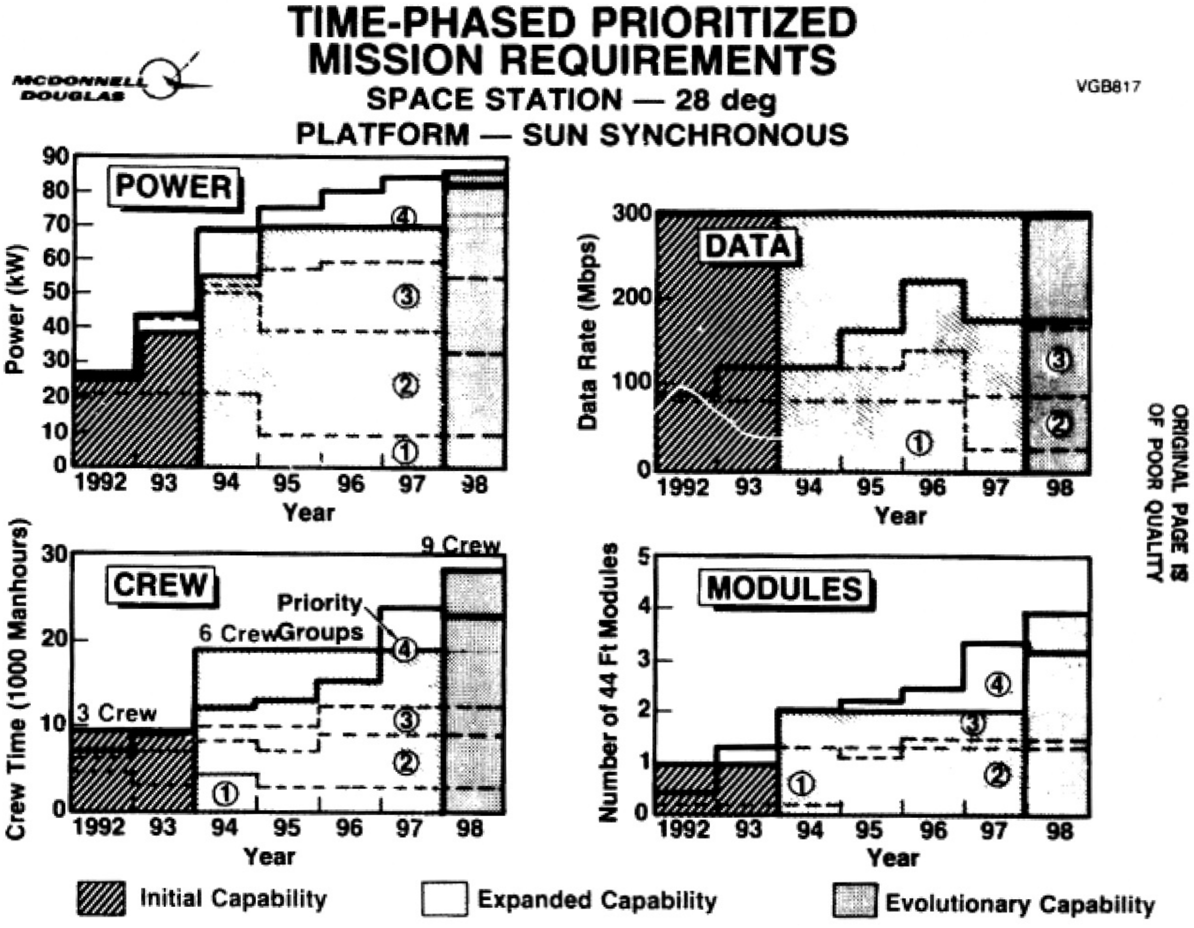

Figure 17.—McDonnell-Douglas Phase A study results.

TABLE II.—COMPUTER CODES DEVELOPED BY STAIGER[a]

Code Name	Description
SHADES	Determines the length of the illuminated and eclipsed portions of a circular orbit.
ATMOS	Determines the atmospheric drag force acting on Earth-orbiting spacecraft. The program allows for Sun-pointing surfaces and surfaces of fixed projected area into the velocity vector.
ATOMO	Determines the atomic oxygen flux impinging on the surfaces of an Earth-orbiting spacecraft and the accumulated exposure over a specified period of time. The program considers surfaces of six different orientations.
ENERGY	Determines how much power the space station EPS can deliver to the user interface at a constant level for one orbit revolution as a function of time. It can treat correctly oriented photovoltaic (PV) and solar dynamic (SD) power systems as well as PV systems with several different incorrect orientations.
TORQUE, DESAT	Calculate the gravity-gradient and aerodynamic torques acting on a space station type of spacecraft as a function of time. Also calculate the accumulated angular momentum that results from the action of these torques. The spacecraft consists of an Earth-oriented core and solar-pointing planar solar arrays or parabolic solar collectors. Makes use of the Jacchia atmosphere model to find the atmospheric density for use in calculating the aerodynamic forces and torques. The TORQUE program is designed to present results for one or two orbit revolutions, while DESAT produces results for longer periods of time (several months).
DECAY	Determines the elapsed time for a satellite to decay from a specified initial circular orbit altitude to a specified final orbit altitude.
MODORBIT	Determines spacecraft decay and reboost cycles with a continuous low thrust.

[a]Reference 13.

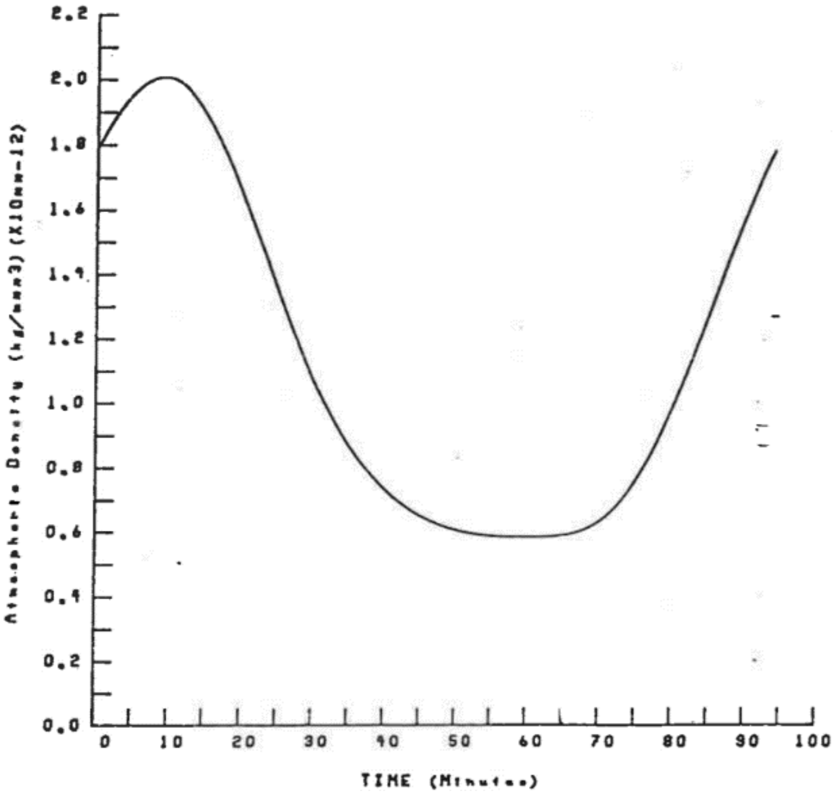

Figure 18.—Typical variation of atmospheric density in one orbit. Results are for one orbit revolution. Case is for an orbit altitude of 500 km, 28.5° orbit inclination, and nominal atmosphere, during vernal equinox of 1992. Sourced from PIR 54.

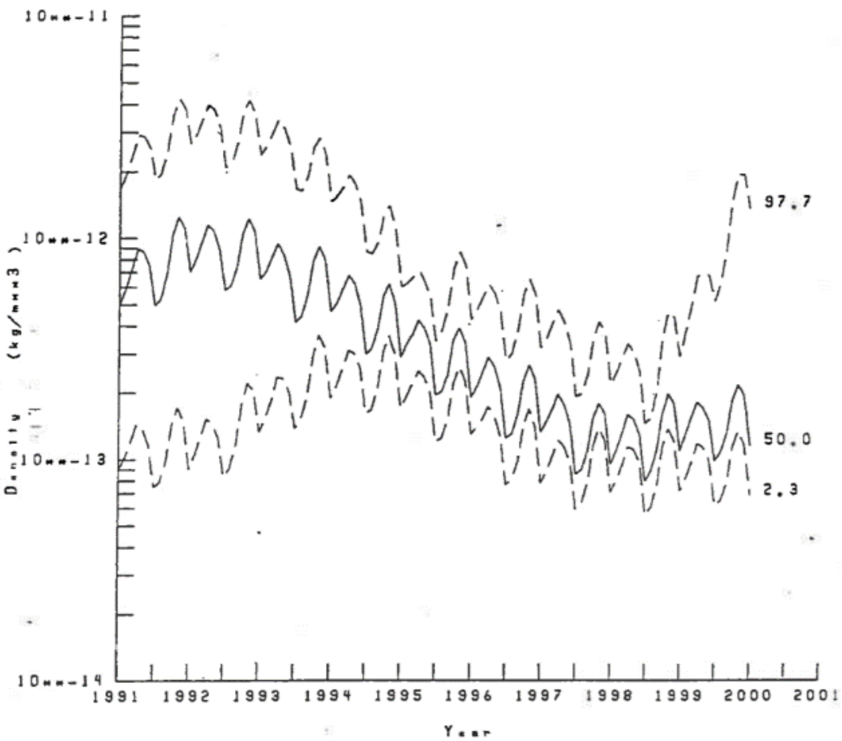

Figure 19.—From 1991 to 2000 predicted atmospheric density at 500 km using Jacchia model with 97.7, 50, and 2.3 percentile values of predicted solar flux and geomagnetic index. Densities shown are daily average values. Sourced from PIR 36.

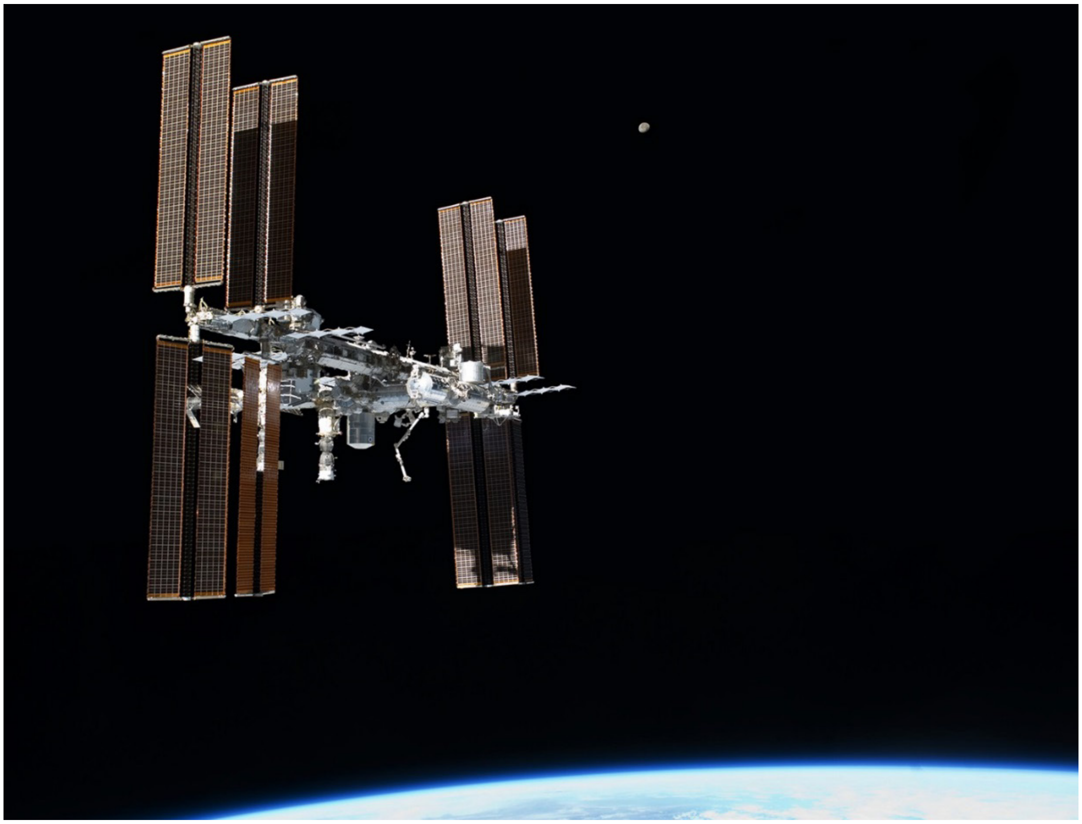

Figure 20.—International Space Station from Atlantis after undocking on STS–135 in July 2011 (s135e011814).

Phase B Definition and Design Studies (1984 to 1987)

The first power profile for the Initial Operating Capability (IOC) configuration was created by Johnson Mission Planning and Analysis Division in February 1984,[14] and is shown in Figure 21. The 48-hour conceptual timeline for a crew of eight included scheduling approximately 900 discrete space station components with an orbital maneuver vehicle (OMV) rendezvous, science experiment activities, Remote Manipulator System activities to service the OMV, and an EVA for satellite servicing.

The peak load approached 111 kW, while the total average load over the 48-hour timeline was 98 kW (48 kW of housekeeping loads plus payloads). The connected load (i.e., all space station electrical loads activated) was 139 kW. Figure 21 illustrates a perpetual issue with early space station studies; projected load demands often exceeded the generation capability of the EPS.

The reference IOC configuration was developed over 4 months by a skunkworks team of experts from various NASA centers. The reference configuration was to be included in the upcoming Phase B Request for Proposal (RFP) to serve as a potential point of departure for the definition phase. John Dunning, Pete Kempke, and Dick Donovan from Lewis supported the skunkworks team in developing the power system description. The reference configuration power system used a planar solar array with silicon solar cells, regenerative fuel cells for energy storage, and a high-voltage AC distribution system. The SAWs were Sun tracking with two gimbals. The power system provided 50 kW to payloads with 25 kW allocated to housekeeping for a total capability of 75 kW. The Johnson Mission Planning and Analysis Division updated their power profile analysis for this reference IOC configuration, as shown in Figure 22. This analysis was for a six-person crew. The Mission Planning and Analysis Division report indicates that the power demand exceeds the 75-kW system capability "primarily due to the size of the reference payload complement and a current lack of understanding of payload operation phasing."[15]

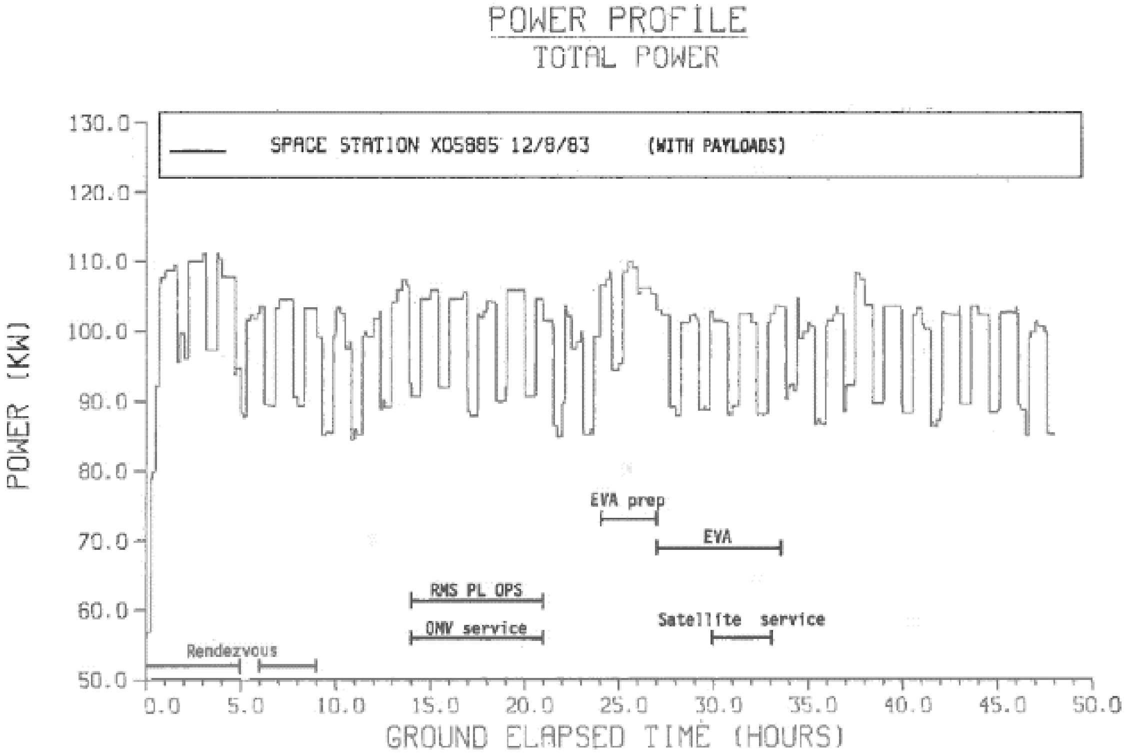

Figure 21.—Space station total power profile for Initial Operating Capability configuration with eight-person crew.

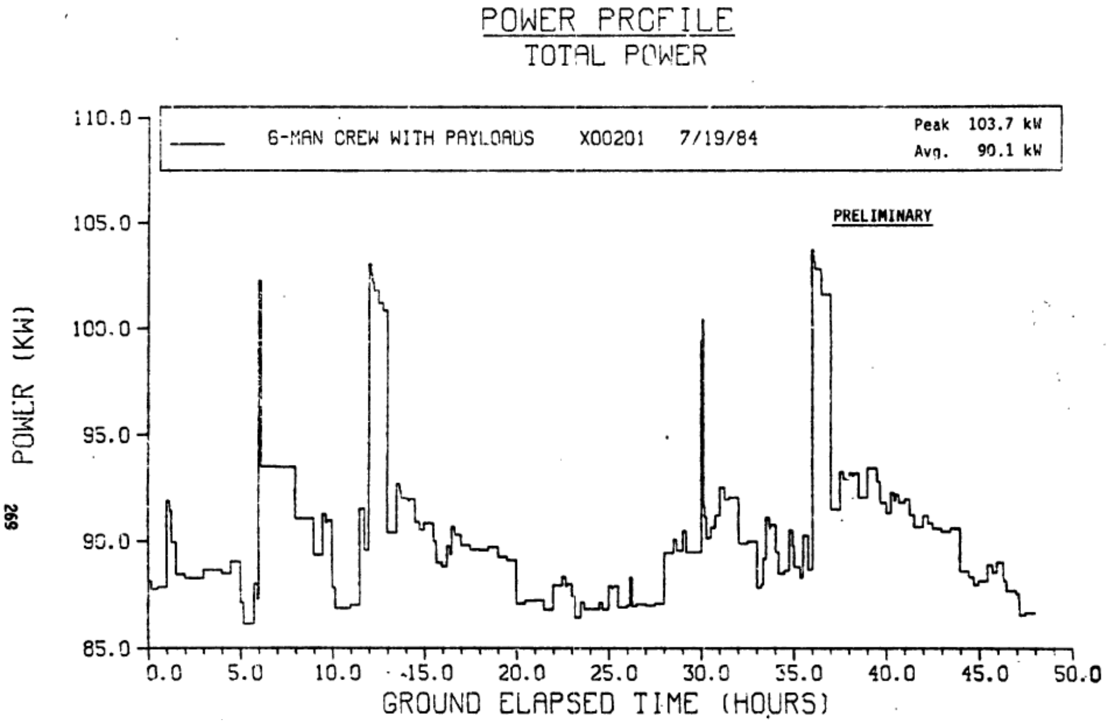

Figure 22.—Total power profile for six-person crew with payloads.

In June 1984, NASA announced the four centers assigned roles for space station studies as follows:[16]

- Marshall (Work Package-01 (WP–01)): pressure shells to be used for the U.S. laboratory and habitat modules and the adjoining nodes, certain module outfitting, environmental control system, internal audio and video, and internal thermal control
- Johnson (WP–02): overall architecture responsibility; truss; utility integration; thermal, data, communications, tracking, navigation, and control systems; a mobile base for the Canadian Mobile Servicing Center, and certain module outfitting
- Goddard (WP–03): polar platform, external payload attachments, flight telerobotic servicer, certain module outfitting, co-orbiting platform, satellite servicing facility
- Lewis (WP–04): EPS
- NASA Langley Research Center: coordinated design analyses and systems engineering

On September 1, a space station directorate was formed at Lewis with 94 employees co-located in the Development Engineering Building. Ron Thomas was appointed to lead the new directorate, with Tom Cochran as his deputy.[17,18]

In the fall of 1984, each NASA center supporting the space station issued an RFP for space station definition and design studies for their portion of the configuration.[19] NASA received a total of 13 proposals in response to the RFP, including three bidding teams for the power system work managed by Lewis: Garret, Rocketdyne, and TRW.[20] Rocketdyne and TRW both received $6M, 21-month contracts from Lewis for studying the space station EPS in May 1985.[21] Various vehicle configurations were analyzed (Figure 23), with Lewis and the contractor team assessing photovoltaic (PV) and solar dynamic (SD) options for power generation.[22] After 1 year, the contract with TRW was terminated as TRW indicated that they did not wish to pursue a preliminary design of a hybrid (PV plus SD) power system.[23] For more information on SD technology, see the summary in Reference 22 (an article published in Aerospace America). A detailed description of the SD can be found in Reference 24. The IOC for the power system was projected to be 75 kW. There were three EPS growth scenarios to increase the EPS generation capability within the first 10 years of operations: low growth (150 kW), base growth (300 kW), and high growth (450 kW).[25]

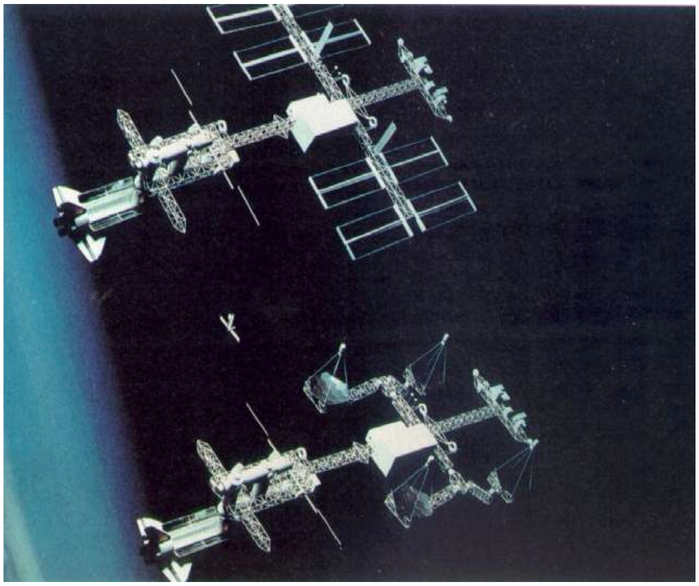

Figure 23.—Illustrations of two early space station configuration options. Top configuration uses photovoltaic power modules, while bottom uses solar dynamic power modules.

In 1985, two papers were published with results from the Staiger codes:

- Design tradeoffs for a space station solar-Brayton power system, assessing mass, area, and station-keeping propellant needs[26]
- An analysis of low-thrust, resistojet reboost for the space station[27]

At the conclusion of Phase B, two space station programmatic options were identified: the Enhanced Configuration option and the Phased Program option. The Enhanced Configuration option utilized 37.5 kW of PV power and 50 kW of SD power for a total power of 87.5 kW (Figure 24). The Phased Program included 75 kW of PV power in Phase 1, followed by 50 kW of SD power in Phase 2 for a total power at the end of Phase 2 of 125 kW. Both options utilized a 440-V 20-kHz single-phase AC power distribution system.[28,29,30] The Phased Program option was selected as the program baseline, eventually referred to as Space Station Freedom (SSF).

Figure 24.—Final phase B enhanced configuration with photovoltaic and solar dynamic power modules.

Rocketdyne delivered a two-volume summary of the results of their Phase B activities: Volume 1 contained the Executive Summary of the results,[31] while Volume 2 provided details of systems analysis and trades and the EPS preliminary design.[32] Rocketdyne performed 103 trade studies in Phase B. Twelve were system-level trade studies, which assessed two types of PVM energy storage (batteries vs. regenerative fuel cells) and two options for SD power conversion cycles (Brayton versus Organic Rankine) for the 75-kW initial capability and 300-kW growth power systems. The principal strengths of PV power were identified as technology readiness (low schedule and cost risks), tolerance of pointing errors, flexibility to accommodate lower initial power requirements, and inherent capability to handle large peak loads. The major strengths of SD concepts were their growth potential, flexibility for lower orbit altitudes (due to their small drag area), and significantly lower life cycle costs (LCCs). Noting that the Phased Program required SD development in parallel with construction of a full PV station, Rocketdyne accurately predicted that "programmatic pressure may delay SD development indefinitely, resulting in limited station growth potential and high power costs."

In June 1987, Staiger prepared an Internal Branch Report (IBR) about ENERGY.[33] Staiger described the model as "an essential tool for evaluating the space station power system reference design or evaluating design or configuration option." This code served as an initial building block for the SPACE computer code.

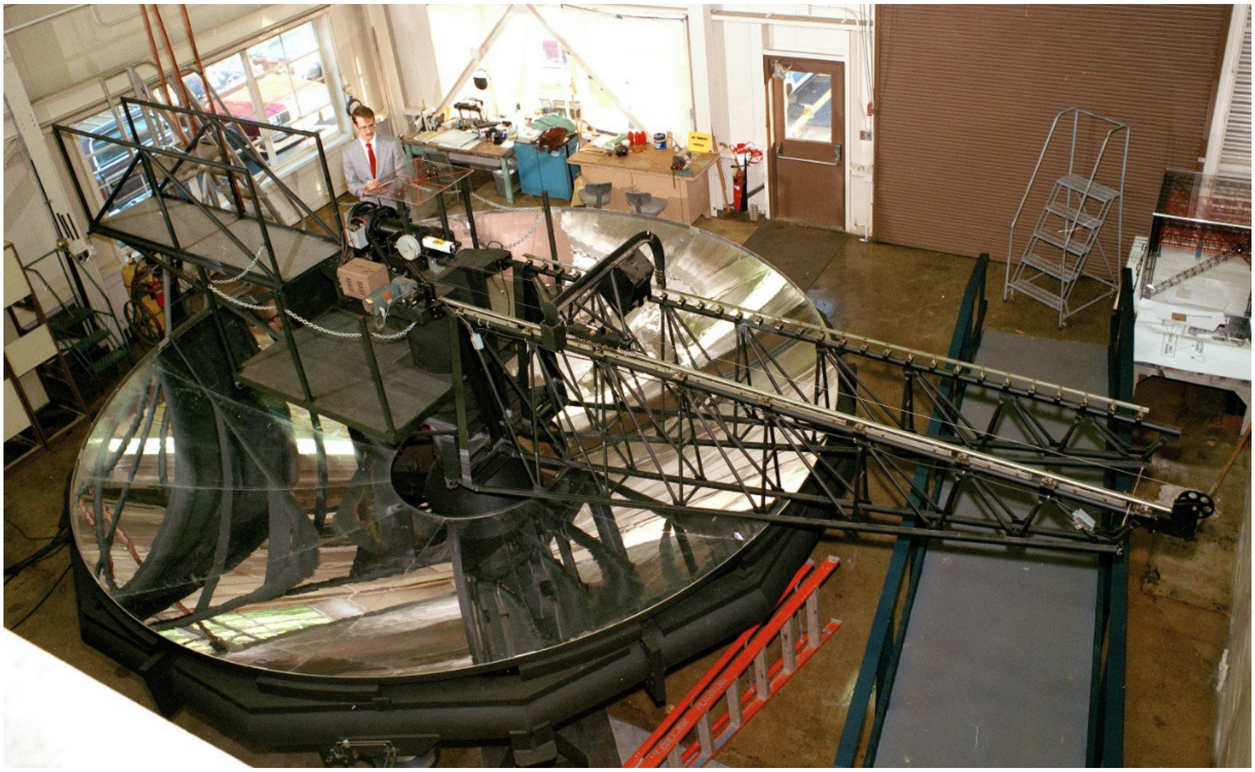

Figure 25.—Michael Ciancone, lead engineer for the concentrator testing, inspecting a development unit in the solar concentrator optical test facility at Lewis (C-86-7828).

Figure 26.—Dave McKissock (left), Jose Davis (seated on right), and Peter Staiger (standing), discussing SPACE analyses results (GRC-1986-C-08569).

Figure 27.—Ten astronauts and cosmonauts dine in Zvezda Service Module in August 2001 (s105e5198).

Results from the ENERGY code were included in the Power System Description Document (PSDD). The PSDD, approved by the Lewis space station change control board on September 11, 1987, contained a high-level description of the reference EPS design as of February 1987 for the space station and the co-orbiting and polar platforms. This reflected the results of the WP–04 Phase B preliminary design effort (specifically the Enhanced Configuration option described above, with 37.5 kW of PV and 50 kW of SD). Figure 28 shows the orbital average power capability at the design altitude (180 nmi) with 3 years of on-orbit degradation. These were often referred to as squiggly curves, with the shape driven by the annual variation in distance between Earth and the Sun as well as short-term variations in the orbital eclipse durations. The minimum value of 87.5 kW matches the design conditions.

Figure 29 shows the amount of time (in days per year) that the capability of the EPS exceeds a given value. For example, on approximately 50 days per year, the EPS capability exceeds 96 kW. These exceedance curves were very popular in the early years of the space station program.

The exceedance curve in Figure 30 shows the orbital average power capability of the PV portion of the EPS for one orbit revolution assuming loss of the alpha gimbal rotation. The SD portion produces zero power under off-pointing conditions, and thus is not depicted. Both of the alpha gimbals are assumed to be locked at the specified angle. The batteries are discharged beyond their normal depth of discharge (DOD) to their contingency DOD of 80 percent.

A power flow diagram for the hybrid EPS is shown in Figure 31 for the design condition. The figure shows the nominal power flow paths from the SAWs (four wings) and the two SD units through the various PMAD components to the user load converters. It also illustrates the power required to charge the energy storage assembly during the Sun portion of the orbit and the energy storage output during eclipse.

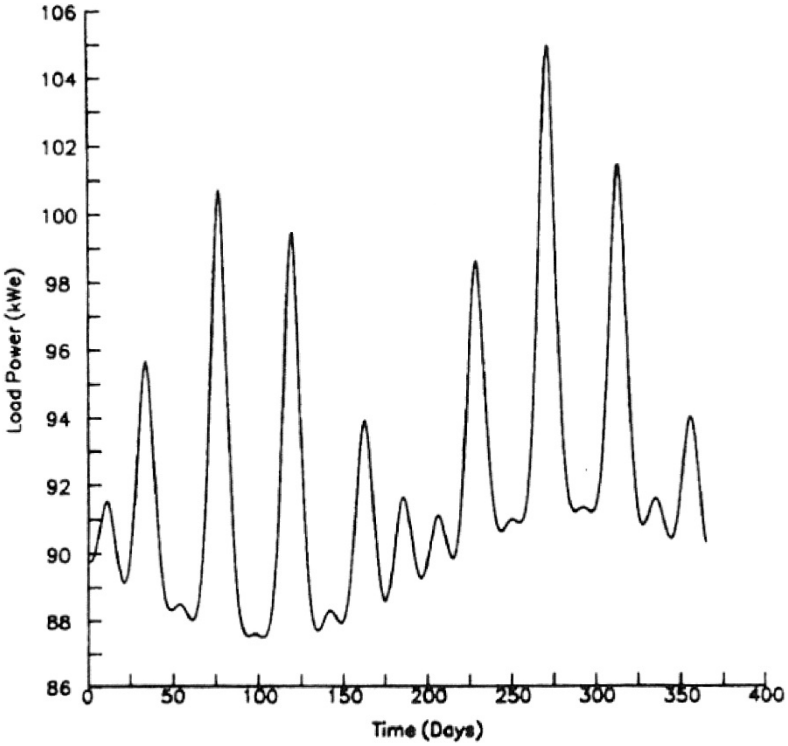

Figure 28.—Electrical Power System orbital average power capability (i.e., load power) at 180-nmi altitude with 3-year degradation conditions.

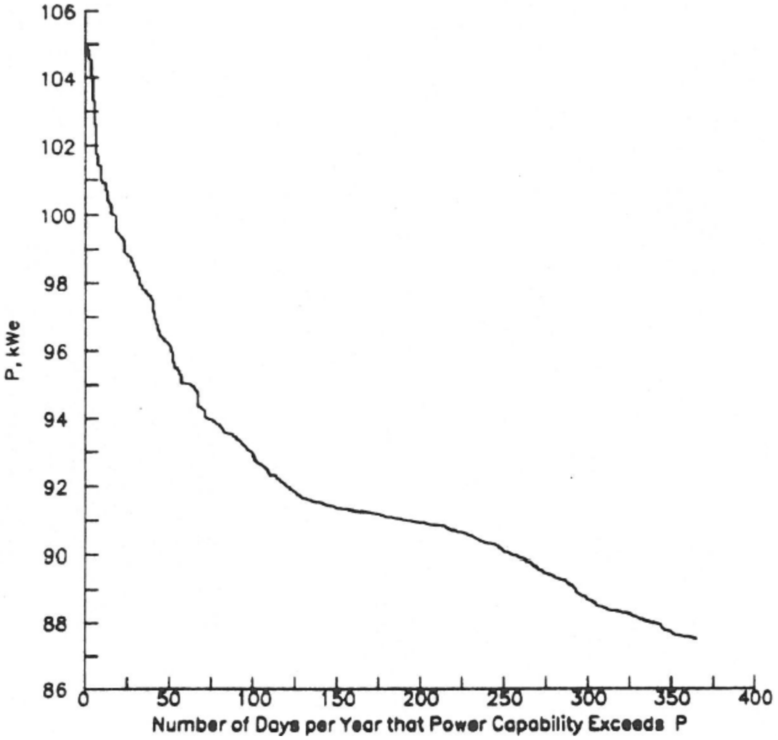

Figure 29.—Exceedance curve for orbit average power capability at 180-nmi altitude with 3-year degradation conditions.

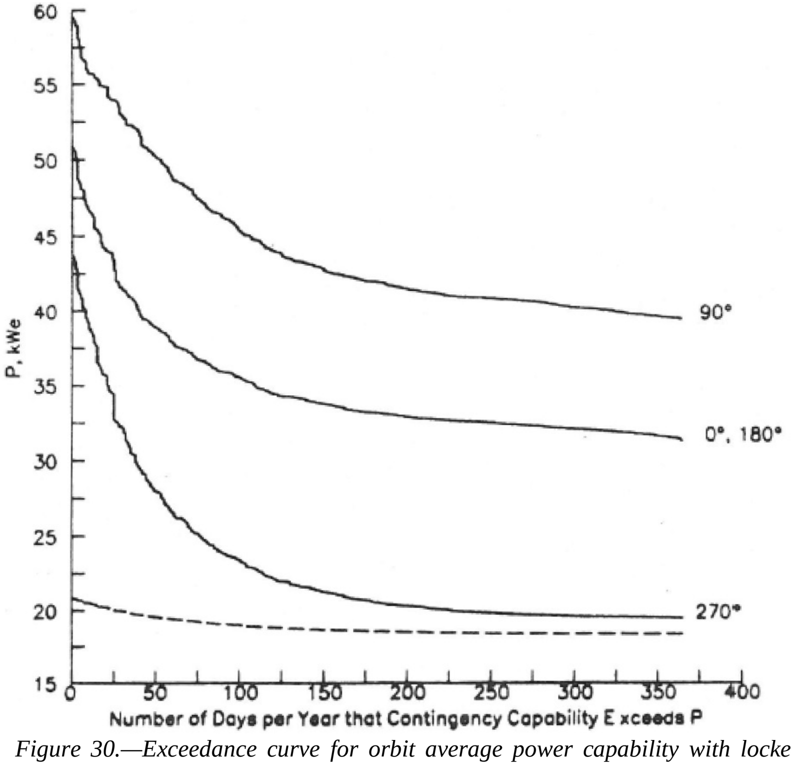

Figure 30.—Exceedance curve for orbit average power capability with locked gimbals. Both port and starboard alpha gimbals are locked at indicated position. Dashed line is contribution of batteries resulting from additional discharge.

Following the Challenger accident in 1986 and the re-appointment of James Fletcher as NASA administrator, NASA announced a sweeping management shakeup to keep the space station program on track. Andrew Stofan (former Lewis director), was named associate administrator for the space station.[34] The Level II management of the space station program was moved from Houston to Reston.[a]

In 1987, Lewis issued an RFP for the detailed design and construction of the space station power system. NASA requested industry to submit proposals for each of the two options discussed above: the Phased Program (starting with 75 kW of PV and adding 50 kW of SD) and the enhanced configuration (37.5 kW of PV and 50 kW of SD).[35]

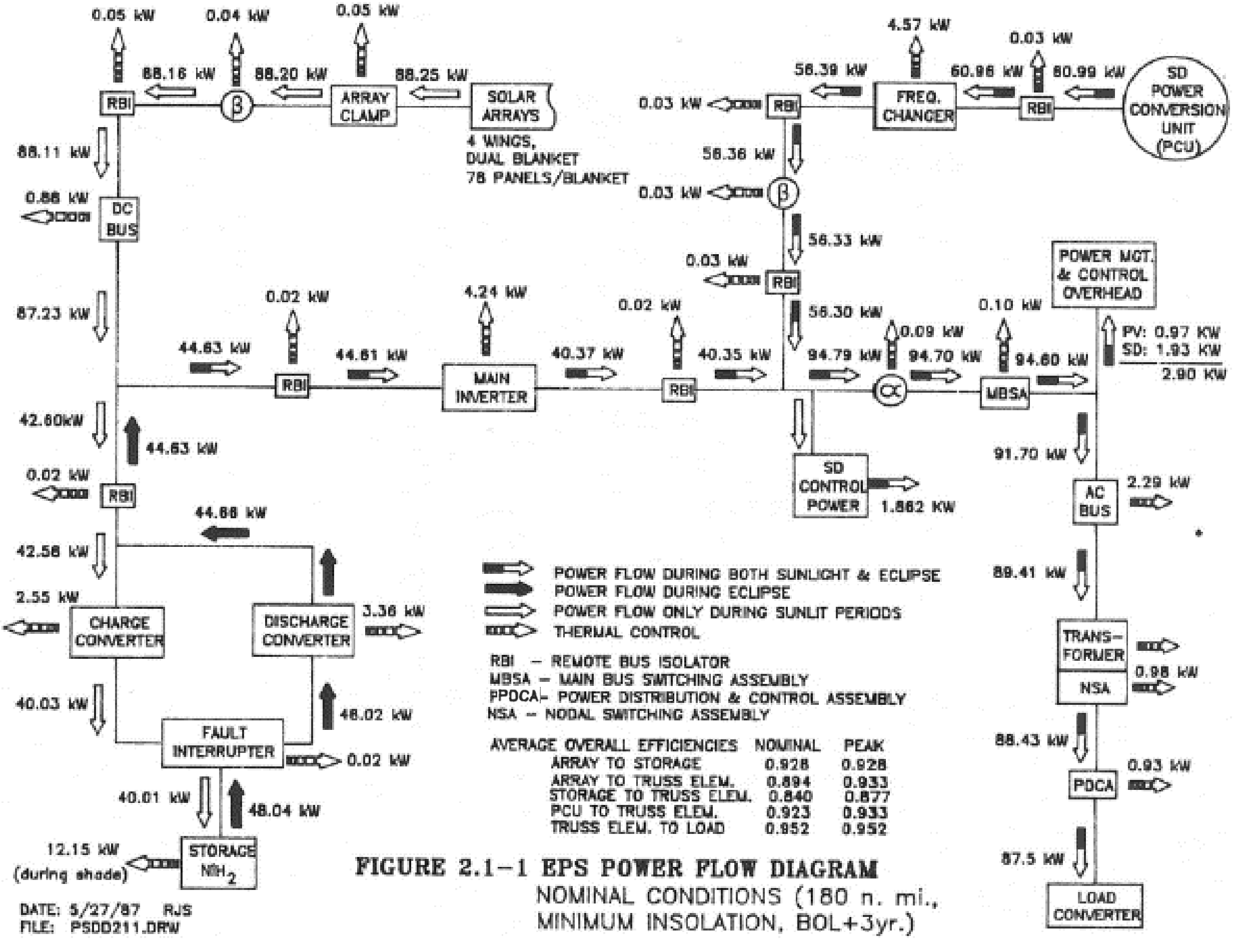

Figure 31.—Electrical Power System power flow diagram with minimum power conditions, 180 nmi, minimum insolation, and 3-year degradation.

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[a] Level I was located at Headquarters in Washington, DC, and was responsible for overall policy and program direction. Level II (moved to Reston with this change) provided program management and was responsible for technical content. Level III centers provided hardware element definition and development.

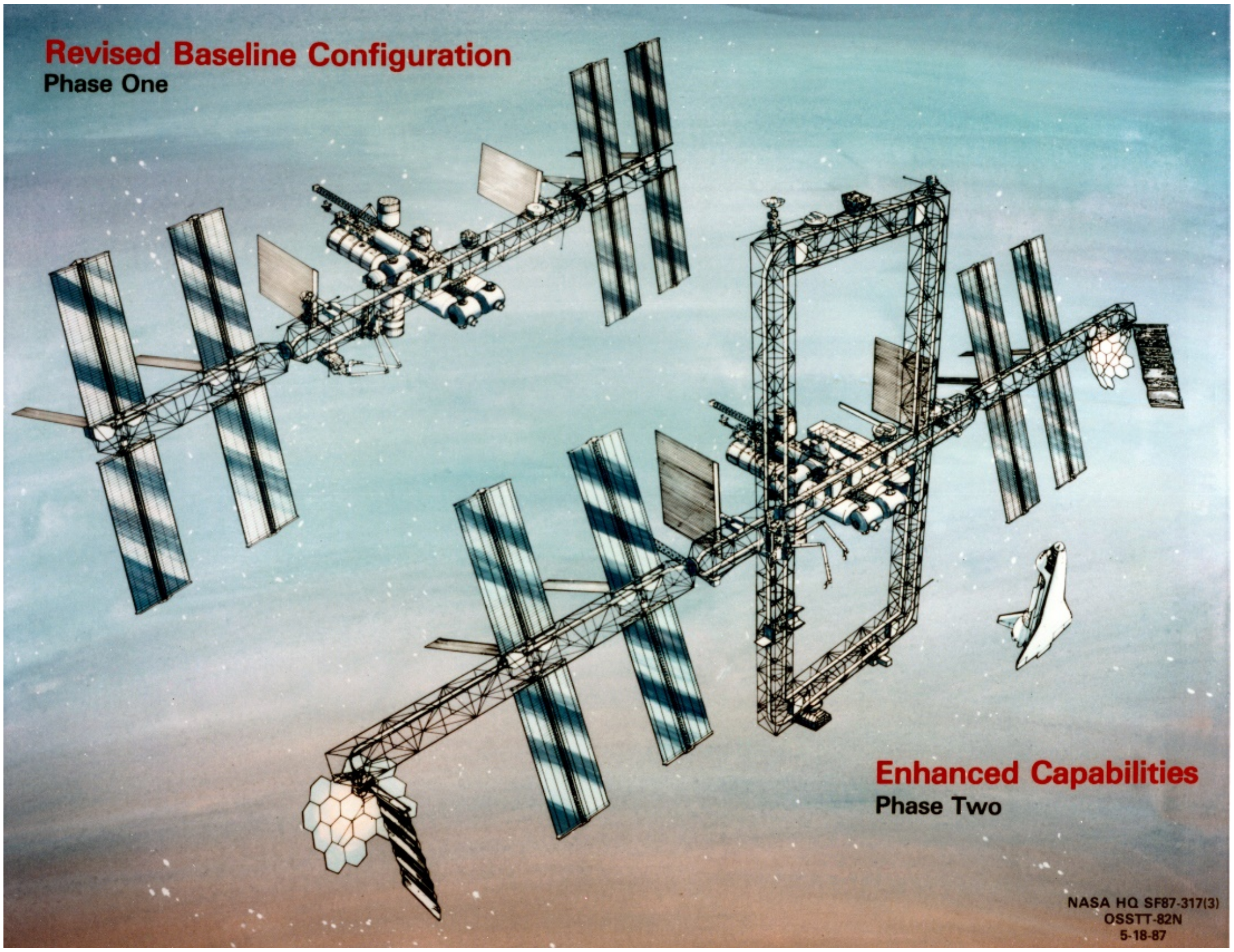

Figure 32.—Reference space station configuration for Phase C/D (GRC-1987-C-07808).

Initial SPACE Code Development, Begin Phase C/D (1988)

In early 1988, Lewis began development of SPACE as a tool for independent verification and validation of EPS performance estimates from the prime contractor (Rocketdyne) and to perform studies in support of overall program integration activities. The team began by documenting the model objectives and scope, defining the inputs and outputs, and planning the modeling approach and structure.[36] Management provided one objective: "to develop a computer program to evaluate the EPS design and its end-to-end performance for all orbital conditions." Following a series of planning meetings led by Jeff Hojnicki over the summer of 1988, a more detailed definition of the EPS performance model was prepared.[37] In parallel with developing the new SPACE code, the Lewis team continued to use the ENERGY code.

In addition, the team members supported the ongoing efforts to develop a contract with Rocketdyne for the design, development, test, and engineering of the space station EPS (i.e., Phase C/D). The 10-year contract was definitized in September 1988[b] and was valued at $1.6 billion.[38] For Phase 1 of the program, the EPS was composed of silicon-PV solar arrays, NiH_2 batteries, and 440-V 20-kHz distribution technology, providing 75 kW continuously to the users with a peaking capability of 100 kW. The contract included an option to implement Phase 2, which would add two 25-kW SD modules. This contract option was never exercised. The reference configuration for Phase C/D is shown in Figure 32.[39]

In January 1988 (1 month after the letter of contract was signed), Rocketdyne gave a presentation on the space station EPS to Dale Myers, NASA Deputy Administrator.[40] Analysis by Johnson showed the projected load demand significantly exceeded the EPS capability (Figure 34). This was a concern, as the next slide (Shuttle Power Growth History, Figure 35) indicated that the space shuttle operated at power levels much higher than originally anticipated. The estimated 30-year LCC of the power system is shown in Figure 36. The $3.3 billion estimated savings by utilizing SD instead of PV for a 300-kW space station was very attractive to management. The LCC advantage with SD is primarily due to reduced flight hardware costs and reduced maintenance (batteries on a PV system require regular replacements, but the thermal energy storage utilized in an SD system has long life). NASA estimates of space station growth power levels exceeded 300 kW.[41] NASA also studied the feasibility of utilizing a nuclear reactor power system on the space station.[42] Three concepts were investigated based on SP–100 program technology and used a 2-km tether, single-boom, or a dual-boom attachment to the dual-keel space station.

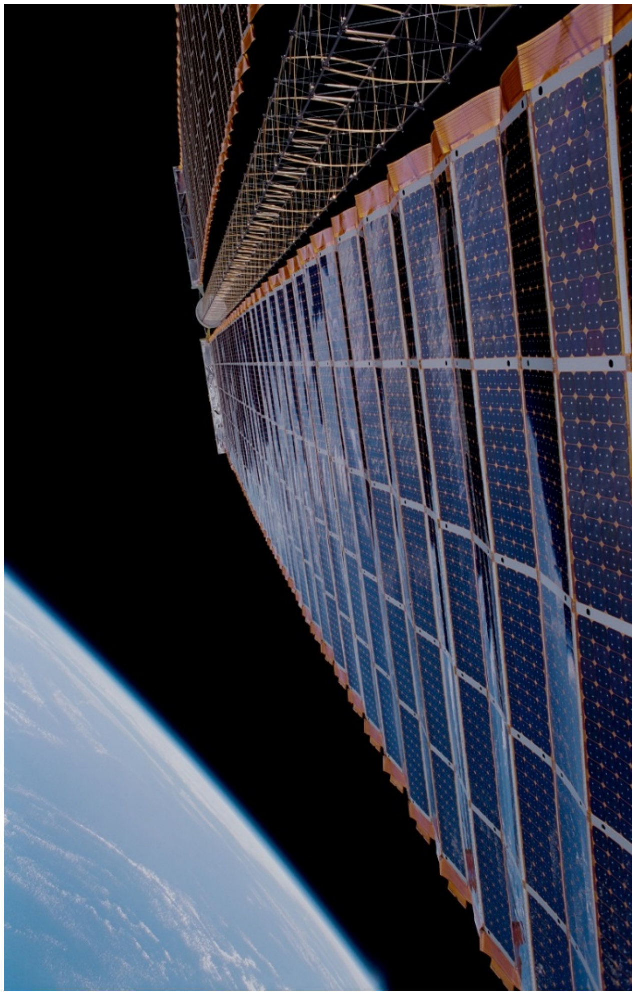

Figure 33.—Closeup view of P6 solar array in December 2000 (sts097-376-019).

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[b] A letter of contract was signed in December 1987, which permitted the contractor to initiate design activities.

A prototype of the upgraded ENERGY code was released in October 1988. This prototype was tentatively named Power and Energy Analysis for Capability Evaluation (PEACE). Up to this point, all the development work for the code was performed by civil servants in the Lewis space station organization. That would soon change. The NASA Level II space station organization in Reston hired a contractor to assist with integration activities across the program. This resulted in the contractor forming local offices at each NASA center. At Lewis, Analytical Engineering, Inc., was the local contractor. Analytical Engineering, Inc., proposed joint development of an Energy Balance Model to model the generation, distribution, and consumption of space station electric power as the supply power, demand at the loads, and switchgear configurations change over time. Lewis eventually negotiated a task with Analytical Engineering, Inc., to develop a load-flow module that was later incorporated as part of the PMAD model in SPACE.

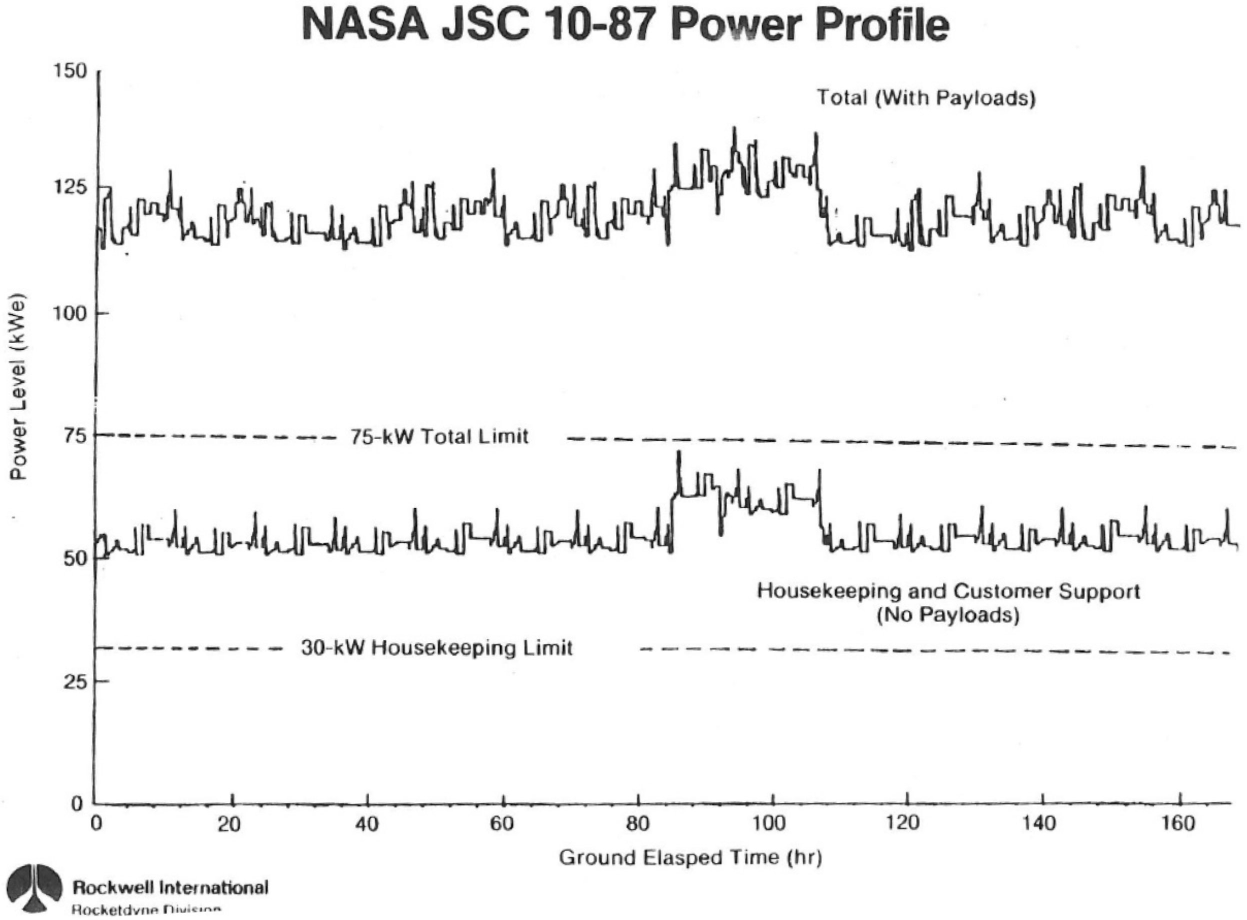


Figure 34.—Projected space station housekeeping and total load demand (with payloads) from Rocketdyne briefing to Dale Myers, NASA Deputy Administrator.

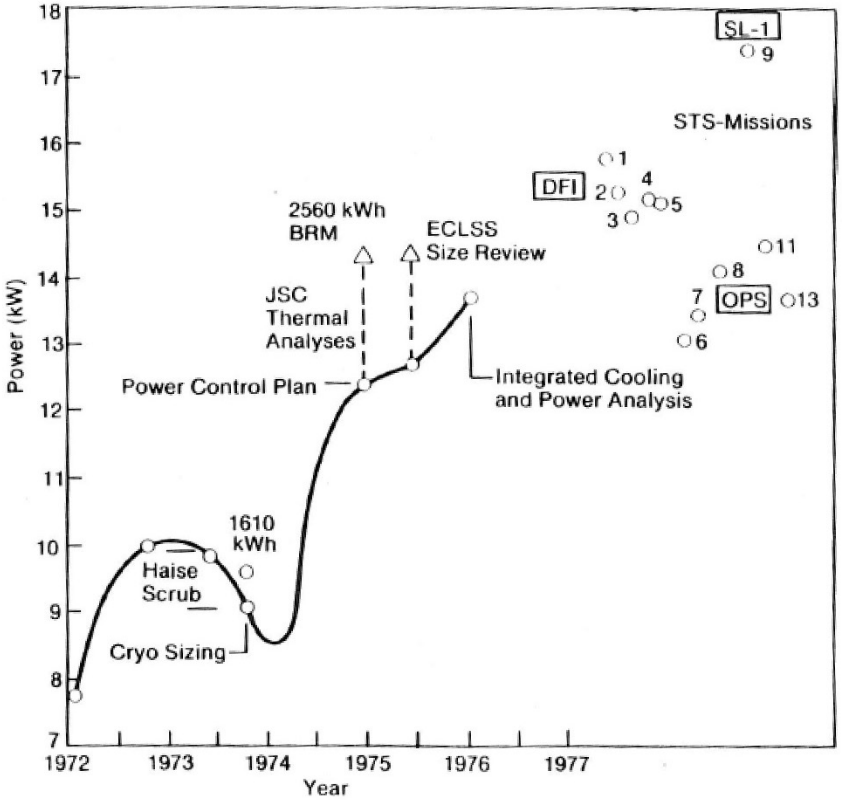


Figure 35.—Shuttle power growth history from Rocketdyne briefing to Dale Myers.

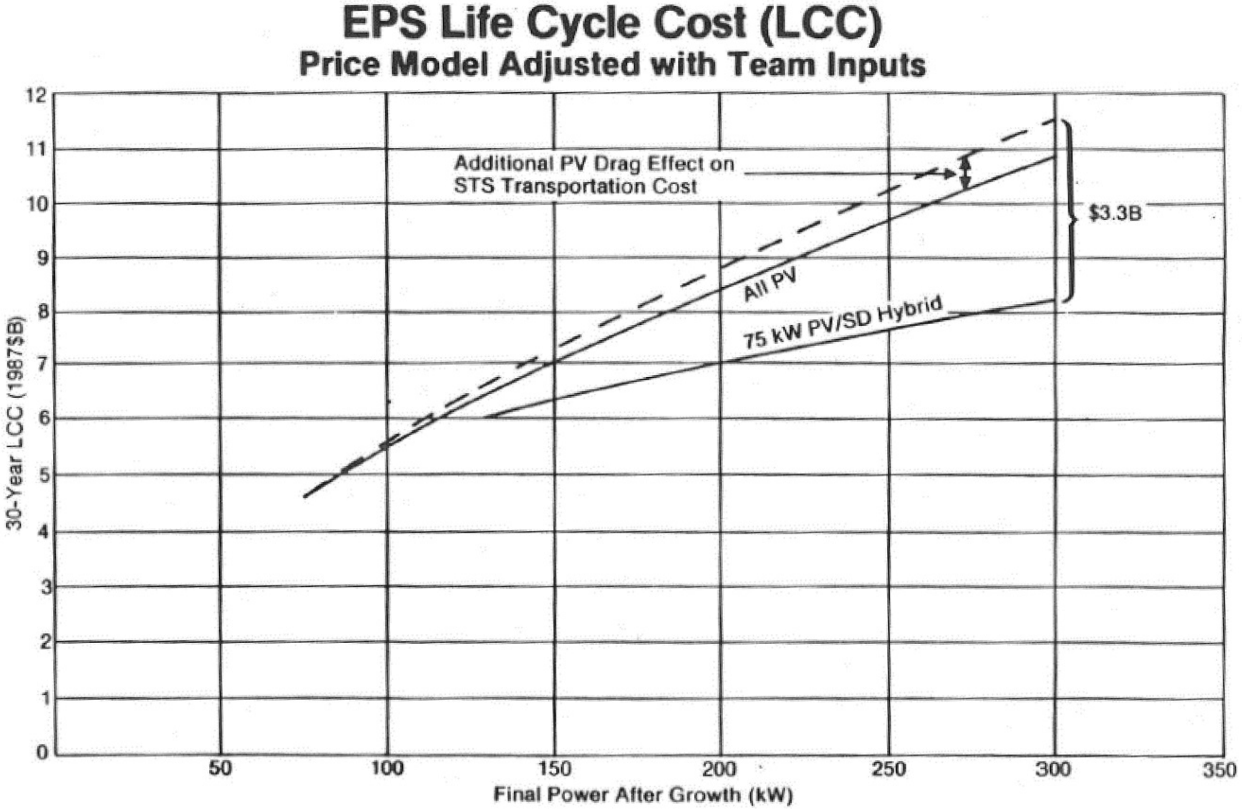


Figure 36.—Electrical Power System estimated LCC from Rocketdyne briefing to Dale Myers.

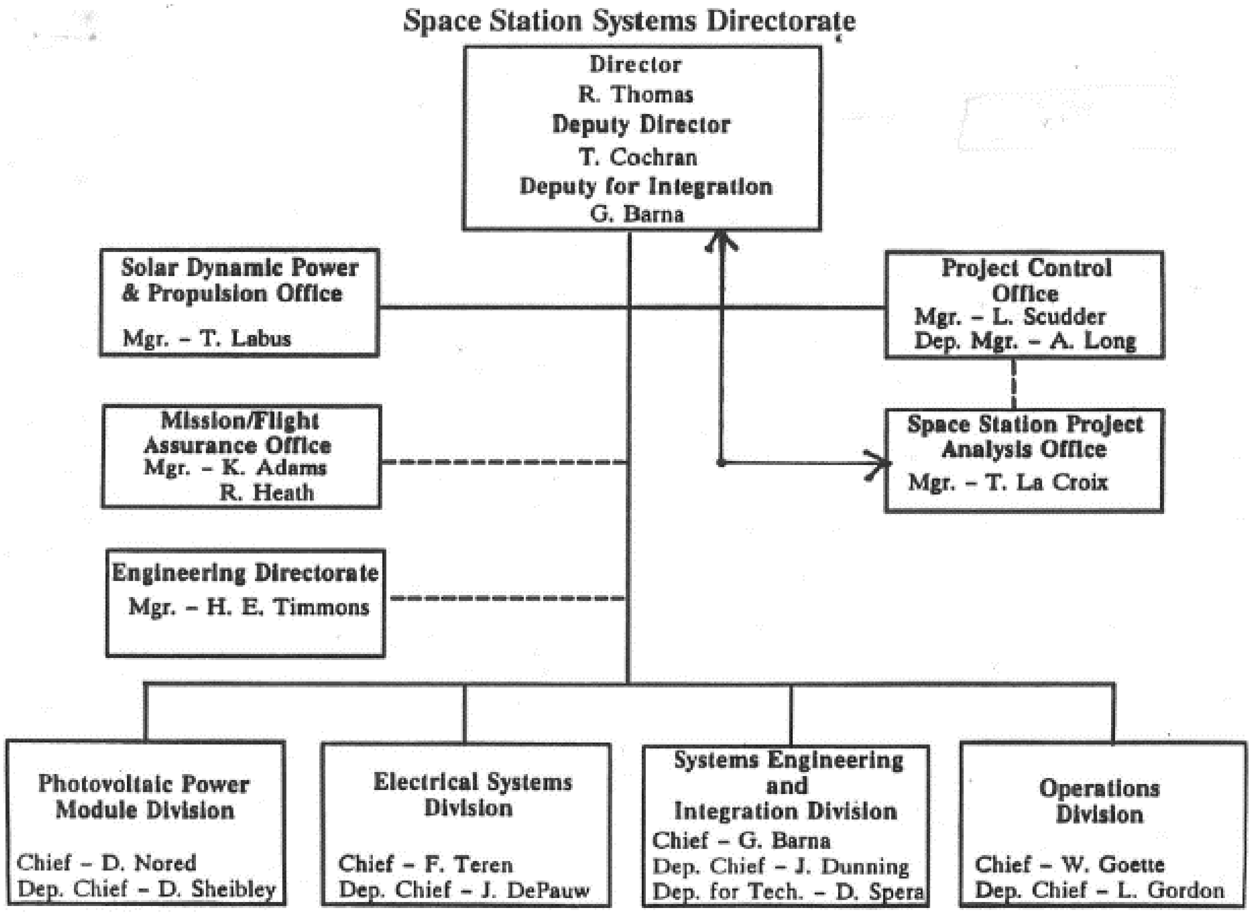


Figure 37.—Lewis Space Station Systems Directorate organization chart in October 1988.

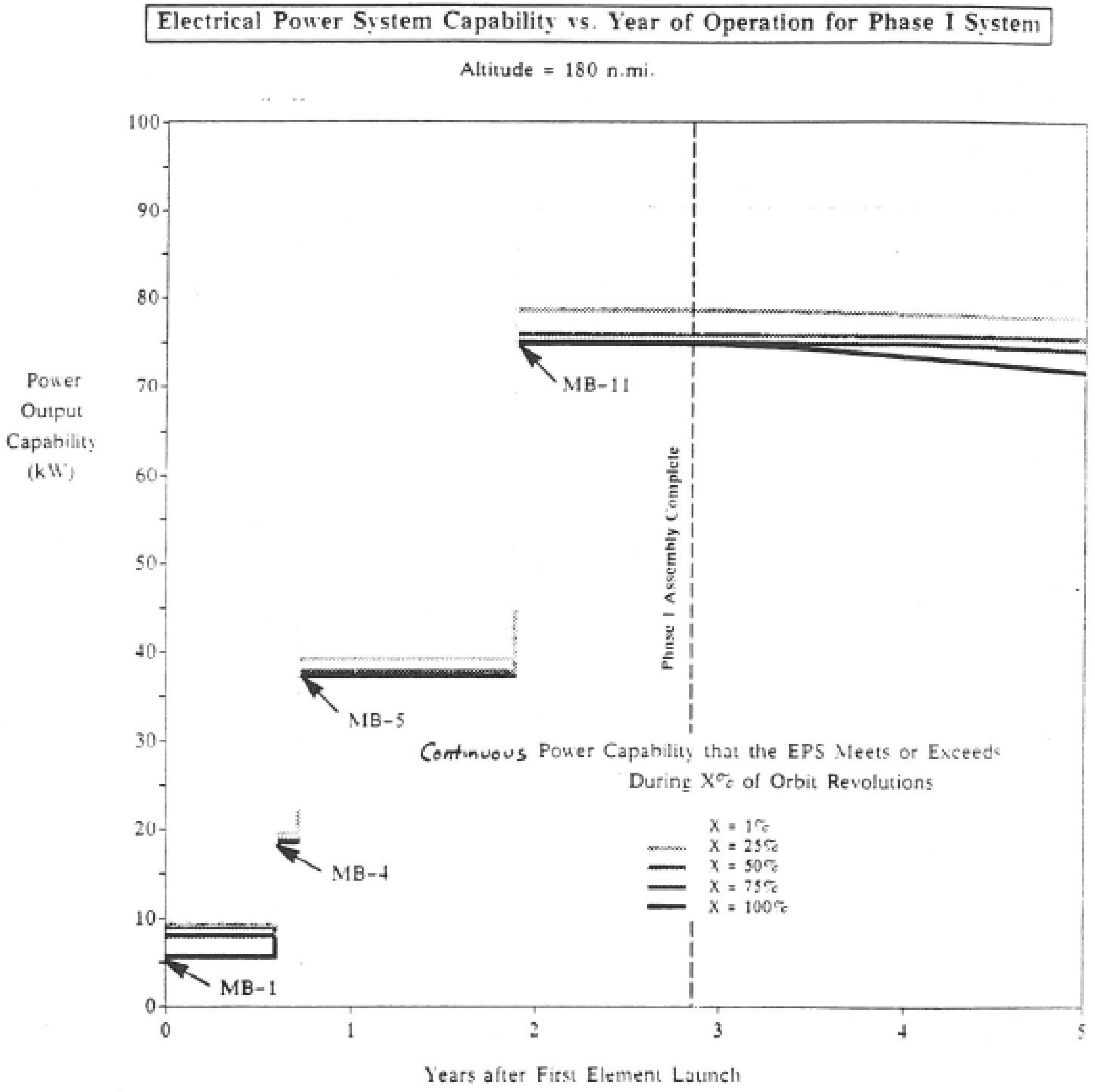
The Lewis space station directorate organization chart from October 1988 is shown in Figure 37. The analysts working on the SPACE code were all located in the Systems Engineering and Integration Division, in the Systems Engineering and Analyses Branch (which is not included in the chart).

Lewis power analyses were at the forefront in the Program Management Review (PMR) held in Reston in September 1988. The PMR was led by Tom Moser, space station program director. Key attendees included reprentatives from Johnson, Marshall, Goddard, Lewis, the Level II integration contractor, and NASA Level II staff. From Lewis, Ron Thomas and Dick Donovan attended the meeting. Donovan was the Deputy Chief of the System Engineering and Analyses Branch and he delivered two briefings at this meeting: Power Availability Profile and Power Augmentation Options. The Level II Chief of the Distribution Systems Architecture office (Bryant Cramer) gave a third briefing on Power Demand and Allocation. Donovan first showed the current version of the traditional squiggly curve. There was one major change from the curve shown in Figure 28—Lewis switched from reporting orbit average power to minimum continuous power through the orbit. Early in the life of the space station with new solar arrays and new batteries, the space station EPS could provide more power to the load in the Sun period than in the eclipse period (presuming the battery DOD is limited to the design value of 35 percent to ensure long life). For example, one PV module could perhaps provide 10 kW in the eclipse period and 14 kW in the Sun period. Level II was intended to allocate the available power to space station systems and payloads, so rather than reporting the average, Lewis determined it was more appropriate to report the minimum continuous power of 10 kW to Level II.

Figure 39 is from Donovan’s presentation at the PMR, showing the buildup in EPS capability through the assembly sequence. Besides showing the minimum continuous power levels, Figure 39 also shows power levels exceeded 1 percent of the time, and 25, 50, and 75 percent of the time. For example, at 5 years after the first element launch, the minimum continuous power level is approximately 71 kW. But for half of the year, the minimum orbital power level exceeds 75 kW, and in 25 percent of the days in a year, the power level exceeds 77 kW.

Figure 40 shows the Level II comparison of the Lewis EPS capability values with their summation of the projected load demand for each space station flight. The different types of assembly flights are noted on the x-axis: Mission Build (MB), Logistics (L), and Outfitting (OF). The solid black bars show the problem—the load demand exceeds the EPS capability by about 30 kW on MB–10 (immediately before the launch of the next two PV modules)—and a deficit of about 10 kW at the end of the assembly sequence. The annotations were added by Donovan during the meeting.

Figure 38.—Participating in the evaluation of a space station program change request are (standing, left to right) Bill Goette, Ron Thomas, Tom Cochran; (seated, left to right) Dan Bernatiwicz, Pete Kempke, Don Nored, and Karen Faloon.



Notes: All EPS hardware assumed to be operable.

For Flights MB-1 and MB-2, the EPS is in a feathered mode of operation at an altitude of 220 n. mi.

Power generated by the EPS is continuous over an individual orbit.

Figure 39.—Continuous power capability through assembly sequence.

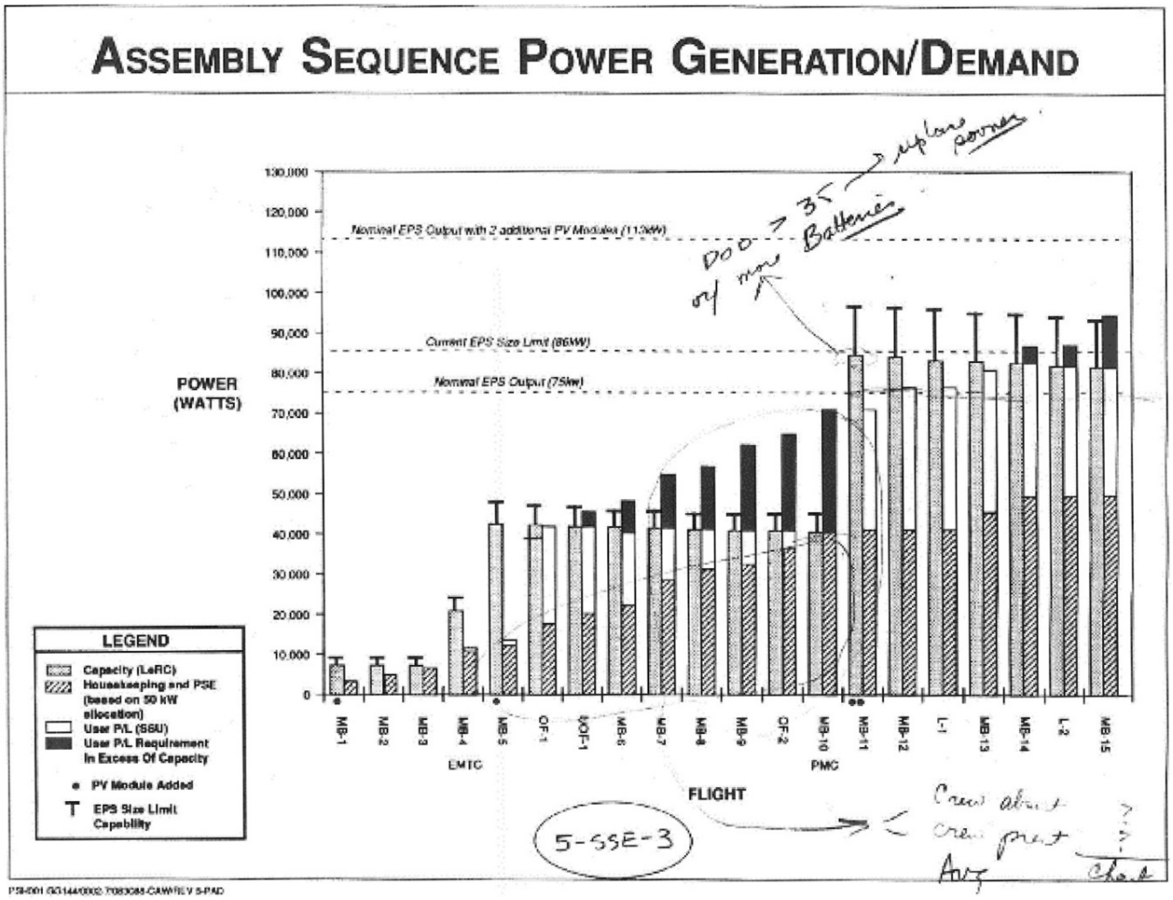


Figure 40.—Level II comparison of Electrical Power System capability versus projected load demand.

Donovan then presented the following material on power augmentation options:

- Increase the size of the PV modules by 15 percent, from 18.75 to 21.56 kW. This would have had an adverse impact on the mass allocations for the first assembly flight (which already had mass challenges), increased program risk (larger solar array mast diameter, larger battery capacity, and tighter program schedules), and increased cost.
- Install two 25-kW SD power modules at MB–11 (instead of the planned pair of 18.75-kW PV modules).
- Add two 18.75-kW PV power modules to the baseline 75-kW PV system at assembly completion.
- Add two 25-kW SD power modules to the baseline 75-kW PV system at assembly completion.
- Add four 25-kW SD power modules to the baseline 75-kW PV system at assembly completion.

The program manager instructed the program to press ahead with the planned power allocations for housekeeping and user support and continue with the planned assembly sequence. He recognized the power deficit and instructed the program to work to alleviate the issue. He asked the assembly sequence team to look into accelerating the launch of the last two PV modules before declaring permanently crewed capability.

The overall program schedule at the beginning of Phase C/D is shown in Table III.

In late 1988, Ron Thomas collaborated with George Hallinan (head of the Rocketdyne space station power system organization) on a paper describing the design of the SSF power system.[43]

TABLE III.—1988 SPACE STATION FREEDOM SCHEDULE

Event	Date
Preliminary Requirements Review	April 1988
Preliminary Design Review	January 1989
Critical Design Review	August 1990
First element launch	March 1994
Man-tended capability	March 1995
Permanently crewed	Early 1996
Baseline complete	Early 1997

Figure 41.—SD Concentrator optical testing in PSF (C-1990-8258).

SPACE 1.0, Re-Examination of Solar Dynamic (SD) Power (1989)

SPACE version 1.0 was completed in June 1989. This initial version modeled an EPS with a primary bus using an AC distribution system and PV solar arrays with batteries. Solar array pointing options included Sun-pointing, feathered, and general off-pointing. Shadowing of solar array surfaces was not included. Sample results from SPACE were documented in internal branch reports.

In early 1989, a new space station program director (Ray Tanner) wanted to take advantage of lower SD LCCs and reinvestigated using off-the-shelf PV with increased SD during Phase 1 of the space station. This director's tenure was short-lived, and the reference configuration stayed with PV in Phase 1.

The Power System Testing Facility (PSF) was dedicated in January 1989.[44,45] Optical tests of a SD concentrator were conducted in the 55-ft high bay in the PSF, as shown in Figure 41. The telescience support center, also located in PSF, was used by the Lewis space station staff (including the SPACE team) during the first few ISS EPS assembly flights to provide real-time support to the Mission Operations Directorate at Johnson.[46]

In 1988 and 1989, a significant quantity of Lewis assessments were conducted to support a Level II trade study concerning the EPS primary and secondary distribution systems. An October 1988 briefing by Bryant Cramer identified four power distribution options:

- All 20-kHz AC system
- Primary bus distribution at 20 kHz, bulk secondary conversion to 120 Vdc for the European Space Agency (ESA) and Japan Aerospace Exploration Agency (JAXA) modules, all U.S. loads at 20 kHz
- Primary bus distribution at 20 kHz, all DC secondary
- All DC system with 160-Vdc primary and 120-Vdc secondary

Cramer coordinated a program-wide assessment to include system efficiency, system stability, electromagnetic interference and/or electromagnetic compatibility, isolation, system safety and safety hazards, regulation of transients, user power supply impacts, and flexibility and ease of growth. He also considered 17 system resources, such as cost, mass, volume, and EVA maintenance hours. Considering all of these variables, Cramer recommended maintaining the primary bus distribution at 20 kHz with an all DC secondary. Canada preferred a 20-kHz secondary, while all the other program participants wanted a 120-Vdc secondary. The program change board elected to modify the primary distribution system from 440-V 20-kHz AC to 160 Vdc, with a 120-Vdc secondary.

In Figure 42, SPACE results for PV wing power at orbit noon are compared with results from the Rocketdyne EPS performance tool (EPSOP). The SPACE predictions are approximately 500 W above the EPSOP predictions. This delta was found to be primarily due to a 3.3 °C difference in solar cell operating temperature (EPSOP at 57 °C, SPACE at 53.7 °C). The SPACE and EPSOP results are for a solar array operating at 8 V below the noon maximum power point, which was the presumed SSU operating set point. This work was conducted in late 1989.[47]

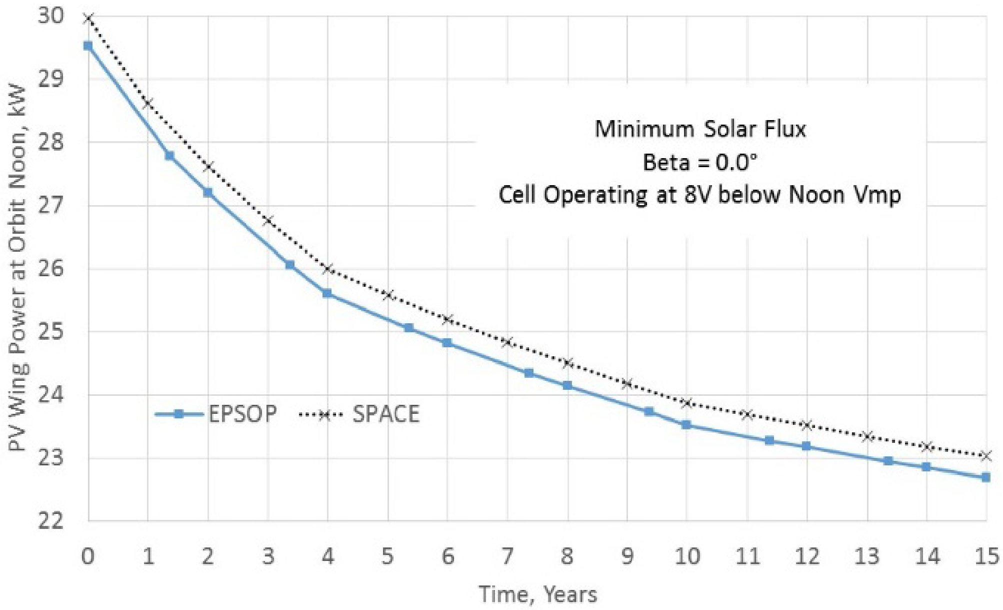


Figure 42.—SPACE/Rocketdyne EPS performance tool (EPSOP) photovoltaic (PV) wing power versus in-service time.

SPACE 2.0, Preliminary Design Review (PDR), Mass Reduction, Solar Dynamic (SD) Again (1990 to 1992)

In January 1990, the SPACE team released version 2.0, which included several enhancements: modeling of the space station assembly sequence, AC or DC power distribution, and single- or multi-orbit power capability assessments.[c] A user's guide for the code was also released.

The space station program office in Reston conducted a turbo team activity to reduce resource requirements for EVA, weight, power utilization, and sensors.[48] SPACE analysis showed that by reducing the quantity of NiH_2 batteries, the launch mass of PV modules could be reduced and the power capability maintained by operating the remaining batteries at higher DODs. This triggered a programmatic change to modify the space station assembly sequence to launch the initial PV modules with a reduced complement of batteries. This change was later reversed, as subsequent mass reporting indicated that the space shuttle could launch a PV module with a full complement of batteries.

SPACE analyses also showed that a spacer truss bay between adjacent PV modules could be eliminated if the solar arrays are off-pointed at higher solar beta angles to prevent solar array-to-solar array shadowing. The power impact was negligible, due to the reduced eclipse periods at high solar beta. This change was implemented during the turbo team exercise and is part of today's ISS standard operating procedures. When the Russians were later added to the program and the orbit inclination was raised from 28.5° to 51.6°, the resulting larger solar beta angles (and associated larger solar array off-pointing) yielded significant reductions to solar array power.

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[c] In a single-orbit power balance, SPACE requires the batteries to be completely recharged at one point in the Sun period of an orbit. In a multi-orbit analyses, where the solar arrays could be locked for one orbit and then Sun tracking in the second orbit, the batteries need only be fully charged in the last Sun period. This flexibility allows the EPS to provide a higher amount of power to users as the batteries can be discharged during the first orbit and not fully recharged due to the off-pointed solar arrays.

TABLE IV.—1991 RESTRUCTURE SCHEDULE SLIP

Event	1988 Space Station Freedom (SSF) Date	Restructure Date
First element launch	March 1994	November 1995
Man-tended capability	March 1995	December 1996
Permanently crewed	Early 1996	September 1999

Headquarters issued direction for implementing a restructured program plan in February 1991.[49] This plan included developing and operating SSF in distinct phases. The first phase developed a vehicle to support temporary crews (man-tended). The space shuttle would then provide two to three utilization flights per year, with visiting crews conducting science experiments in the laboratories. The second phase developed a permanently crewed capability "as early as appropriated funds will support." A follow-on phase would enhance and grow the station capability. The restructured program schedule is shown in Table IV. The restructured program also included the following:

- Shorter modules with integration and checkout on the ground
- Truss segments assembled, integrated, and checked out on the ground
- Two nodes (versus four)
- SD studies stopped
- Permanently crewed power capability reduced from 75 to 56.5 kW (eliminating one PVM)

In August 1991, Lewis presented a briefing on SD at the space station evolution symposium.[50] Although the restructured program resulted in terminating SD activities, there was an activity underway to reinstate a 150-kW SSF growth requirement.

In a February 1992 briefing by the SSF Program Director to Congress, major accomplishments reported by the three lead NASA centers included[51]

- A full-sized pressurized module was built to flight specifications and underwent a series of pressurized tests (managed by Marshall).
- The airlock hatch was tested to determine structural strength and how best to shield against radiation (managed by Johnson).
- More than half of the flight solar cells for the first solar array had been built (managed by Lewis).

Major Upheaval in the Space Station Program (1993)

Work Package-04 (WP–04) Critical Design Review (CDR)

The Lewis and Rocketdyne EPS team was proceeding quickly to the CDR, which occurred in February 1993. Key activities from late 1992 and early 1993 included

- Design activity well underway, with about half of the component CDRs completed.
- Almost enough flight solar cells had been delivered to populate one SAW.
- Battery cell testing was underway at Lewis, the Naval Surface Warfare Center Crane Division, and Space Systems Loral. Approximately 186 cells underwent testing, some with over 3 years of cycle testing.
- Several neutral buoyancy and robotics tests were completed on a PVM cargo element mockup and on a variety of ORU boxes.

- Space Power Electronics Lab test #3 was initiated. The proof-of-concept tests in this lab successfully demonstrated the EPS functionality.
- Remote Power Controller Module breadboards were developed and delivered to other work packages for integrated testing.

Some of the challenges included reducing the mass of the hardware on MB–1 to meet the mass allocation, completing fabrication and assembly of most engineering model articles, accepting delivery of qualification hardware, and implementing the fiscal years (FYs) 1993 and 1994 budget guidelines and the revised program schedule.

Staff from Lewis and Lockheed Missiles and Space Company, Inc., authored a paper describing a Lockheed analysis of the predicted solar array electrical performance over the design life.[52] The paper includes a description of the Lockheed solar array performance model, which is very similar to the model in the SPACE code.

White Paper on Changing Space Station Orbit

In mid-January at SSF Level I Engineering in Washington, DC, a white paper was under review that recommended increasing the SSF baseline orbit inclination from a 28.5° to 51.6° inclination, to co-orbit with the Russia's Mir space station.[53] The largest projected benefit was increasing the operational flexibility and safety as assembly, crew exchanges, and resupplies could occur from either U.S. or Russian launch sites. Other benefits included enhanced international cooperation, using Soyuz as a lifeboat for emergency crew reentry, and better Earth observation for the space station. The largest impact to SSF was reduced shuttle performance at the higher inclination. Although not recognized at the time, this white paper accurately predicted the future of the space station program.

Johnson $500 Million Cost Overrun

On Sunday, January 31, 1993, the Washington Post reported[54] a $500 million cost overrun "occurred in the portion of the mammoth project managed by JSC." Marty Kress (Deputy Director for the space station program at Headquarters) stated: "We all realize the standards that are being applied to this program ... It has been made clear to us that a condition of its support is that there be no cost growth or schedule slippage. The size of the cost overruns did surprise us. We expected $100M, $120M, maybe $140M."

A seven-page report providing NASA's response to the Post article was released on February 11.[55] The report indicates that NASA determined three key sources of the projected cost growth and was working on possible solutions. This was deemed insufficient by the new administration, and on Friday, February 19, 1993, 3 weeks after the initial $500 million cost overrun story, the Post ran another story under the headline "Clinton Orders NASA to Redesign, Streamline the Space Station."[56] The article notes, "The $30 billion, decade-long program to develop a manned orbital laboratory translates into tens of thousands of jobs in some 37 states, notably Texas, California and Alabama. But it has drawn fire for alleged mismanagement and cost overruns. A top Texas manager of the project was fired last Friday." Dan Goldin, NASA Administrator, was quoted in the article stating, "We're going to streamline the space station and meet the president's challenge." Goldin was appointed NASA Administrator in 1992 by President George H. W. Bush. He went on to serve as NASA Administrator under two more Presidents (Bill Clinton and George W. Bush).

$1 Billion Overrun, Redesign Team

On March 1, 1993, NASA internally announced that Joe Shea, former Apollo project manager, was appointed by Goldin to lead the space station redesign effort.[57] His official title was Assistant Deputy Administrator for space station analysis, and he had oversight of all space station-related development activities. Notable members of his team included George Abbey (Goldin's special assistant), Mike Griffin (Office of Exploration), Max Faget (another Apollo manager), and Tom Stafford (former Apollo astronaut). By design, the team had very limited representation from the SSF organization, but included representatives from each NASA center with a work package (Tom Cochran from Lewis was on the team). The International Partners also had representation on the team. They held their first meeting on March 10, with a target completion date of June 1.

Figure 43.—Ron Thomas addressing the members of the Lewis space station directorate (GRC-1989-C-07462).

Meanwhile, top space station managers were called to testify before Congress on the program cost overruns on March 2, 1993.[58] The Post described the hearing as "contentious" as the NASA program managers "attempted to trace the labyrinthine paths that led to a potential $1B overrun." Aerospace Daily, in their reporting on the hearing,[59] stated, "The NASA testimony fell on skeptical ears among subcommittee members … The skepticism was heightened for some by a letter from Administrator Daniel S. Goldin reporting that he has ordered an independent Station cost analysis by NASA budget officers because he has 'been concerned with regard to the validity of the present cost and schedule estimates.' Rep. James Sensenbrener of Wisconsin … said he had never been warned by the head of an agency not to believe the agency's testimony." Commenting on the Shea team activities, Arnold Aldrich, NASA associate administrator for space systems development, said that given the mature design of Station components, "it is likely that many of them can be used in a redesigned Station as well." Aldrich was correct; many of the EPS components were used in the redesigned space station.

Goldin outlined the space station redesign process in a speech at an American Astronautical Society conference on March 10, 1993, based on a memo from Goldin to NASA senior management on March 9.[60] He indicated the redesigned program must "bring both near-term and long-term annual funding requirements within the constraints of the budget, continue to accommodate and encourage international participation, and reduce technical and programmatic risks to acceptable levels." The memo also established 10 constraints including "achieve initial on-orbit research capability by 1997, new opportunities for Russian participation should be considered, be configured for significantly lower cost operations (in the order of a factor of two), greatly reduce on-orbit assembly and checkout, implement a simplified and effective program management structure, provide adequate budget reserves, and plan for a shorter on-orbit lifetime (e.g., 10 years extendible to 15 years)."

As the space station redesign was tasked to consider Russian participation, Earle Huckins (Head of Level I Engineering), asked the Level I Engineering staff to quietly begin working the Russian option. The prior year, Huckins was the Contracting Officer on a NASA contract with NPO Energia to study the potential use of Russian hardware in the U.S. space station program. This study included the use of Russian launch vehicles and Mir hardware. As part of the contract, Huckins had traveled twice to Russia and had developed important contacts within the Russian Space Agency and NPO Energia. Level I Engineering staff began researching Russian space systems. As an example, Level I Engineering staff created a report titled "The Electrical Power System on Mir."[61] The authors were asked to provide a briefing on the Mir EPS to the EPS Subcommittee of the National Research Council Committee on Space Station.[62] The team assessed using the core Mir module as a bus, adding U.S., JAXA, and ESA lab modules and using U.S.-provided solar power modules.

The White House also wanted an independent view of the space station redesign, so Vice President Al Gore appointed Dr. Charles Vest to chair an Advisory Committee on the Redesign of the Space Station.[63] Sixteen experts with varied backgrounds in the space program, industry, academia, and the military were appointed to the committee.

Final Space Station Freedom (SSF) Design Review

In May to July 1993, NASA successfully completed a program incremental design review at Reston. This was the final major review of SSF at Reston.

Redesign Team Activities

Goldin sent a memo to NASA senior leadership on April 13, 1993, providing a status of the redesign activities.[64] The Station Redesign Team (SRT) was now led by Joe Shea and Bryan O'Connor.[d] The team planned to develop three options for the redesign, costing $5 billion, $7 billion, and $9 billion (compared to the $14.6 billion estimate for SSF). The Russians were invited "to participate as consultants to the redesign effort. The Russians will be available to provide information on Mir and the Russian systems and capabilities that might be useful to the redesign activities."

The SRT provided the first glimpse of their results on April 22 during a public presentation to the Advisory Committee. The SRT had developed three redesign options, labeled Options A, B, and C. Committee members confused these three options with the three cost bogies ($5 billion, $7 billion, and $9 billion). O'Connor predicted that Options A and B would probably come in three flavors, one at each funding level.

At the end of the long day (9:30 a.m. to 7 p.m.), Vest (Chair of the Advisory Committee) complimented the SRT as the degree of clarity in the presentations, saying he was "astounded" at the high level of detail in the briefings on the three design options, given the very short time period.

Russians Arrive in Crystal City

The Russians arrived in Crystal City on April 21, 1993. Goldin welcomed them, and staff members from the White House Science Advisor explained that the Russians were here to receive briefings on the space station redesign options and provide a critique. Over the next week, SRT members briefed the Russians on the redesign options.

The NASA Level I Engineering staff investigating the Russian option began conducting face-to-face meetings with the Russians in the first week of May. Over approximately 5 hours, the power subsystem team met with their Russian counterpart to discuss the EPS of SSF, Mir-1 (the existing Russian space

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[d] Shea would eventually resign with O'Connor leading the redesign effort.

station) and Mir-2 (the design for a proposed new Russian space station, which would use silicon solar cells as well as an SD power system. Elements from the Mir-2 design eventually became part of the ISS).[65]

Using information from these meetings, Level I Engineering prepared a report on Russian options that was provided to Goldin.

SPACE Analyses of Redesigned Station Power Systems

Lewis participated heavily in the space station redesign activities, and SPACE was used to determine Options A, B, and C power generation capability included in the June 1993 report from NASA to the Advisory Committee on the Redesign of the Space Station.[66] See Figure 44 for an example. The predicted continuous power capabilities are shown for 1 year for both the daylight portion of the orbit (sunlight) and during the eclipse period. The continuous power capability during the eclipse period rises in orbits when the duration of the eclipse period is short. At solar beta angles above 40°, the beta gimbals are no longer Sun-pointing to prevent solar array-to-solar array shadowing.[e] Hence the continuous power capability during the sunlight portion of the orbit starts to rise as the beta angle increases (and the eclipse time decreases), but then the sunlight power begins to drop due to beta-backtracking.[f] Lewis filled a 3-in. binder with analyses conducted during the space station redesign activities.

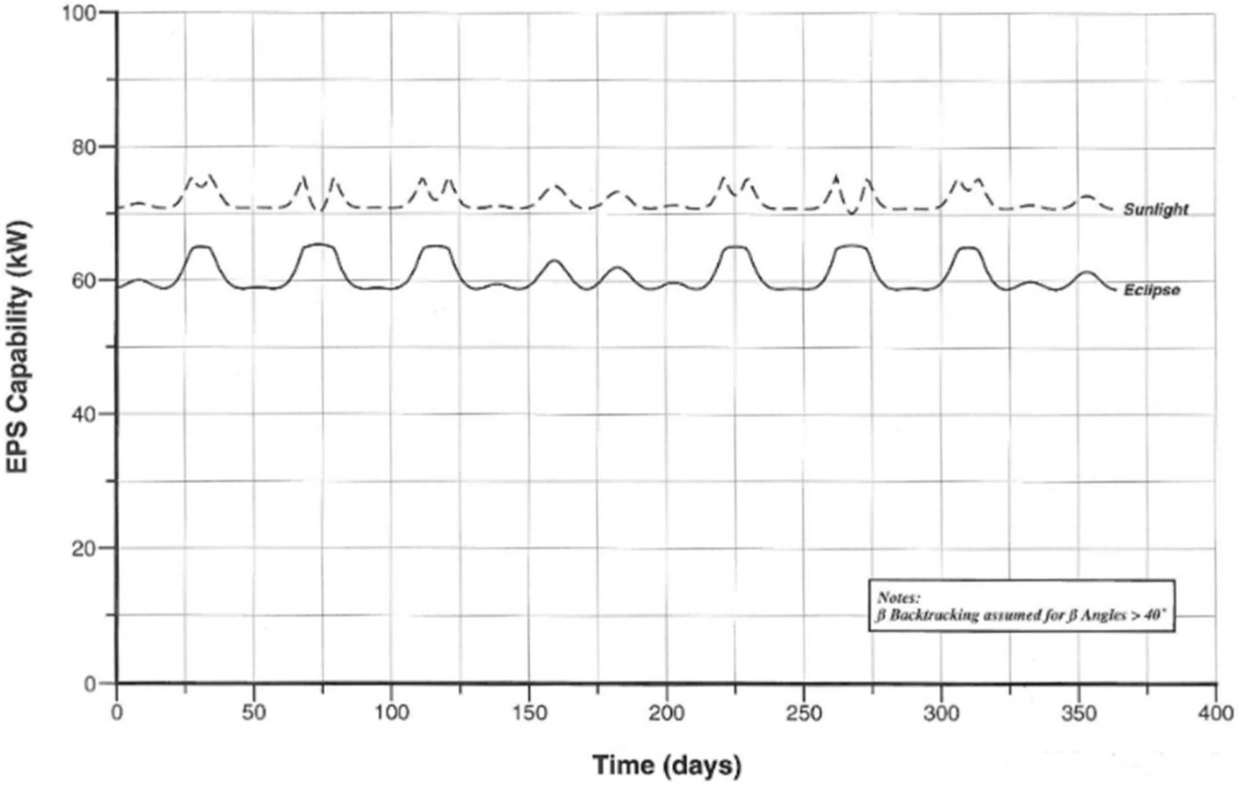

Figure 44.—SPACE results for option B during 1993 space station redesign.

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[e] The solar array spacing was reduced to save mass during the turbo team exercise; see the earlier discussion on mass reduction.

[f] Beta-backtracking refers to off-pointing adjacent SAWs to reduce shadowing on the rear wing. This results in partial power loss on the two adjacent SAWs. In the Sun-pointing case, the front wing provides high power but the rear wing is highly shadowed, and thus can generate much less power. In extreme Sun-pointing cases, the rear wing can produce zero power due to significant solar array-to-solar array shadowing, such that the voltage levels are too low to provide power to the bus.

SPACE was updated to simulate on-orbit operations for any spacecraft attitude, with a rapid calculation of solar cell temperatures for the entire orbit, including frontside and backside environmental heating on the solar arrays from the Earth albedo and infrared radiation. The SPACE alpha gimbal and beta gimbal pointing algorithms were updated to reflect hardware and software rates and acceleration limits. The algorithms utilized in the flight software for pointing the alpha and beta gimbal were also incorporated into SPACE.[67] These updates enabled rapid estimates with SPACE of any vehicle attitude or solar array pointing operation, especially studies involving solar array shadowing. The modeling of the solar array frontside and backside environmental heating was critical for a later update of SPACE to include backside solar array power generation.

Redesign Results

The report from the Advisory Committee to the President,[66] released on June 10, 1993, included the following recommendations:

1. “None of the fully implemented phases of the three station redesign options meets the cost targets provided by the Administration of $5 billion, $7 billion, and $9 billion for fiscal year 1994 through fiscal year 1998, nor does any option meet the annual funding target while simultaneously achieving the schedule milestones desired. All options, however, do represent major cost savings relative to Space Station Freedom.”
2. “Redundancies and overlapping responsibilities such as in the existing Space Station Freedom management structure must be eliminated. Management layers must be reduced, and program authority and responsibility must reside in the Program Manager.”
3. “A reduction of at least 30 percent in total civil service and contractor employees assigned to the Space Station Program.”
4. “A single prime contractor, preferably selected from among the current major prime contractors for Space Station Freedom, should be responsible for total system integration, including cost, schedule, and performance.”

Recommendations 2 to 4 were quickly implemented. But the decision on the final design of the space station was still open.

The next day (June 11, 1993), an anonymous memo titled “Space Station and Russian Cooperation” circulated at Headquarters.[68] The memo notes that NASA started working with the Russians in 1990 on planning a space shuttle mission to Mir in March of 1995. An astronaut would stay on Mir, returning to Earth 90 days later via another shuttle mission. The memo explains that the three U.S. space station redesign options are not expected to be available until 1998. In the interim, the SRT investigated, providing earlier research opportunities using the shuttle and Mir. Following the March 1995 mission, a series of shuttle-Mir missions would be flown approximately every 6 months. These missions would also provide additional resources to assist the Russians in maintaining Mir in order to extend its life and support research. The report concludes with the following: “We have not yet had detailed discussions with the Russians concerning a cooperative Space Station … The present redesign effort culminated with the Advisory Committee Report to the White House of June 10, 1993. A decision would then subsequently be made based upon the three options. A cooperative program with Russia is not only feasible but desirable from a number of standpoints. If a cooperative Russian space station is, however, to be considered, it should be evaluated in light of the present June redesign schedule and recommendations to be provided to the Congress.”

The White House issued a press release on June 17, 1993, indicating that the "specific design we will pursue will be a simplified version of SSF." The final design of the space station remained an open question.

Space Station Program Transition

Goldin appointed Bill Shepherd to assist with the transition team activities. Shepherd worked closely with O'Connor in completely revamping the space station program. Their responsibilities included staffing a new program office at Johnson, implementing a new contract with Boeing (chosen as the new prime contractor), and deciding on the final space station design.

In late July 1993, Goldin signed an agreement with the head of the Russian Space Agency regarding cooperating in crewed spaceflight activities.[69] The agreement called for continued cooperation in shuttle missions to Mir and for a team of Russians to return to Crystal City to work with the transition team. Huckins (head of Level I Engineering) was included on this team to work with the Russians on developing suggestions for Russian participation in the new space station program.

NASA developed three teams to work with the Russians in Crystal City to investigate utilizing[70]

- Existing Russian Mir for science and to test U.S. space station hardware
- Russian transportation systems (i.e., Russian Proton rockets to launch Progress resupply vessels to Station)
- Russian systems and hardware on the U.S. space station

John Dunning from Lewis was a member of all three teams. This was nothing new for Dunning; he almost lived in Reston in 1993, supporting continuing SSF meetings in Reston as well as numerous SRT meetings.

A NASA and Russian power splinter meeting was held on August 6, 1993.[71] The Russian requirements for enhancing the Mir EPS included two PV wings, each producing 7 kW at the base of the array, for a total of 14 kW. For the joint space station, the Russians requested the U.S. EPS to provide 120-Vdc power to the Russian modules. The Russians indicated they planned to build a truss on the space station to accommodate two SD power modules.

In mid-August 1993, a midterm status review of the Russian option was conducted.[72] The review included O'Connor and Shepherd. The planned elements for the space station were very similar to what was eventually flown (under the new name of the ISS):

- A crew of six
- Russian participation included
    - A core module
    - Service module
    - Docking module with an airlock
    - Progress vehicles for resupply and reboost
    - Soyuz spacecraft for crew rotation
- U.S. elements included
    - A laboratory module
    - Two nodes
    - A truss structure with three PV modules
    - An airlock

The other international partner elements remained unchanged.

Adding the Russians to the program solved a long-standing issue with the initial assembly flight for SSF. Due to mass issues, flight MB–1 under SSF was planned to be dormant. NASA was unable to develop a concept with a fully functioning spacecraft after the first assembly flight. In the ISS program, a Russian core module served as the first assembly flight, providing all of the necessary subsystems (i.e., power, attitude and thermal control, communications, a pressurized environment, etc.).

NASA announced the new space station host center (Johnson) and prime contractor (Boeing) in a press release on August 17, 1993.[73] The new program organization structure would have "about 1,000 civil servants" with 300 at the new Johnson program office and 700 spread among all involved NASA centers (including Johnson), a reduction from the 2,400 civil servants working SSF. The effect at Lewis was a reduction in the civil service work force of 170 positions, achieved through normal attrition and early-outs.[74]

This announcement resulted in closure of the Reston space station integration office and reassignment of NASA employees supporting space station at Marshall and Lewis. However, the SPACE team at Lewis continued to support space station power analyses, now working with Johnson. In addition, Lewis maintained a small group of array, battery, and PMAD experts who also supported the new Johnson program office.

Commenting on the station redesign in his column in the center paper, Larry Ross (Lewis center director) wrote, "I want to recognize the truly outstanding performance of our Work Package 4 Project Team. The way in which the redesign and transition activity has been handled has left the unfortunate impression that there has been something lacking in the performance of the Space Station Freedom team. … I can say without reservation that our Station Team ranks among the very best in the world. They have taken an extremely difficult project and have managed it extraordinarily well. Our part of the Freedom Program is well under control with respect to cost, schedule, and technical matters. This is even more exceptional considering that this undertaking posed several extra measures of challenge. Our Team had to overcome an almost annual upheaval in technical requirements, schedule revision, and funding cutbacks. It had to deal with an unprecedented number of in-depth external reviews (some of which were clearly adversarial in intent). It also had to cope with frequent changes in Headquarters managers. … There is much work to be done to get station through this transition and back on track toward launch. There will be some stress along the way as jobs change and new managerial and contractual relationships are formed. I'm proud that we have the caliber of people on our Team who have shown that they are true professionals and can deal with tough challenges. So, in case the history books of the future present a different perspective on this era of NASA, I want the record to show that the Lewis Work Package 4 Team did everything asked of them with remarkable success which will enable the space station to make good on its future promise."[75]

Vice President Gore and Russian Prime Minister Viktor Chernomyrdin announced a cooperative agreement between the United States and Russia on Space, Aeronautics, and Science, on September 3, 1993.[76] The agreement defined a "phased approach for cooperation on human space flight." Goldin also issued a statement:[77] "The cooperative ventures now under study represent an advantageous blend of Russian and American capabilities. The program baseline for the space station will be based on the designs already developed by the United States and our partners in Europe, Japan and Canada. Russian participation in the space station program could be readily accommodated with the modular redesigned space station that we have been working on." Goldin's statement also notes that Russia and the United States will jointly develop an SD power system; SD is reborn.

On October 18, 1993, O'Connor was in Paris for a meeting with the space station International Partners.[78] They issued a joint statement on the potential Russian involvement in the space station. Recognizing the Russian "impressive record of accomplishments in space," the station partner governments "wish to extend to the Government of the Russian Federation their invitation to collectively explore a possible Russian partnership in the International Space Station Program."

For more information about the space station redesign activities, see a report by Marcia Smith from the Congressional Research Service, "NASA's Space Station Program: Evolution and Current Status."[79]

In the midst of all the space station redesign activities, the SPACE team prepared two conference papers:

- An overview of the SPACE code[80]
- SPACE results for two typical cases: an electric load driven case and a maximum EPS capability case[81]

Updates to SPACE (1994 to 1995)

The SPACE code is not static; many new features and bug fixes are always being incorporated into the code. For example, in April 1994, staff in the Lewis Engineering Directorate providing support to the SPACE team modified over 100 SPACE subroutines. These changes were required to get the ECAPS version fully operational, anticipating that Lewis would soon be called on by Johnson to perform assessments of proposed EPS power timelines. Design Analysis Cycle #1, in March 1995, was the first time Lewis performed assessments of time-phased load demands for Johnson. This assessment covered the first six shuttle assembly flights as well as the final flight in the assembly sequence.

The SPACE ISS shadowing model was documented in a conference paper.[82] Two key model inputs are the space station geometry and the shadow analysis surface mesh size. The model uses a collection of four-vertex polygons to represent all of the key surfaces of the space station. The mesh size is the resolution limit for which the surface must be analyzed for shadowing. The mesh on the ISS solar arrays is at the cell submodule level, with eight solar cells in each submodule. This resolution is adequate based on ISS solar array cell module interconnections and characteristics. The shadowing model arranges the spacecraft components as they should appear at each time step in the orbit. This involves activating or deactivating or relocating components, placing approaching or departing vehicles at the correct distances and orientations from the ISS, and articulating gimbal joints for the PV arrays and thermal control system radiators. Lastly, the vehicle is oriented based on the attitude for that time step. These were the first SPACE published results for the new ISS design with Russian participation.

Figure 45.—Russia's Mir Space Station with Mir Cooperative Solar Array in foreground. Photo from Space Shuttle Atlantis on September 24, 1996 (STS79-E-5327).

Mir Cooperative Solar Array (MCSA) Delivered to Mir (1996)

NASA flew 11 space shuttle missions to the Russian Mir space station as part of Phase 1 of the ISS program. One of the early flights delivered the MCSA to Mir.[83,84] The MCSA is shown deployed on Mir in Figure 45. The MCSA was jointly developed by the United States and Russia to produce 6 kW of power for Mir.[g] The United States provided ISS solar cells mounted on a Kapton™ blanket, and the Russians provided the array frame. The assembly of MCSA panels is shown in Figure 46, and a closeup of the MCSA mounted to Mir is shown in Figure 47. The power from the MCSA was used to extend Mir's useful life and support U.S. experiments conducted under Phase 1 of the ISS. The on-orbit data collected on the MCSA performance were subsequently used in SPACE validation episodes.

Results from an ECAPS load-driven case were published.[85] The scenarios in the paper include a DDCU activation, geometry changes (relocating Pressurized Mating Adapter-3) and transferring the Multi-Purpose Logistics Module (MPLM), and array tracking changes during shuttle docking and separation and during a reboost. SD power for the ISS was revived one last time in the summer of 1996. NASA and Russia had been jointly developing an SD power module slated to fly to Mir as a demonstration in Phase 1 of the ISS program, referred to as the SD Flight Demonstration (SDFD).[86,87] The Russians were providing the concentrator and radiator, while the United States provided the heat receiver and the power conversion unit. This effort with the Russians was terminated in early 1996 when NASA and Russia elected to use the last shuttle flight to Mir to launch logistics supplies instead of the SD power module. Lewis proposed developing an all-U.S. SD system using flight hardware from the joint program with the Russians and launching the SD system to the ISS. A system requirements review was conducted for this new project in July 1996.[88] SPACE was adapted to include a simplified model of the SD system, and SPACE predictions of power generated by the SD system on the ISS were presented at the review (see Figure 48). This particular case operated continuously through the year. This project was eventually terminated, due to funding issues.

Figure 46.—Hand-sewing U.S. blankets into Russian frame for Mir Cooperative Solar Array. Photo taken in Russia.

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[g] As mentioned earlier, the original Russian requirement for a Mir power enhancement was two 7-kW arrays for a total of 14 kW. However, the U.S. and Russian hardware that was available only supported building a single array that produced 6 kW. Both parties agreed to this lower power requirement for the MCSA.

Figure 47.—Base of Mir Cooperative Solar Array mounted to Mir Kvant-1 module.

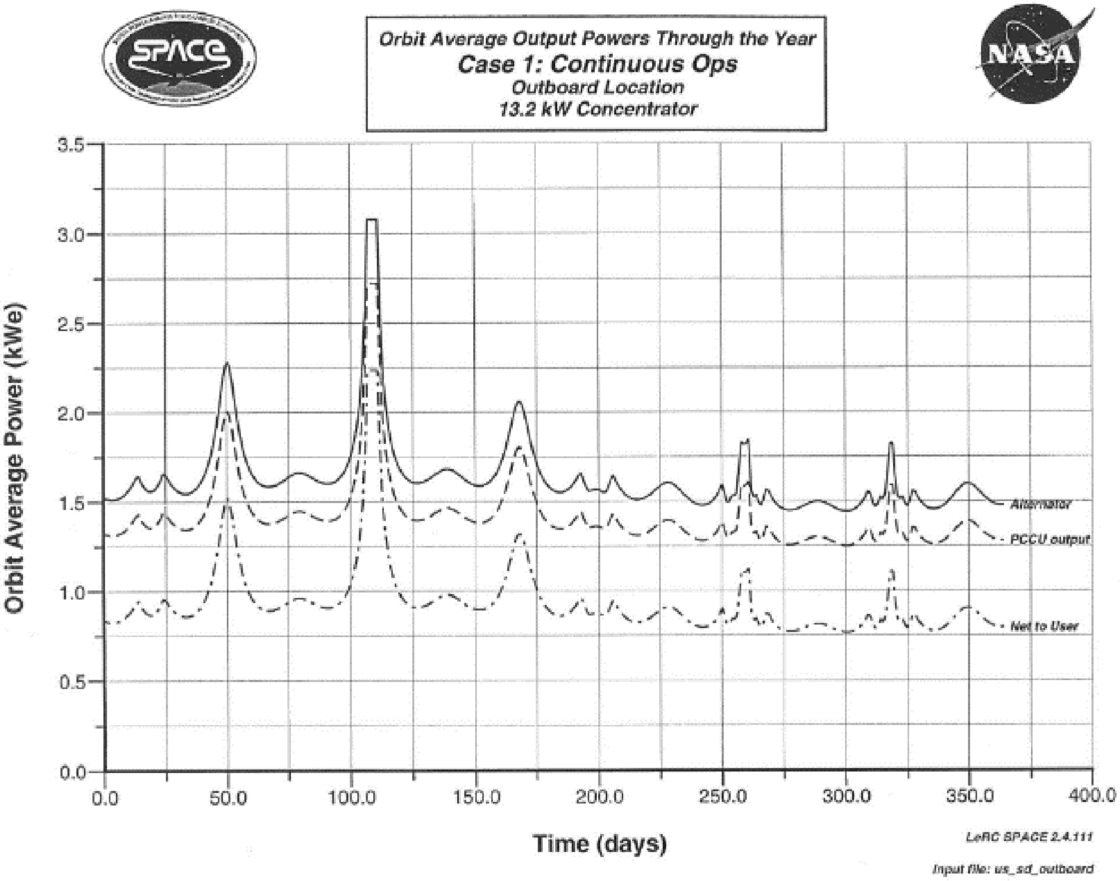


Figure 48.—Power from solar dynamic demonstration unit on International Space Station.

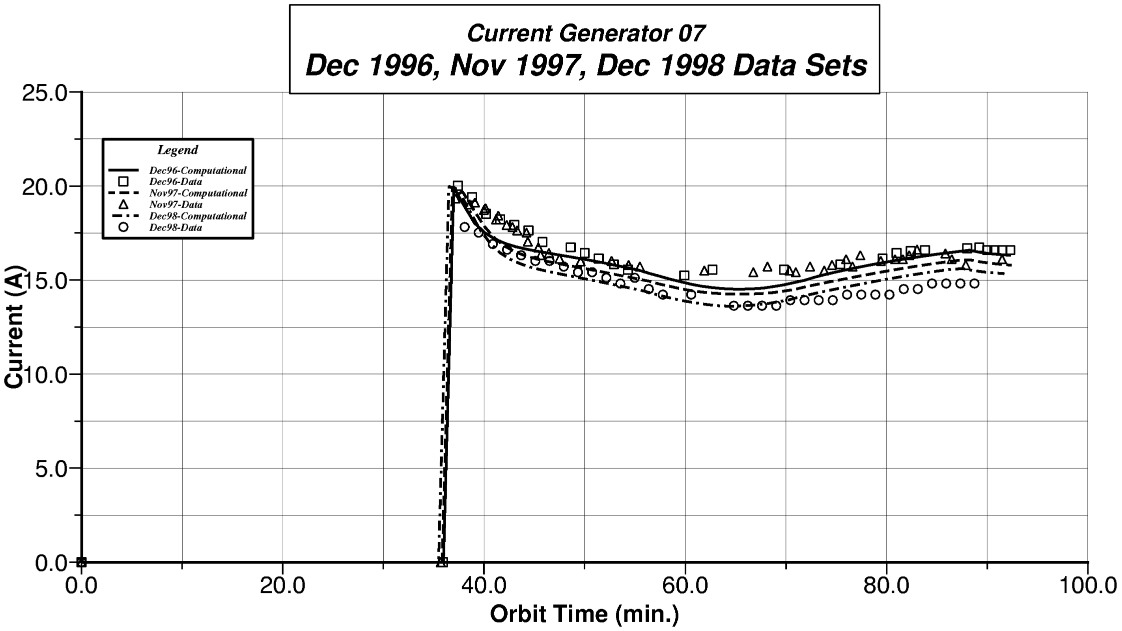


Figure 49.—Mir Cooperative Solar Array generator 07 current output.

Mir Cooperative Solar Array (MCSA) Flight Performance (1997)

Two specially designed test sequences were executed in June and December of 1996 to measure MCSA performance on Mir. These test results were compared with SPACE predictions and documented in Reference 89. Additional on-orbit tests were conducted in December 1998. Specifically, a current sensor measured the performance from a section of the MCSA referred to as a generator. The results of comparing SPACE predictions with MCSA on-orbit tests for all of the tests for generator 07 are shown in Figure 49. The data are well behaved and consistent with the predicted 8 percent current degradation from December 1996 to December 1998.[90,91]

Zarya Launch (1998)

Zarya (Functional Cargo Block (FGB)), the ISS first element, was launched by Russia in late November 1998. Shortly thereafter, the Unity Node was added during STS–88 (Figure 50). Unity received power from the Russian-American Converter Units installed in the FGB. Lewis and Khrunichev State Research and Production Space Center (KhSC) collaborated in performing analytical predictions of the on-orbit electrical performance of Zarya’s solar arrays.[92] Using SPACE, Lewis assessed the shadow patterns on Zarya’s solar arrays to determine the average solar incident energy on the arrays. SPACE was modified to model the FGB solar array pointing control system. The FGB solar arrays do not rotate continuously. The FGB uses eight Sun sensors to detect the location of the Sun and commands the solar array to rotate to the middle of 1 of 16 zones and stop. An example of the Lewis results for the Flight 2A configuration (Zarya with the Unity Node) is shown in Figure 51. Five vehicle attitudes are shown in Figure 51: Xpop (x-axis perpendicular to the orbit plane), two +Xvv (x-axis in the velocity vector), one –Xnadir (minus x-axis pointing nadir), and Xnadir spin (+x-axis pointing nadir with the vehicle spinning). See Reference 92 for a further discussion of the early ISS flight attitudes. KhSC used the incident energy results to estimate Zarya’s electrical power generation capability.

As a result of this success, SPACE was also used to perform similar services for ESA, for their Autonomous Transfer Vehicle (ATV) development.

Figure 50.—James Newman near completion of his third spacewalk on STS–88. U.S.-built Unity Node (foreground) is attached to Zarya (beyond Newman) (S88-E-5145, December 12, 1998).

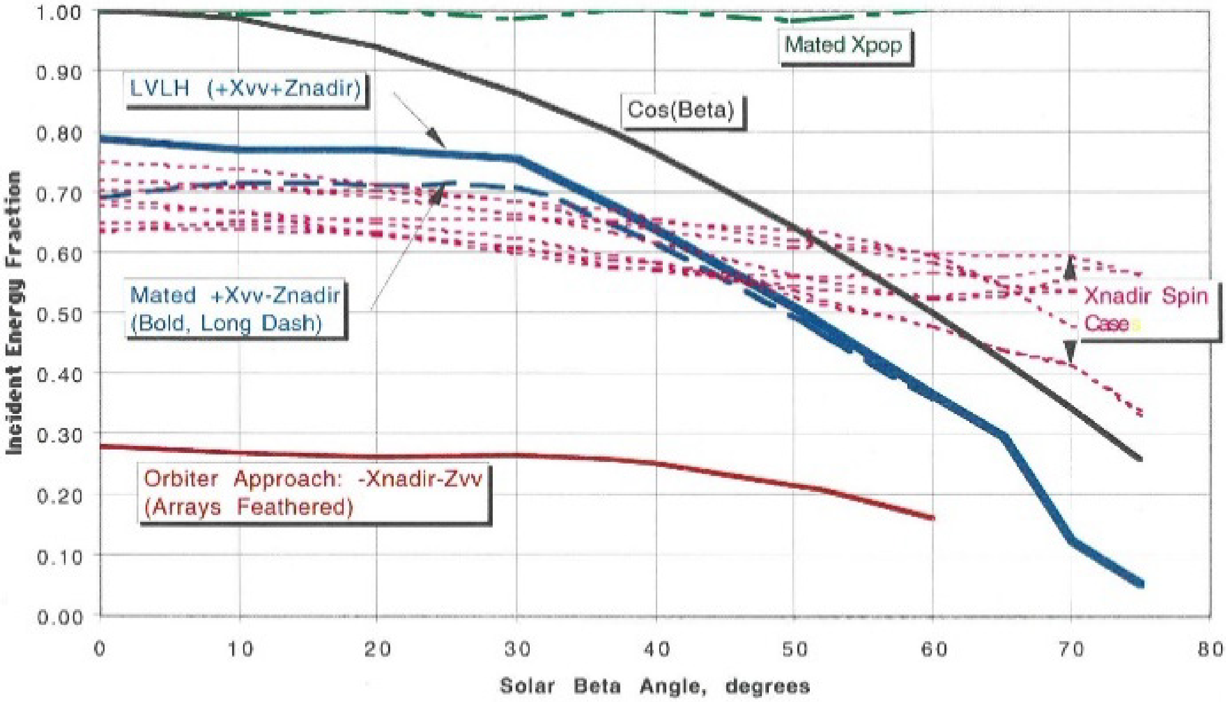


Figure 51.—Zarya average incident energy fraction for Flight 2A.

Adding Solar Array Backside Power (1999)

The Interim Control Module (ICM) from the U.S. Naval Research Laboratory was under consideration as a propulsion module for the ISS. SPACE analyses of the shadowing of ICM solar panels were assessed and the results were published.[93]

Up to this point in the space station program, power generation analyses did not include power generation from the backside of the solar cells due to a lack of data on backside performance. ISS solar cells were tested at Lewis for backside power generation, and SPACE solar array algorithms were modified to account for bifacial performance.[94] The cell I–V properties were normalized by those obtained with normal incidence frontside illumination. To demonstrate the impact of this change in solar array modeling, SPACE was used to assess the planned ISS assembly flight where P6 would be relocated from the top of the Z1 truss to its final location outboard of the P5 truss segment. During this maneuver, the Space Station Remote Manipulator System (SSRMS) would be used to reach across the inboard PV module, which required locking the beta gimbal of one of the inboard solar arrays to avoid interference. The selected lock angle resulted in the backside of the solar array viewing the Sun for the first half of the insolation period. Results from SPACE modeling of this configuration are shown in Figure 52, without accounting for backside power. Figure 53 shows similar data but includes backside power. This assessment was performed with the most recent projected channelized load demand from Johnson. With only frontside power, the batteries were almost fully discharged by the beginning of the sixth orbit. However, after including backside power, the maximum battery DOD was reduced to 28 percent.

The presence of backside power was tested on orbit in early January 2001. The BGAs were commanded such that the backside of the solar array was directly pointed toward the Sun at solar noon. The test data showed that the backside power was 40 percent of the frontside power.[95]

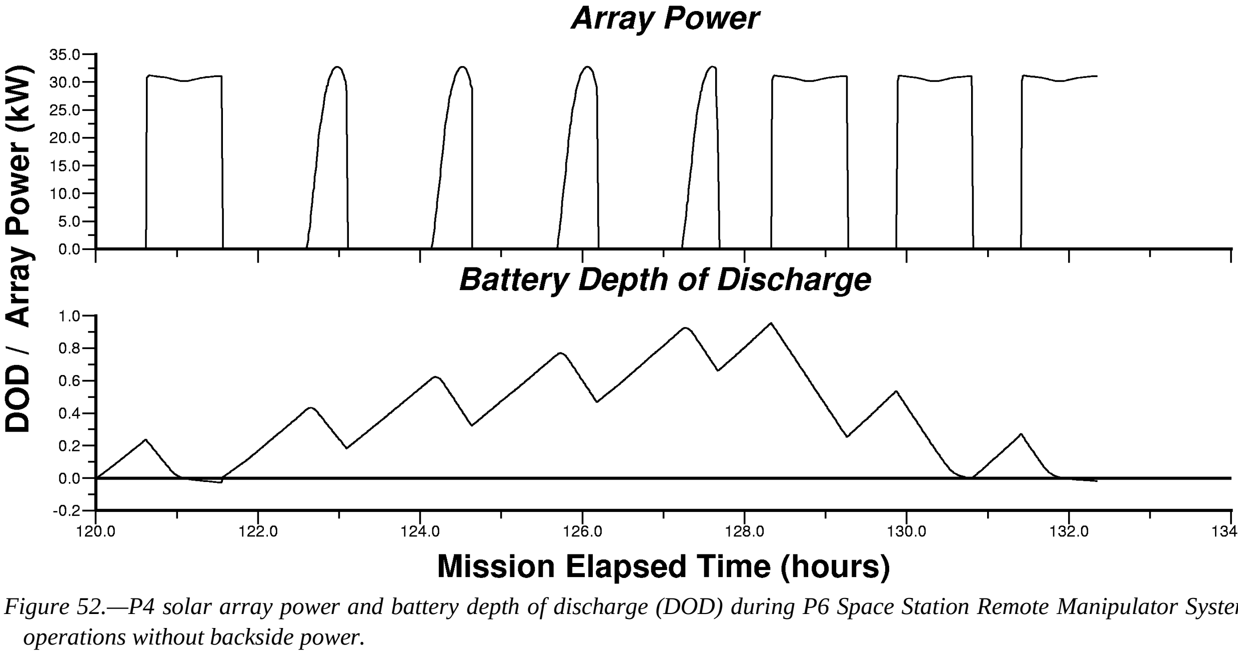


Figure 52.—P4 solar array power and battery depth of discharge (DOD) during P6 Space Station Remote Manipulator System operations without backside power.

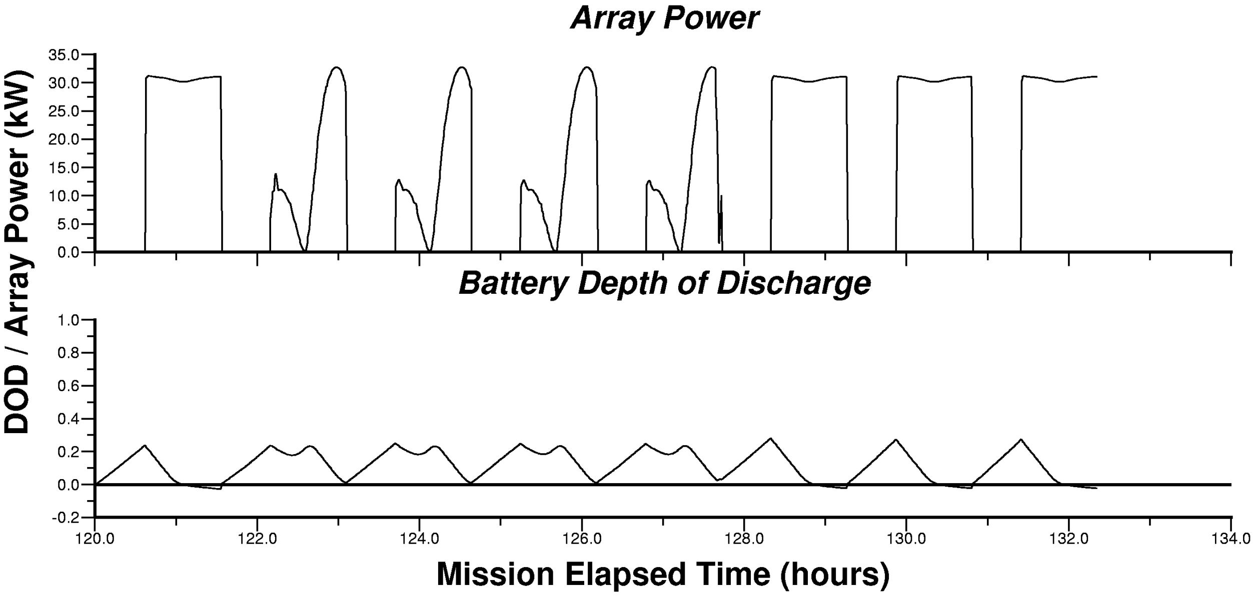


Figure 53.—Photovoltaic solar array power and battery depth of discharge (DOD) during P6 Space Station Remote Manipulator System operations with backside power.

Launch and Activation of International Space Station (ISS) Electrical Power System (EPS) (2000)

Space Shuttle Endeavour delivered ISS element P6 to the ISS in December 2000. This key milestone was celebrated at the Glenn Visitor Center during a 2-day event open to the public, "Powering the Future." The event included live coverage of the Endeavour mission via NASA TV, hands-on activities, and displays about the Glenn contributions to the space station. In addition, a reception was held for employees involved in the design and development of the ISS EPS (Figure 54).[48]

Figure 54.—Former space station Director Ron Thomas (center) accepts kudos for his leadership from Dr. John Dunning and Sandra Reehorst.

During the deployment of the first SAW (channel 2B), unexpected adhesion between the solar array panels caused some adjacent panels to stick together. When the panels eventually broke free, the resulting dynamic motions in the panels were dramatic. The 2B solar array was fully deployed, but two of the tensioning cables jumped from their spiral pulleys. An EVA was conducted to repair the 2B blanket tensioning mechanism (Figure 55). The channel 4B solar array deployment procedures were modified, and the 4B solar array was deployed with no issues.[96] The ISS configuration with P6 is shown in Figure 56.

After the first week of continuously rotating the U.S. solar arrays, higher than expected electrical currents on the drive motor in one BGA were observed. The magnitude of the motor currents increased over time on both 2B and 4B BGAs, creating concerns about the ability of the gimbals to continue pointing the solar arrays toward the Sun. SPACE analysis was used to assess various BGA pointing algorithms to minimize gimbal rotations while maintaining sufficient solar array power. This activity was referred to as the BGA Anomaly Resolution Team, or BGA ART.

Reference 97 documents the results of SPACE analyses for the BGA ART. A summary of the U.S. segment power balance for a year starting with December 2001 is shown in Figure 57 (from Ref. 97). Xpop is the preferred operational flight attitude, producing the most robust power generation across the solar beta regime while reducing cumulative BGA travel. The Dual Angle Mode provides adequate power generation for solar beta less than 25° and reduces cumulative BGA travel by at least 50 percent. In the Dual Angle Mode, the BGA was parked at two different angles at different times of the orbit. This minimized gimbal travel while producing sufficient power. The success of this operating mode saved the space station program from a costly and risky on-orbit replacement of the gimbal and enabled continued assembly of the space station as planned.

Figure 55.—Astronaut Carlos Noriega during an Extravehicular Activity to repair 2B tension system. Array blanket box is shown at top of image with tensioning spools are on left (sts097-376-009).

Figure 56.—International Space Station configuration in December 2000. From bottom to top: Soyuz, Zvezda Service Module, Zarya (Functional Cargo Block), Node 1 (Unity), P6 (sts097-704-074).

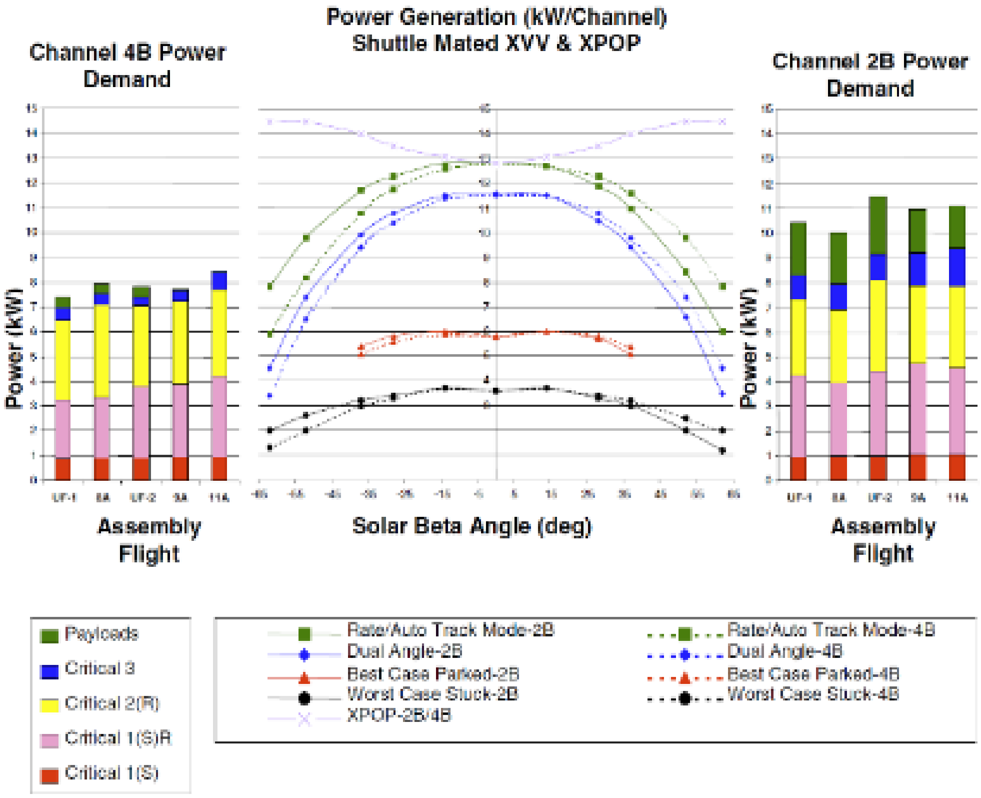


Figure 57.—U.S. segment power balance in 2001.

SPACE Validation Episode #1 (2001)

SPACE results were compared with on-orbit data for a 24-hour period on day 136 of 2001. Substantial effort was required to perform this assessment by Glenn staff including

- Obtaining access to the on-orbit data at Johnson
- Learning about the identifiers for each piece of data and the techniques for pulling data and transferring the information to Glenn
- Modifying SPACE to generate voltage and current values at the locations of on-orbit instrumentation
- Developing scripts to process the on-orbit data and overlay the results onto SPACE predictions

To better match on-orbit results, the following adjustments were made to SPACE:

- As previously noted, the solar array model had been modified to include backside performance (Figure 58). In addition, the frontside off-pointing factors were modified, albedo power production was added (Figure 59), and cell temperature coefficients were revised.
- In the battery model, the Loral 35 and 60 percent DOD charge and discharge voltage curves were replaced with data from Crane testing, the battery temperature dependency was removed, and the battery heater duty cycles were revised.
- The DDCU and BCDU efficiencies were updated (Figure 60), as well as the BCDU and SSU voltage regulation bands.
- The alpha and beta gimbal pointing errors were reduced.

Results showing SPACE and on-orbit battery SOC, voltage, and current as well as SSU current and number of active strings are shown in Figure 61 to Figure 65.

The battery SOC is computed by the on-orbit software from battery temperature and pressure measurements. The resulting SOC levels are sometimes above 1.0 near the end of insolation periods, indicating that the batteries are slightly overcharged (an SOC of 1.0 indicates 100 percent charged). Due to low power demands, the batteries operated at 80 percent SOC (see Figure 61). The ISS battery team published a paper concluding that "the batteries are operating nominally and have exceeded all ISS requirements."[98]

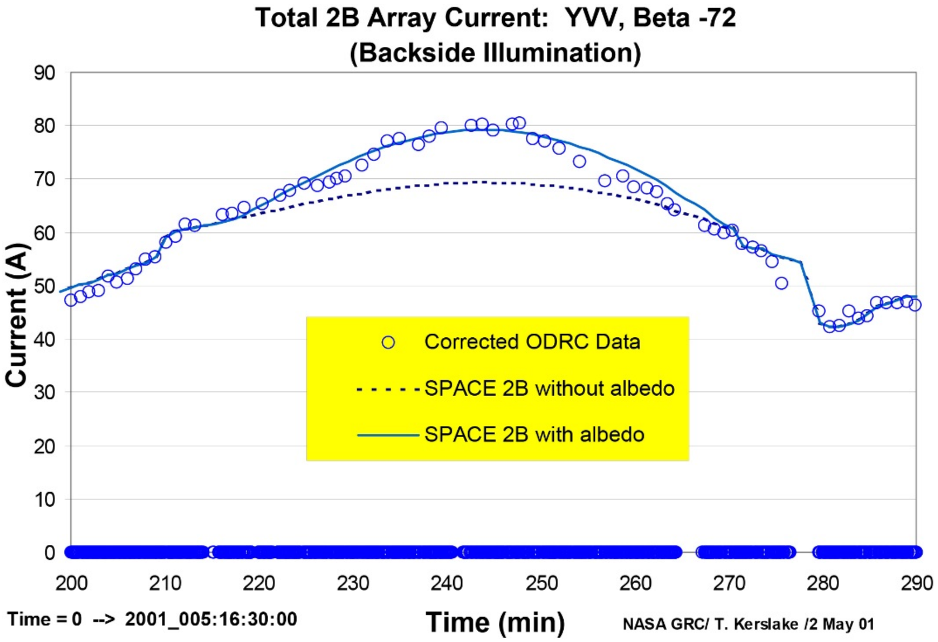


Figure 58.—Back illumination with moderate frontside and backside albedo contributions.

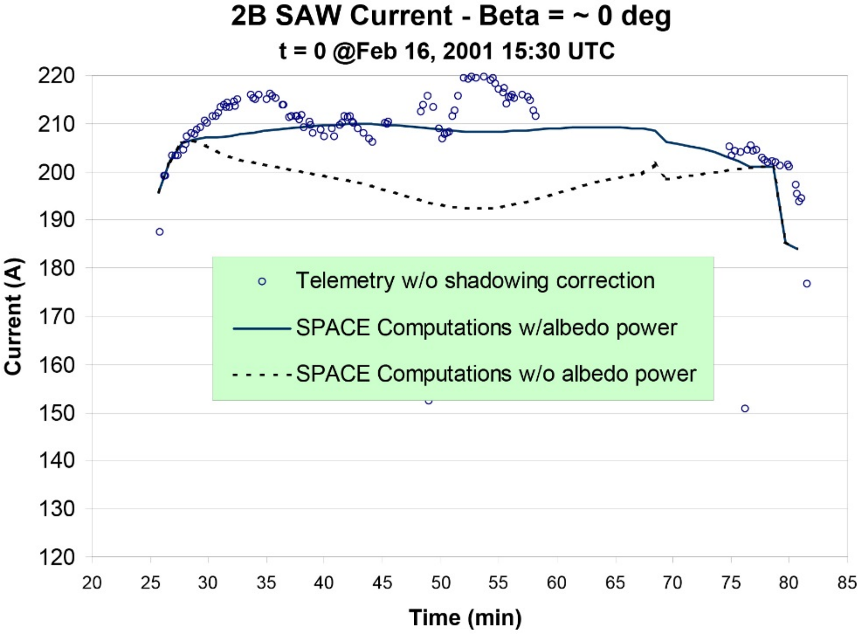
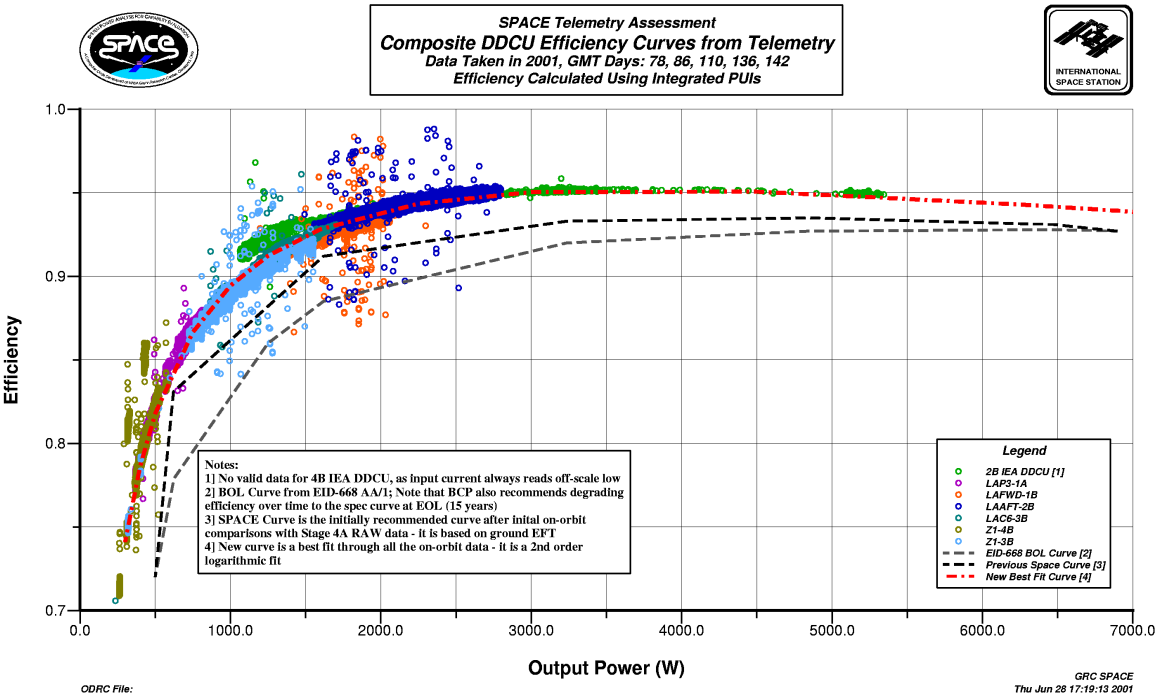


Figure 59.—Front illumination with minor frontside and large backside albedo contributions.



Notes:
1] No valid data for 4B IEA DDCU, as input current always reads off-scale low
2] BOL Curve from EID-668 AA/1; Note that BCP also recommends degrading efficiency over time to the spec curve at EOL (15 years)
3] SPACE Curve is the initially recommended curve after inital on-orbit comparisons with Stage 4A RAW data - it is based on ground EFT
4] New curve is a best fit through all the on-orbit data - it is a 2nd order logarithmic fit

Figure 60.—DC-to-DC converter unit (DDCU) efficiency curve update during validation episode #1.

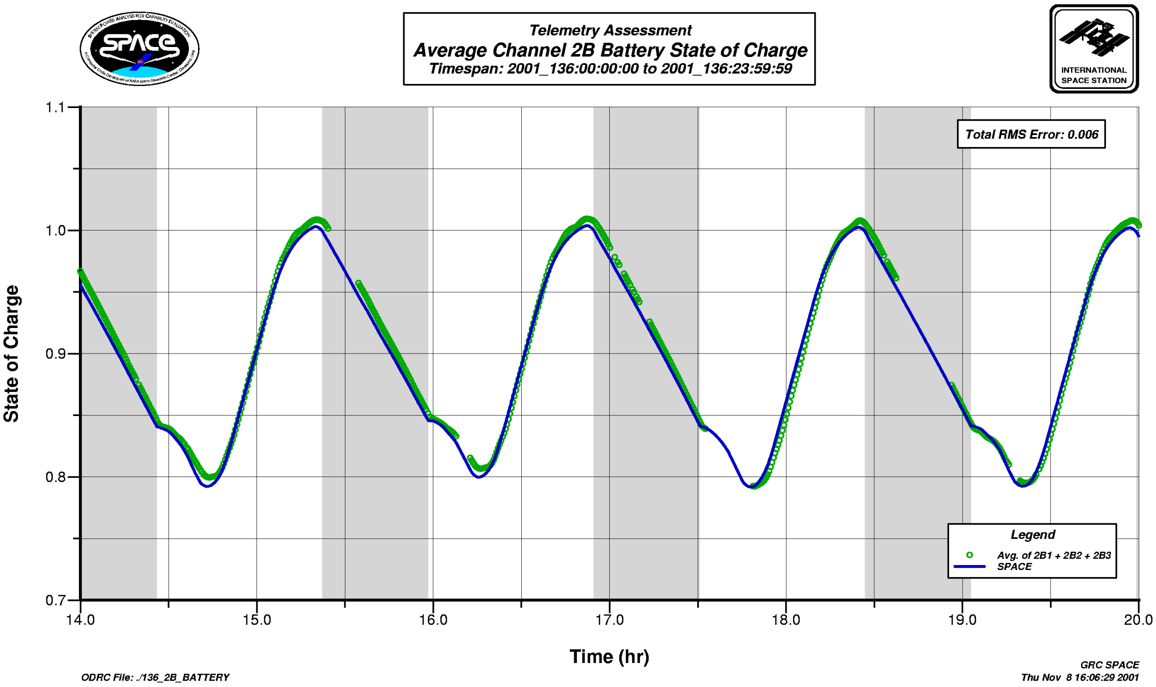


Figure 61.—Day 136 channel 2B battery state of charge comparison.

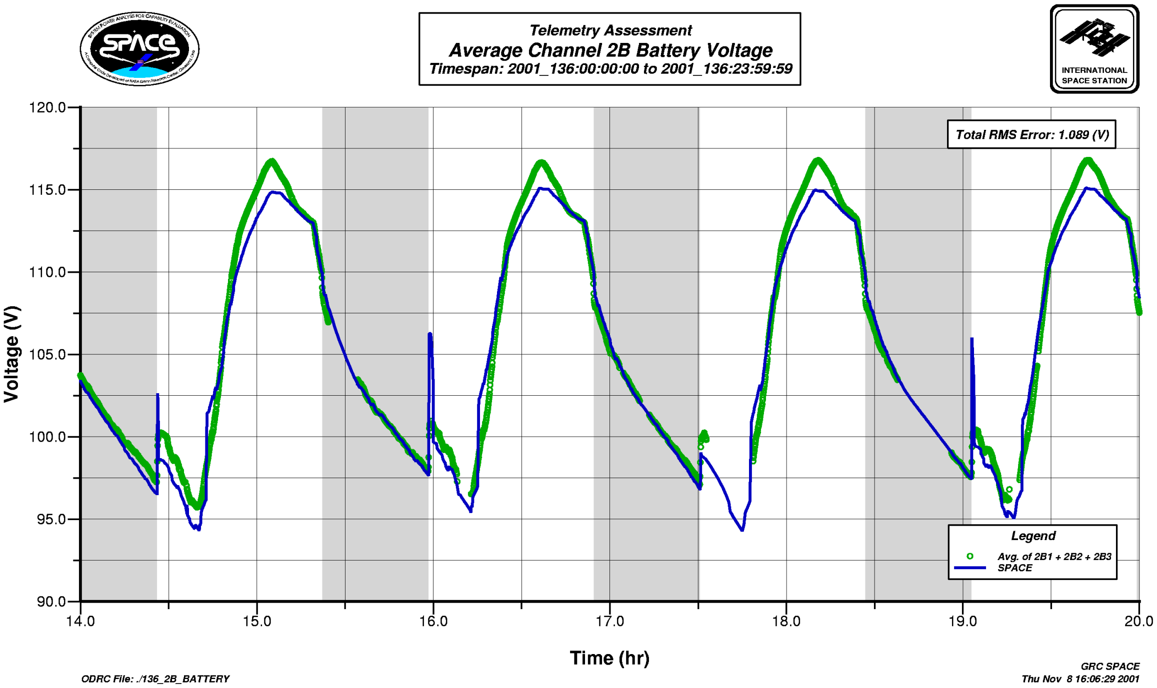


Figure 62.—Day 136 channel 2B battery voltage comparison.

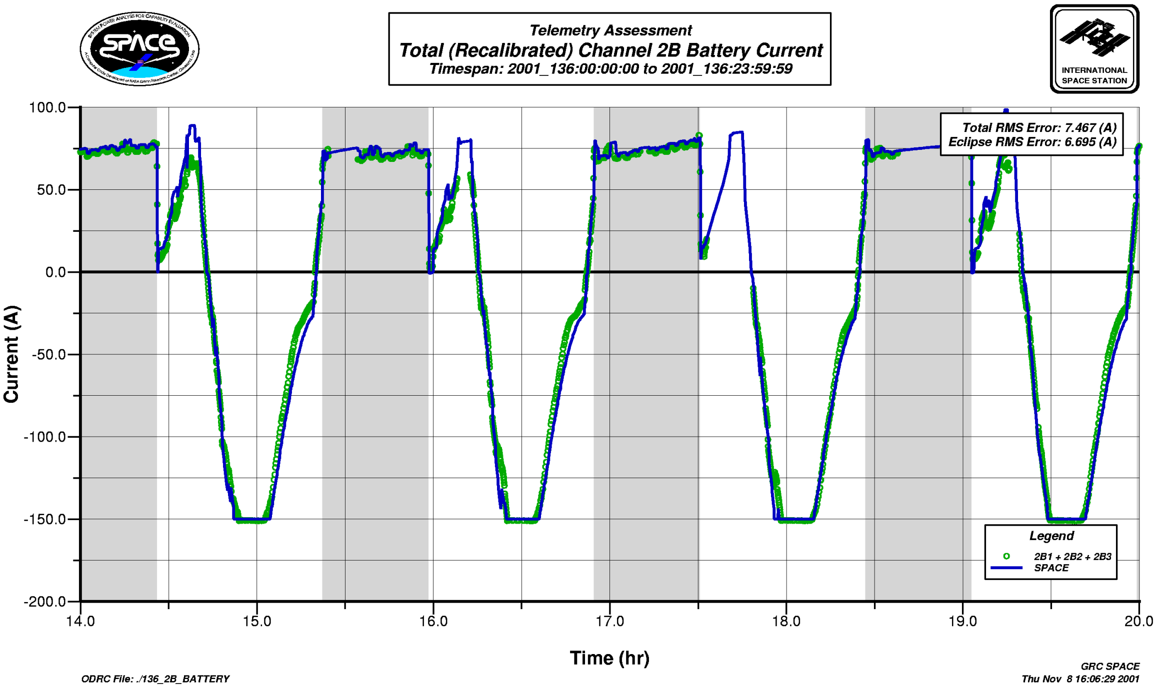


Figure 63.—Day 136 channel 2B battery current comparison.

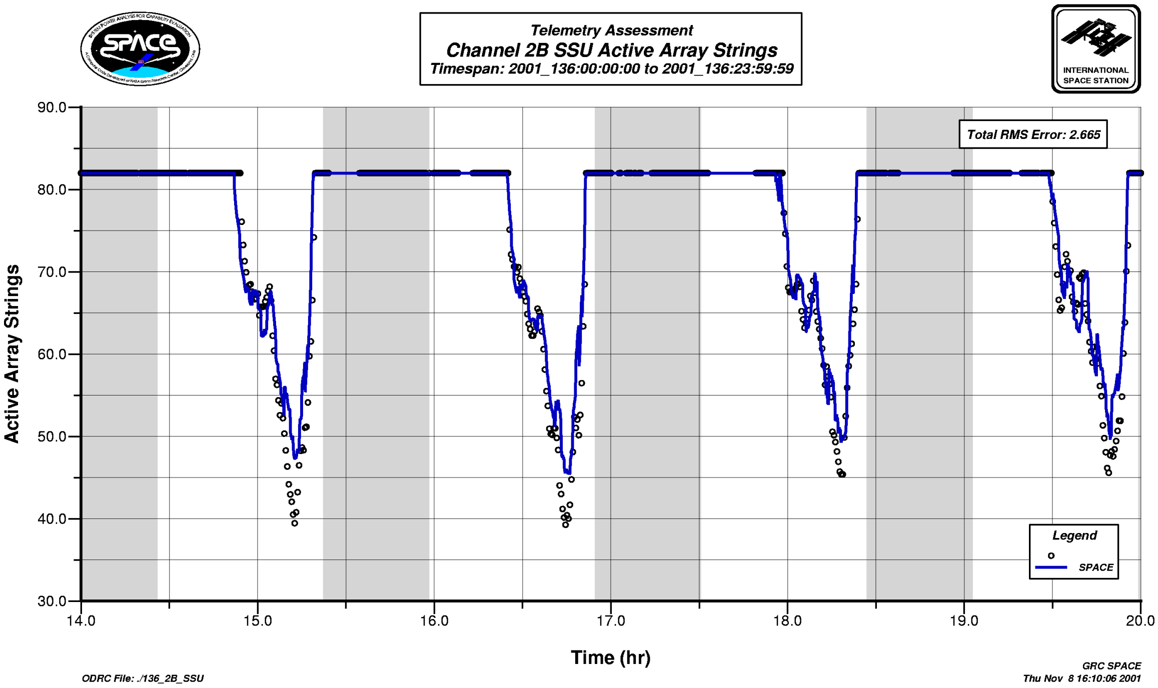


Figure 64.—Day 136 channel 2B sequential shunt unit (SSU) number of active strings comparison.

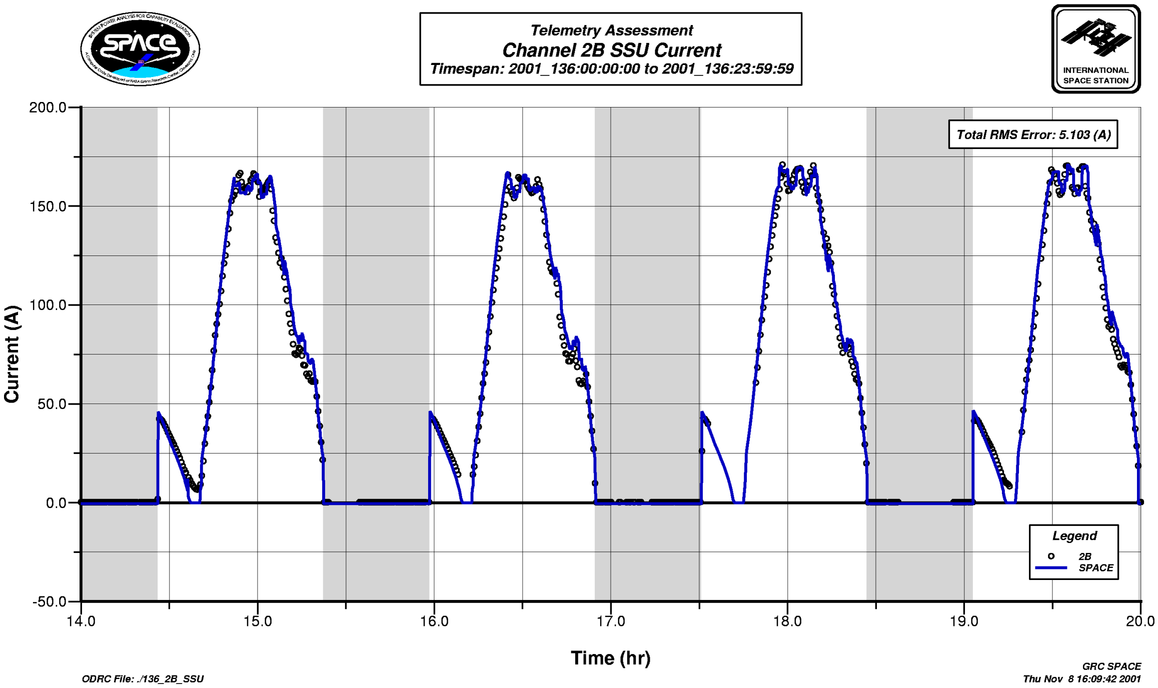


Figure 65.—Day 136 channel 2B sequential shunt unit (SSU) current comparison.

SPACE Validation Episode #2 (2002)

In this validation episode, the solar array model was updated to include failed solar array strings. The battery model was also changed to a single discharge voltage curve (using on-orbit data), with Loral contingency data used to model continued discharge beyond a normal eclipse period. No changes were implemented in the charge voltage curves.

The one-orbit case from episode #1 was rerun. In addition, on-orbit data from flight 8A (April 2002) was assessed. Flight 8A included two water dumps (each requiring a vehicle 90° yaw maneuver with the 4B beta gimbal locked), three shuttle reboost events (off-nominal vehicle attitude), and four EVAs. During the first EVA, the 4B solar array was pointed toward the wake to minimize shocking hazards. For the three subsequent EVAs, (the solar array was shunted for the first 10 minutes of each isolation period to minimize shocking hazards). The results of validation episode #2 were documented in Reference 99.

Two companion papers regarding SPACE model validation were also prepared. The first compares the bifacial performance predictions of the PV solar array with on-orbit data,[100] while the second compares shadow patterns from ISS photos with shadow pattern predictions from SPACE.[101] An example from the second paper is shown in Figure 66, which provides both a qualitative and a quantitative comparison of the SPACE-predicted versus actual shadow patterns. The photos are from on-orbit video frames, providing a qualitative comparison with SPACE-computed shadowing in the graphic to the right of the photo. The top portion of Figure 66 shows a quantitative comparison of the SPACE- and on-orbit measured solar array operating current. The SPACE values are shown with two albedo values, recognizing that reflections of sunlight from Earth on the solar array front or back changes the performance (higher albedo values result in higher current levels). Several years after Reference 101 was published, the developers of the NASA Handbook for Models and Simulations[102] included Figure 66 in their publication as a positive example of model validation with a “real-world system.”

An additional paper reported on analyses performed using the SPACE shadowing code to assess shadowing and incident energy for various ISS floating potential probe preliminary design options.[103]

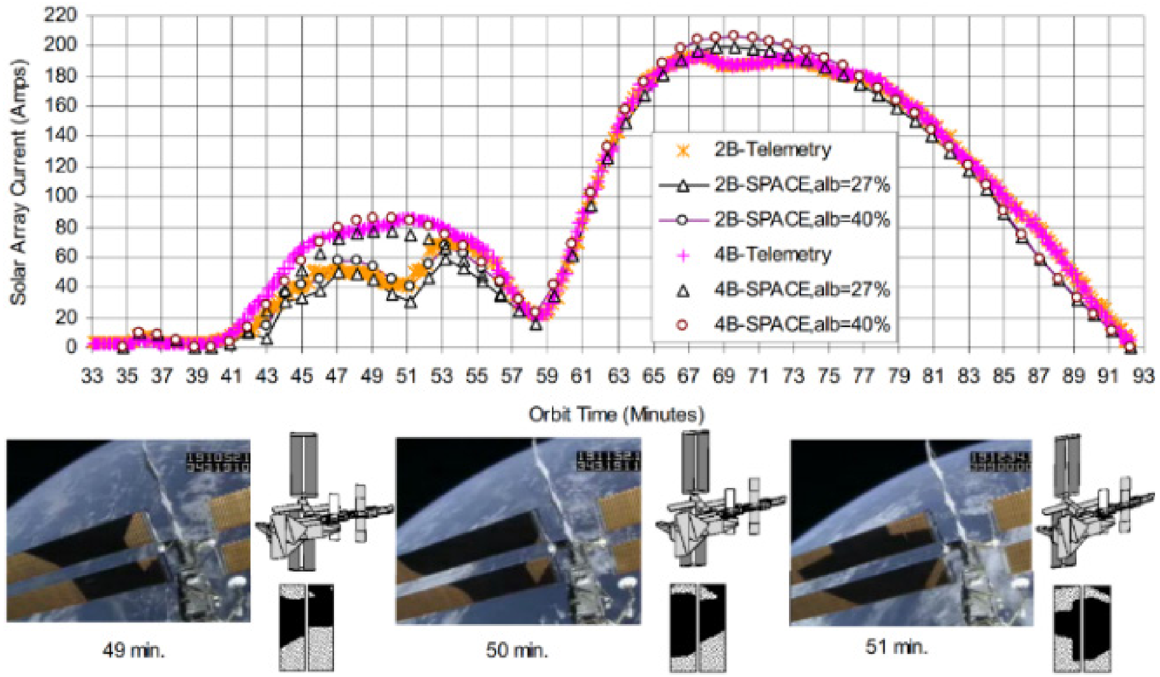


Figure 66.—Shadowing during International Space Station flight 4A free drift.

Reviews of on-orbit data by the battery team showed that five batteries were operating very well. However, in the sixth battery, the difference in cell pressures between the two ORUs exceeded the recommended range. A battery reinitialization procedure was developed and successfully implemented to reduce the pressure differential.

The SPACE team published a paper on updates to the solar array performance model for generalized bifacial illumination conditions.[104]

Figure 67.—Aurora Borealis over Regina and Saskatoon, Sasketchewan, in 2017 (ISS053-E-23915).

Figure 68.—Earth observation taken by the Expedition 52 crew (iss052e081327).

Software-of-the-Year (SOY) Award (2003)

SPACE Runner-Up for NASA SOY Award

The annual NASA SOY Award is selected by the Inventions and Contributions Board for software "that has significantly enhanced the Agency's performance of its mission and helped American industry maintain its world-class technology status." The SPACE code was selected as the best software from Glenn in 2003 and was runner-up for the Agency SOY Award.

Several customer endorsements from government, industry, and academia supported the SOY Award application. Sandy Reehorst (Chief, Power and Propulsion Office) wrote the following in her endorsement:

> *"SPACE has been a critical tool to the success of the ISS program nearly from SPACE's inception. The SPACE tool was originally envisioned as a cross check for the contractor performed analysis. As a direct result of the extraordinary effort of its creators, however, it quickly became known as the leading state of the art tool. Furthermore, SPACE has successfully been used to support the program in the Work Package 4 PDR and CDR (under the Space Station Freedom Program), the redesign of the program which resulted in ISS, the certification of initial launch of the power system and through all system/program reviews. It continues to be used to support numerous on-orbit anomaly events. It is a highly capable, adaptable tool which has proven its worth on many occasions."*

Key SPACE component models were supplied to the developers of the Battery/Solar Array Method (BSAM) code for use by analysts in the backrooms supporting ISS Mission Control at Johnson. In his SPACE SOY Award endorsement letter, their lead developer stated, "…you guys have been nothing short of consistently outstanding in all your support to us …there's no way we'd be anywhere near the level of fidelity and accuracy we're at in our BSAM predictions…without your continued support."

ESA provided an endorsement regarding rapid SPACE assessments of the shadowing and power production of the ATV solar arrays, which saved the program significant time and cost. ESA stated that "with the help of the SPACE programme and our ATV geometrical information they estimated the solar flux (that we converted in power output) on different ATV solar array configurations more especially for a fixed and Sun tracking array configuration. The support we got from SPACE saved about 6 months in our development programme at a critical moment where we had to strive for meeting the 300W requirements."

RSC-Energia provided an endorsement from SPACE analyses for the MCSA project. The RSC-Energia ISS Program Director stated, "The [MCSA] project was a significant milestone, wider and more complicated than "Soyuz-Apollo" mission. …The SPACE software was used to support our international team …We were impressed on how predictions made by SPACE software matched the real measurements."

Bill Gerstenmaier, then manager of the ISS program, included these words in his endorsement letter:

> *"I am aware of the tremendous effort that the SPACE Team at Glenn has put forth in support of this Program. SPACE analyses in support of the Verification Analysis Cycles have identified important power system issues and provided operational solutions to solve them. As we move toward installing the next sets of solar arrays in the coming flights, we face some of the most complex operations in the life of the Program. … SPACE has been used numerous times to address issues on these flights. In fact, many of the flight procedures that we will be using have been developed based on the SPACE Team's recommendations. … In conclusion, the NASA Glenn SPACE Team has continuously provided the International Space Station Program with the unprecedented analyses and solutions necessary to make this Program a success."*

Columbia Accident, SPACE Validation Episode #3

With the shuttle fleet grounded due to the Columbia accident, the SPACE team conducted validation episode #3, which focused on updates to the battery model. The battery discharge voltage curve was modified to use on-orbit data from a Soyuz docking, where the batteries were discharged to a high DOD.

The on-orbit data for validation episode #3 were from 3 days in 2003: day 99 (which included an SSU Shunt Test to measure the solar array short circuit current), day 162 (docking of Progress 11P), and day 193 (nominal stage operations). Episode #3 also includes comparing the revised SPACE code with on-orbit data used in episodes #1 and #2.

P6 Shunt Current Degradation

The short circuit current (I_{sc}) is the cleanest approach for assessing solar array degradation as I_{sc} is not dependent on SAW operating voltage, has moderately low temperature dependency, a portion of the SAW strings are generally shunted making data always available, and shunt current data are less sensitive to uncertainties in computationally derived data corrections. The primary disadvantage is the expected I_{sc} degradation rate, at about 0.8 percent per year, is small and thus hard to measure.

The SAW I_{sc} per string determined for wings 2B and 4B is shown in Figure 69 over the 26-month period from wing deployment in December 2000 until February 2003.[105] These data represent orbit-Sun-period averaged values normalized to 28C, 1-Sun illumination, without Earth albedo contributions. Data points are shown with ±3 percent error bars to reflect data uncertainties. Using linear regression, the measured I_{sc} degradation rate is 0.45 percent per year for 2B and 0.15 percent per year for 4B. These degradation rates are consistent with and even lower than the 0.80 percent per year predicted by SPACE and shown as a dashed line in Figure 69. The I_{sc} data points at day 0 were obtained from ground-based acceptance testing using Large Area Pulsed Solar Simulator test equipment and are shown for reference.

Battery Performance

In April 2003, the battery team reported on the performance after approximately 13,700 cycles: “The data clearly shows that the batteries are performing within their design specifications over the operational range.” The pressure delta on the troublesome battery had been stabilized well below the redline delta pressure (Figure 70).[106]

Battery Reconditioning (2004)

NiH_2 Reconditioning

The ISS NiH_2 batteries were starting to show some effects of aging after 3.5 years of on-orbit operations (see Figure 71). Battery reconditioning was proposed to reduce cell voltage divergence and provide data that can be used to update the SOC computation.[107] ISS on-orbit procedures eventually were updated to include reconditioning for NiH_2 batteries every 4 to 6 years.

NiH_2 Extended Discharge Battery Model Enhancement

The SPACE battery model was enhanced to more accurately model battery discharge performance beyond the normal eclipse period.[108]

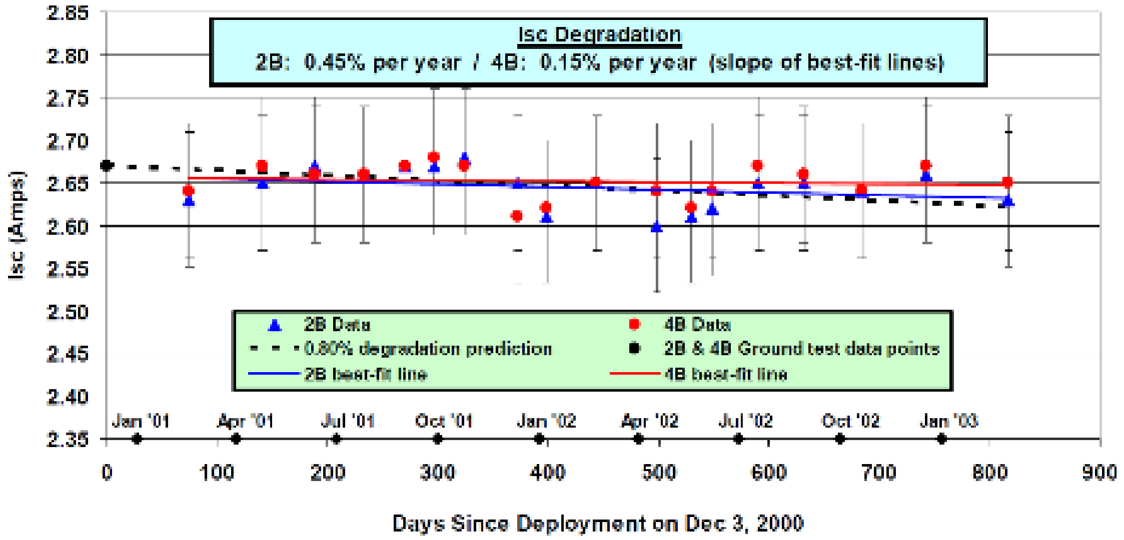


Figure 69.—Solar array wing short circuit current (I_{sc}) per string for 2B and 4B.

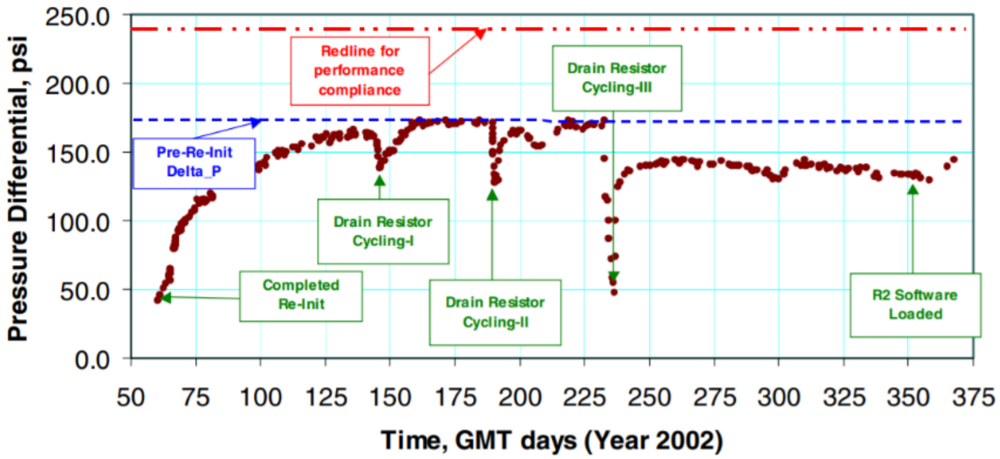


Figure 70.—Battery 4B2 orbital replacement unit delta pressure trend.

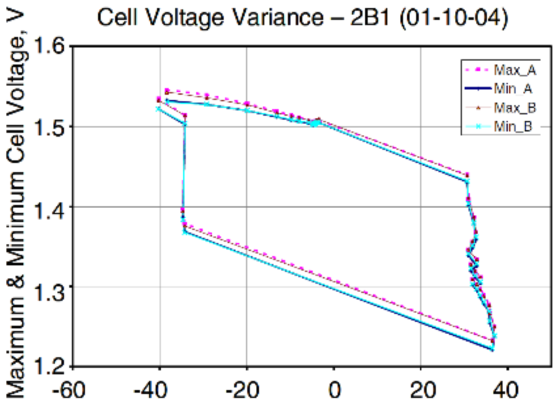


Figure 71.—Channel 2B battery discharge unit #1 battery cell voltage variances.

Probabilistic Power Predictions

SPACE is a deterministic model and thus the results do not account for uncertainties in the inputs. Probabilistic assessments allow quantification of the uncertainty at the system level. For example, accounting for changes in Earth albedo during the Sun portion of an orbit, as well as accounting for vehicle attitude variations, results in a power capability probability distribution function. SPACE was integrated with an approximation of a Monte Carlo Simulator to generate probability density functions for the space station EPS power system capability (see Figure 72 for an example).[109]

The Johnson staff supporting ISS real-time operations might be interested in probabilistic EPS power predictions. However, the customers of the SPACE results in the ISS vehicle project office prefer the deterministic model results that use conservative assumptions for selected inputs (such as minimum annual solar flux), and long-term average values for other inputs (such as Earth albedo). Thus, the probabilistic SPACE work was abandoned after this proof-of-concept activity.

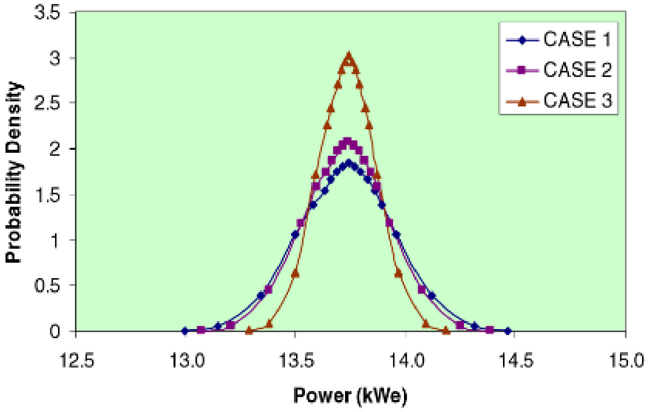


Figure 72.—Probability density versus power level.

Figure 73.—Atlantis docked to Mir with Mir Cooperative Solar Array on right (sts079-789-097).

Figure 74.—Cloudscape with thunderhead anvils in Philippine Sea in 2016 (ISS048-E-10018).

Analyses of International Space Station (ISS) Solar Array Wing (SAW) With Nonsolar Light Sources (2005)

During an EVA for the removal and replacement of an SSU, astronauts could be at risk from current and/or voltage hazards when disconnecting the cable from the solar array to the SSU. This operation would be performed during an eclipse period, but nonsolar light sources (such as a full Moon or EVA lighting) might still pose a risk. During the development of EVA procedures for an SSU replacement, Glenn was asked to assess the risks of changing an SSU with the solar array experiencing nonsolar lighting. Tests and analyses were performed to quantify the ISS SAW performance under low-intensity low-temperature (LILT) (operating conditions with nonsolar light sources). The analyses were performed by SPACE team members, using modified versions of the solar array model for the LILT conditions. The results showed there is no EVA crew member shock hazard for full Moon illumination or EVA helmet lighting conditions, or a combination of the two. Hazard limits were exceeded for certain video camera luminaire lighting cases, but operational solutions to mitigate this hazard were identified (powering down the lighting or selecting a pan angle to point the beam away from the SAW).[110]

Figure 75.—Astronaut Michael Good (left) presenting a Silver Snoopy award to Jeff Hojnicki for his work with the SPACE code (C-2005-1413).

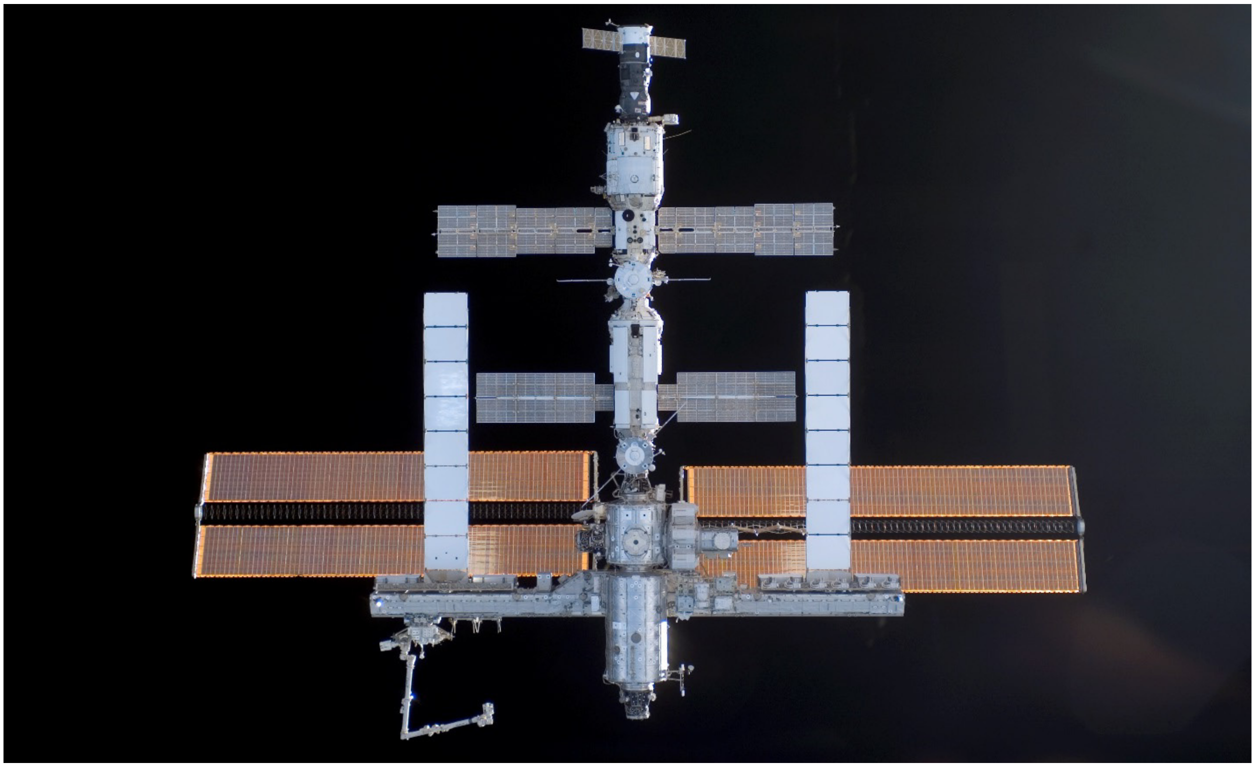


Figure 76.—International Space Station configuration in fall 2006 prior to P4 installation.

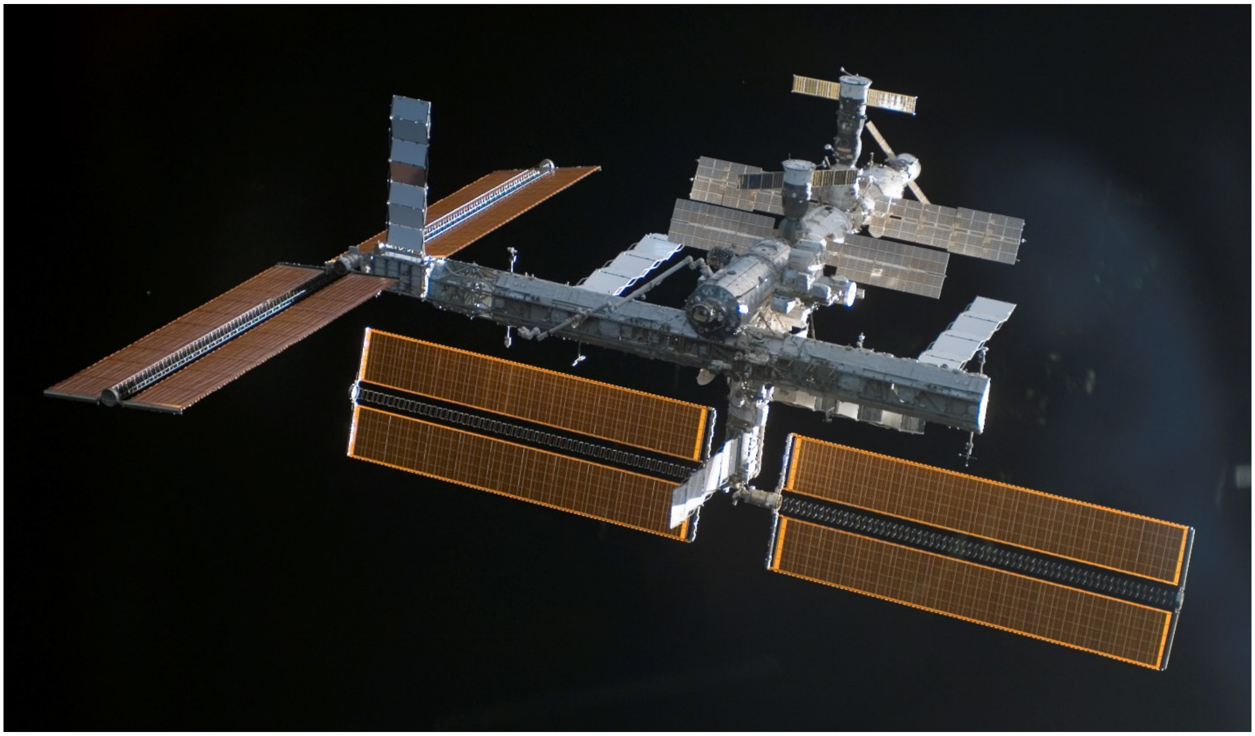


Figure 77.—International Space Station configuration after P4 installation in fall 2006 with two power channels online (s115e06750).

P4 Launch (2006)

International Space Station (ISS) Launch and Activation of P4

During the approach to the ISS on STS–115 (flight 12A) in September 2006, astronauts onboard Space Shuttle Atlantis captured the picture shown in Figure 76. This was the first assembly flight to the ISS after the Columbia accident.[h] The ISS truss structure is shown in the foreground, with one panel from the port and starboard central radiator panels deployed. This was the last assembly flight where both the 2B and 4B power channels were active and in their temporary location on Z1.

STS–115 delivered the new P3/P4 truss to the ISS, which included power channels 2A and 4A. Although the 2A and 4A solar arrays were deployed and the channels were activated, these new power channels were not included in the ISS power grid as the MBSUs were not yet activated. The ISS configuration following the departure of STS–115 is shown in Figure 77.

The Glenn analysis for Verification Analysis Cycle 12A first began in 2003, shortly before the Columbia accident, and was restarted in 2006. The assessment included 22 planned ISS flight attitudes, as unique attitudes were needed during the P4 SAW deployments at different solar beta angles as well as in the overnight park positions for the new P3/P4 truss structure to maintain proper thermal conditions.

Results from Verification Analysis Cycle 12A for channel 2B during EVA–3 are shown in Figure 78. During this EVA, the solar arrays are latched for P6 BGA retainer clip installation and Materials International Space Station Experiment (MISSE) 5 retrieval, resulting in low power capability and very low battery SOC. These results are at a solar beta of 0°. Glenn analysis found similar issues for absolute solar beta less than 20°. Glenn recommended either flying an alternate attitude or reducing the solar array feathering time by moving tasks from EVA–3 to an earlier EVA.

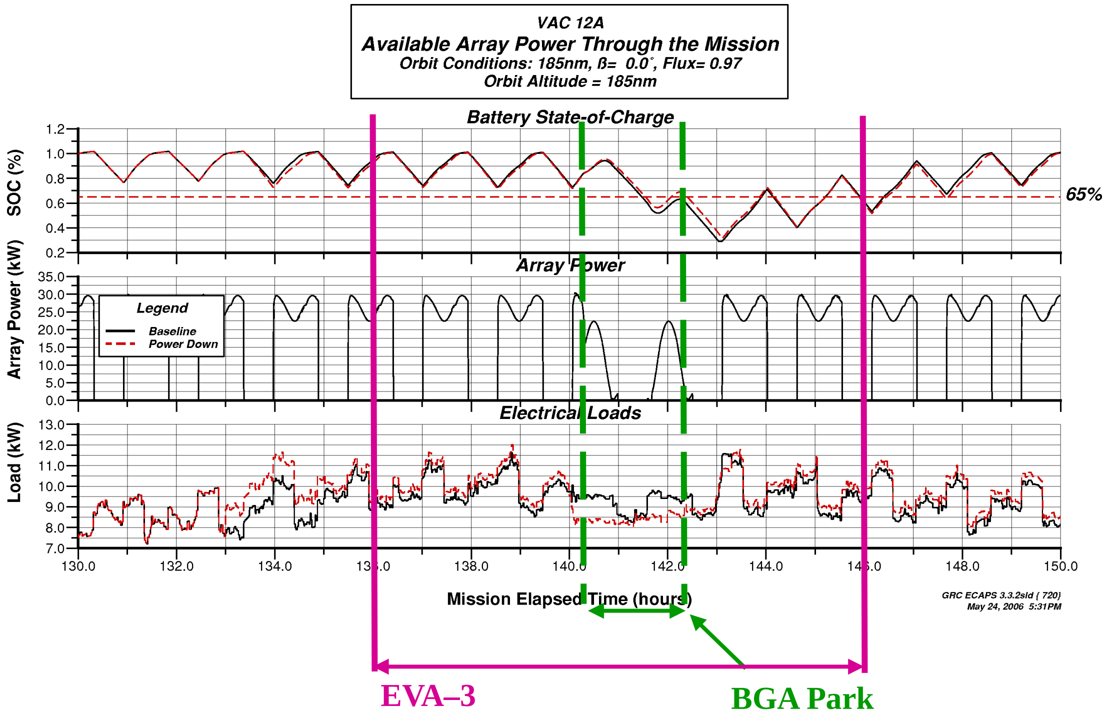


Figure 78.—Extravehicular Activity 3 (EVA–3) powerdown and alternate attitude insufficient for maintaining 2B state of charge (SOC).

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[h] Flight LF–1 (STS–114) was the first shuttle flight 2 years after the Columbia accident, providing much-needed supplies to the International Space Station (ISS), followed by ULF1.1 (STS–121) with more supplies and cargo for the ISS.

Figure 79.—International Space Station configuration with 4B retracted in December 2006 with three power channels online (s116e07151).

Figure 80.—International Space Station configuration in June 2007 with four power channels online (S117E08032).

In December 2006, STS–116 delivered the P5 spacer truss to the ISS. The STS–116 and Expedition 14 crews retracted the 4B SAW (due to possible physical interference with P4, see Figure 79) and reconfigured the ISS EPS to bring the P4 channels 2A and 4A online.

Begin Development of SPACE-Multi-Purpose Crew Vehicle (MPCV)

To support NASA studies of the proposed Orion spacecraft, the SPACE–ISS code was modified to model the performance of the Orion EPS.

S4 Launch (2007)

International Space Station (ISS) Launch and Activation of S4

Space Shuttle Atlantis delivered element S4 to the ISS in June 2007. Following activation of S4 (channels 1A and 3A), SAW 2B was retracted. The P6 power module, with retracted solar arrays 2B and 4B, was still in position on the Z1 truss above the Unity Node (visible in the center of Figure 80). This figure also illustrates that the ISS solar arrays are not always pointed toward the Sun. The shadow patterns indicate that the Sun is up and off to the left in this picture. Thus, the ISS PV solar arrays approximately edge-on (located above the truss in this picture) have the highest view factor to the Sun. For the two solar arrays located below the truss, the frontside of the solar array on the left is facing away from the camera, while the frontside of the lower right solar array is facing the camera.

International Space Station (ISS) P6 Relocation From Z1 to Permanent Position on Port Side

STS–120 delivered Node 2 to the ISS. During this mission, element P6 was relocated from its temporary location on Z1 to the permanent home outboard of P5. After P6 was relocated, on flight day 8, the 2B solar array was 100 percent redeployed. During the second redeployment of the channel 4B solar array, deployment activity was aborted at 25 bays due to a tear in the right blanket (see Figure 81). The EVA was terminated and repair procedures were developed. On flight day 12, another EVA was conducted and the 4B solar array was successfully repaired and fully deployed. Rocky Mountain News described this event as follows: “Parazynski … performed what NASA is calling one of the greatest ‘space saves’ in the history of manned spaceflight. … [He] floated outside with wire cutters, pliers, and homemade tools to fix the torn wing.”[111] The 4B repair conducted by Parazynski is shown in Figure 82.

Once again, Figure 83 illustrates that all of the ISS solar panels are not always pointed directly toward the Sun. In this picture, the Sun is off to the left, with the two starboard solar arrays on the left and four port solar arrays on the right. The starboard alpha gimbal is 90° out of phase from the port alpha gimbal, resulting in the S4 solar arrays being perpendicular to the port side solar arrays. Note the shadow pattern on the top inboard solar array on the port (right) side.

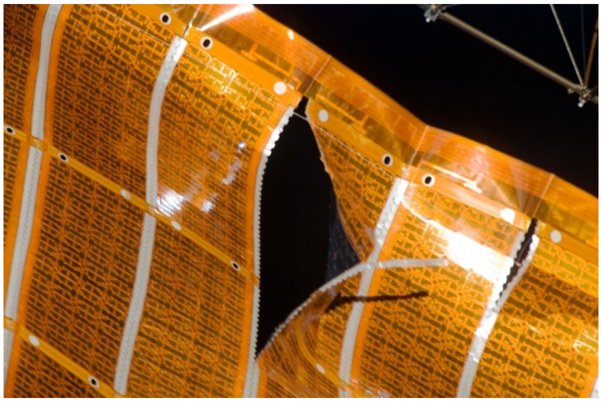


Figure 81.—A 2-ft tear in 4B solar array during redeployment.

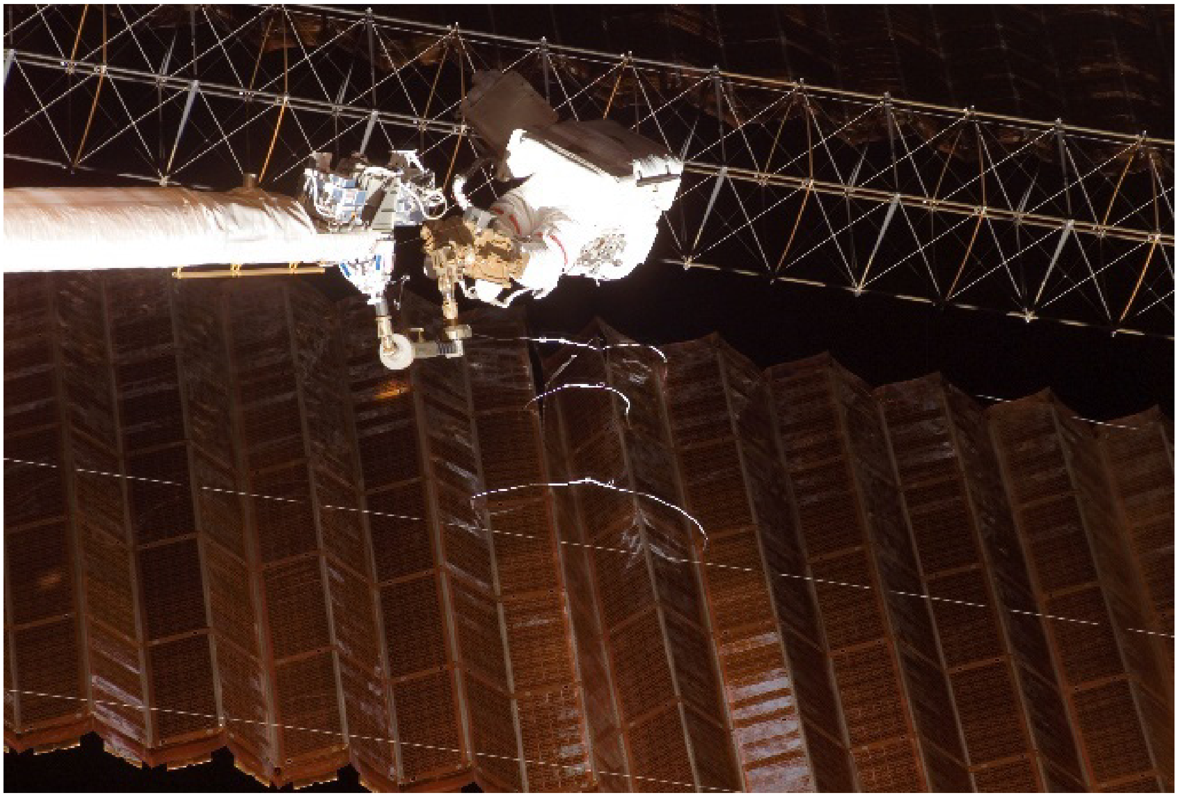


Figure 82.—Repaired 4B solar array (ISS016E009196).

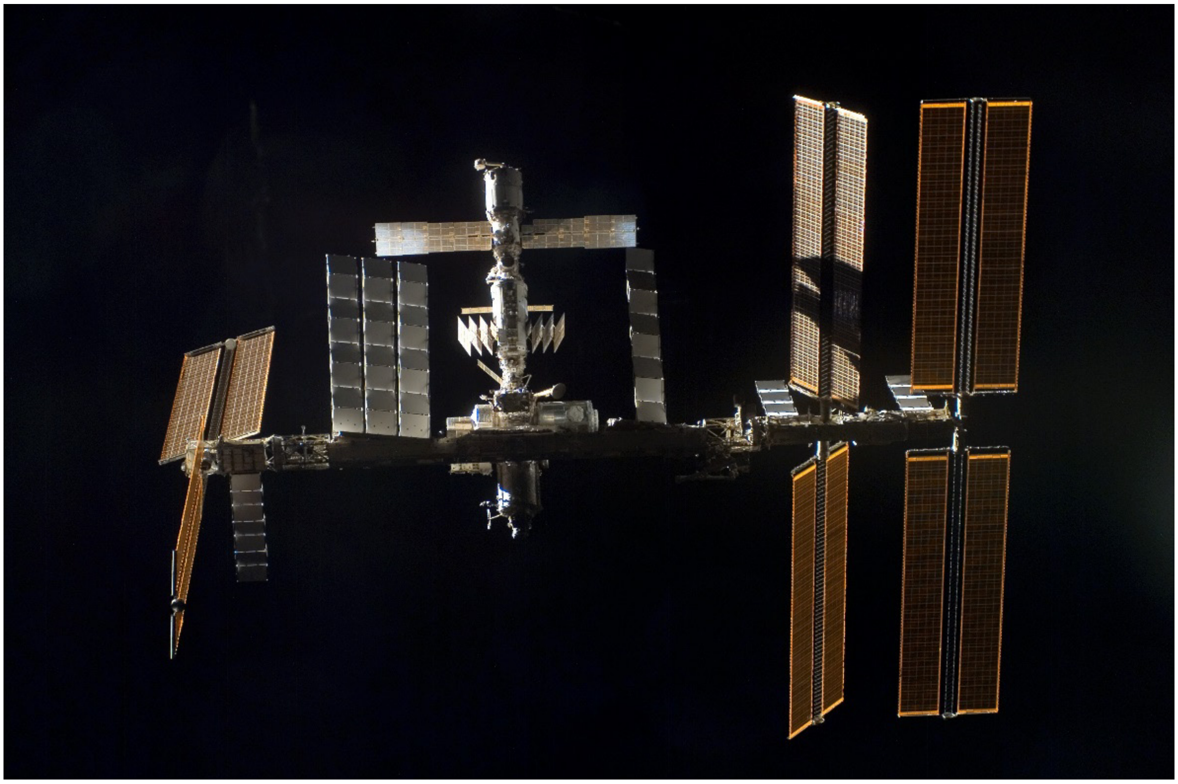


Figure 83.—International Space Station configuration with P6 relocated and six channels online (s120e009604).

SPACE Validation Episode #4, Adapting SPACE for Future Programs (2008)

This was the most extensive SPACE validation episode to date, assessing the following missions:

- Quiescent operations from September 2007, near solar beta 0°
- Quiescent operations from late December 2007, solar beta from –54° to –74° and back to –55°
- Assembly flight 1E in February 2008, covering negative solar beta –10° to –50°
- Assembly flight 1J/A in March 2008, covering positive solar beta from +16° to +53°
- Shunt test (solar beta –1°) and ATV docking (solar beta +27°) in April 2008

The efficiency of six DDCUs was compared between 2001 (Figure 84) and 2008 (Figure 85). The increased scatter in 2008 is due to using Operational Data Reduction Complex (ODRC)-computation for integrated data elements, compared with Glenn computations in 2001 (which included filtering). Similarly, the efficiencies of the three BCDUs on channel 2B were compared between 2001 (Figure 86) and 2008 (Figure 87).

The last trending assessment was for battery 2B–1 end-of-discharge voltage (EODV). This is a common battery trending parameter during ground testing, with EODV generally steady for the first few years of life and then slowly trending downward with a sharp drop near the end-of-life. Due to the ISS experiencing changing orbit eclipse periods and changing load demands, we first investigated both the end-of-discharge SOC (EOD SOC) and EODV (see Figure 88). This shows an overall drop in EODV of about 5 V over the first 300 cycles. However, note that the EOD SOC is also decreasing. Scripts were developed to separate the EODV values by EOD SOC buckets (i.e., EODVs for EOD SOCs from 80 to 81, 81 to 82, 82 to 83 percent, etc.). This results in trend plots of EODV values with similar EOD SOC values. Figure 89 is an example for EOD SOCs between 80 and 81 percent. There is no apparent degradation in the 2B–1 battery EODV for the SOC range of 80 to 81 percent. The results for other SOC bins were similar as well as the results for 4B–1. Thus, the ISS batteries were performing as expected, with no reduction in EODV.

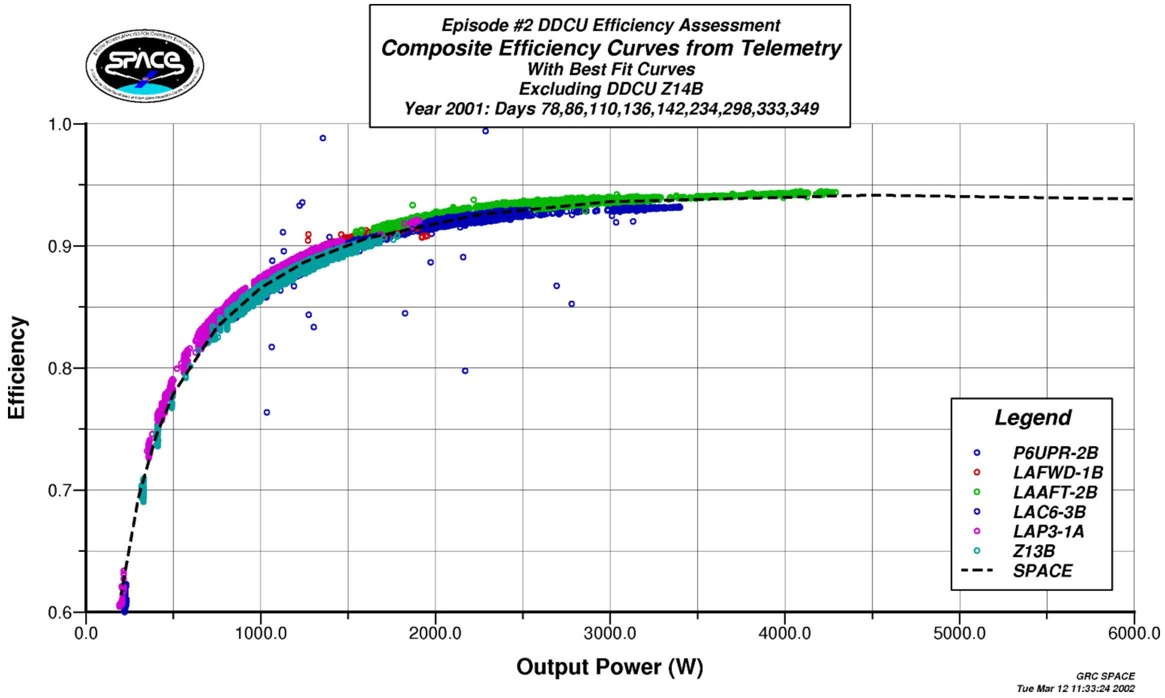


Figure 84.—2001 DC-to-DC converter unit (DDCU) efficiency.

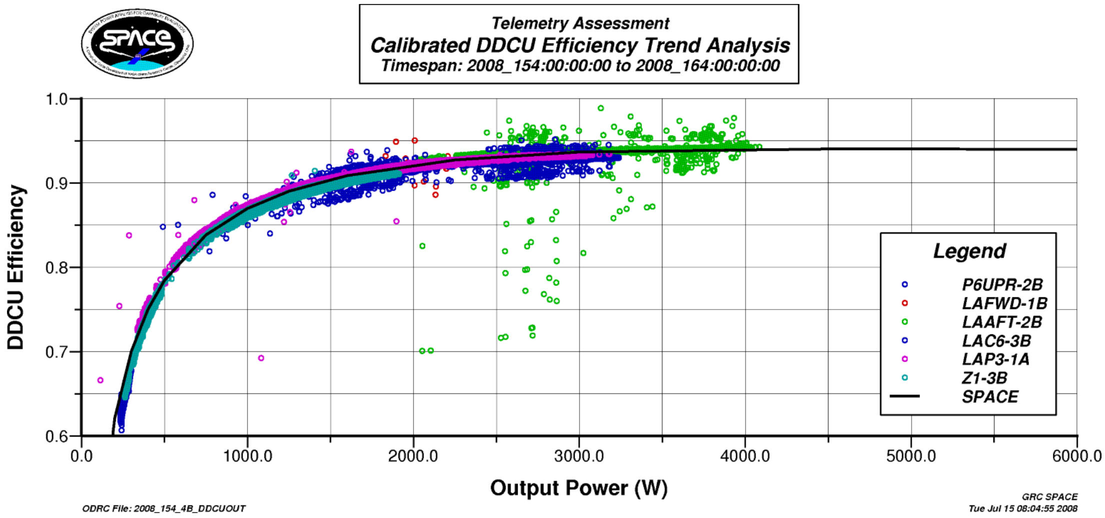


Figure 85.—2008 DC-to-DC converter unit (DDCU) efficiency.

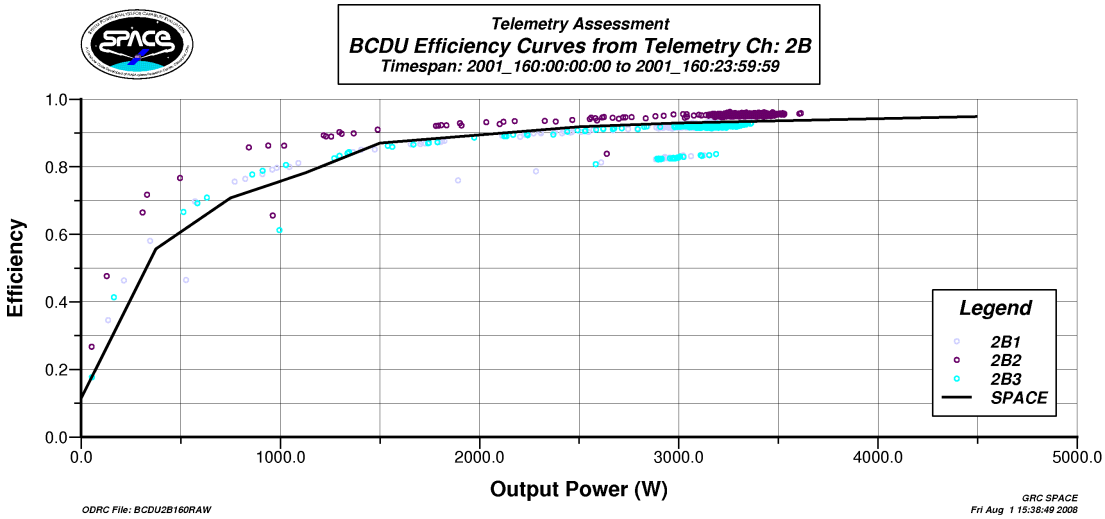


Figure 86.—2001 battery charge discharge unit (BCDU) efficiency.

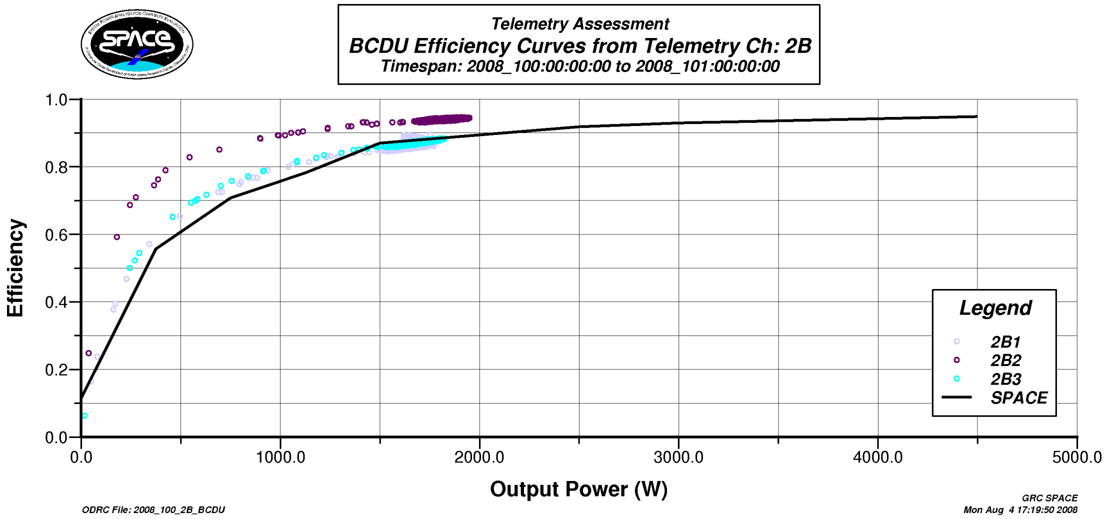


Figure 87.—2008 battery charge discharge unit (BCDU) efficiency.

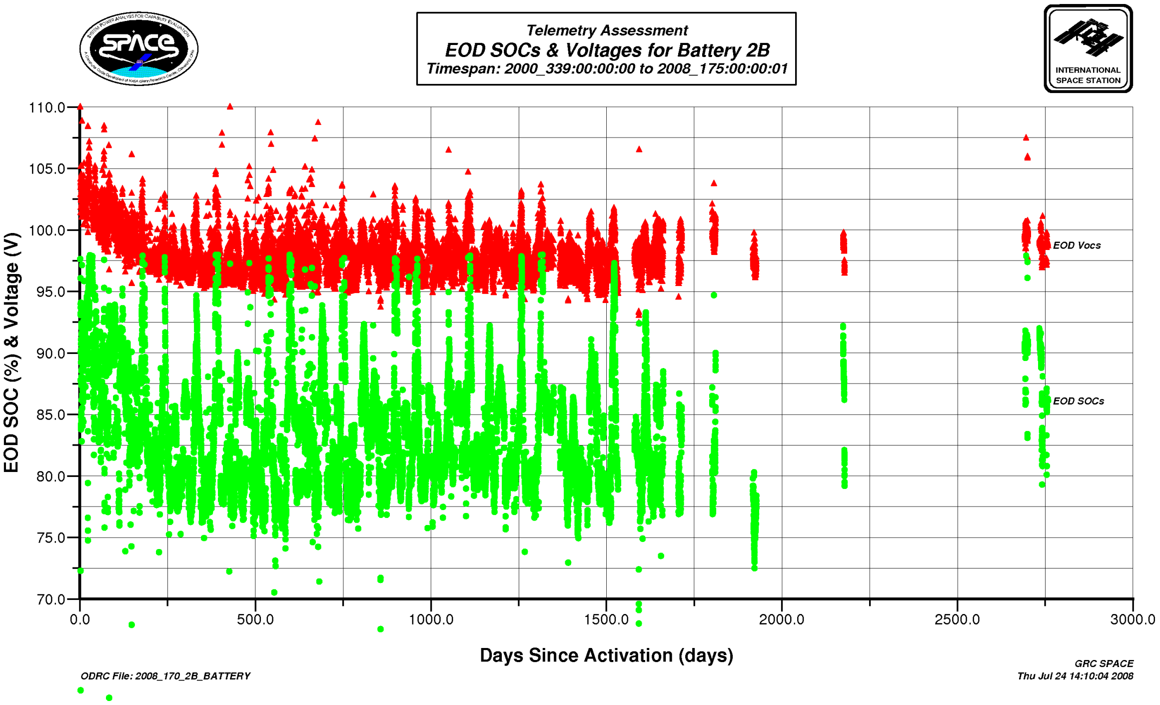


Figure 88.—Battery 2B–1 end of discharge (EOD) state of charge (SOC) and EOD voltage trends from December 2000 to June 2008.

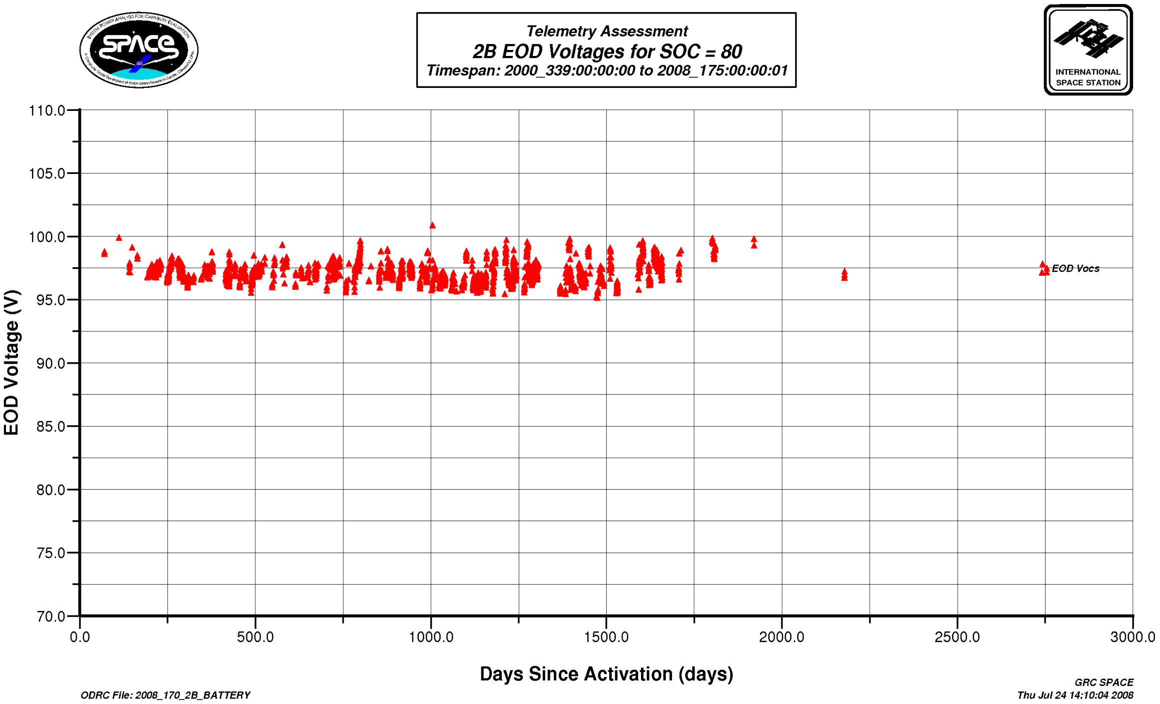


Figure 89.—Battery 2B–1 end of discharge (EOD) voltage trend for 80 < EOD state of charge (SOC) < 81 from December 2000 to June 2008.

The shuttle docking on flight 1E was analyzed in detail. The shuttle docking occurred around a mission elapsed time (MET) of 41.4 hours, at which point the ISS attitude was modified, as shown in Figure 90. The 2A BGA and the port SARJ are both still locked in the docking position when the ISS attitude is changing. The channel 2A SSU parameters for SPACE and telemetry are shown in Figure 91. Around a MET of 41.7 to 42 hours, SPACE is overpredicting the current available from the 2A SSU. This results in SPACE predicting higher battery SOCs in this timeframe, as shown in Figure 92. The minimum 2A battery SOC as computed on orbit was 0.7 at around a MET of 41.2 hours, while SPACE predicted a minimum SOC of about 0.75. Again, the SPACE battery model is fine because the SOC variance is due to SPACE overpredicting 2A SSU current. The highly unusual 2A solar array conditions in this timeframe are illustrated in Figure 93. The three graphics at the bottom of the figure illustrate the ISS orientation and the channel 2A pointing conditions. At the beginning of the orbit, the frontside of the solar array is oriented toward the Sun. But from a MET of 41.7 hours through the end of the Sun period, the backside of the 2A solar array has very poor view factors to the Sun. In addition, the 2A solar array is shadowed by the 4B solar array around orbit noon.

For flight 1J, a comparison of the SPACE and telemetry minimum battery SOCs is shown in Figure 94 for each orbit in the mission and for each of the six channels. Special events during the flight are annotated at the bottom of Figure 94: shuttle dock, EVA, waste water dump, and shuttle undock. Most of the data is within ±0.04, which is within the 5 percent range often quoted for SPACE results. One of the larger errors occurs on channel 1A at docking, where SPACE predicts lower SOC values compared with telemetry by 0.08. The 1A battery current, voltage, and SOC for this case are shown in Figure 95. SPACE predicted slightly higher battery discharge currents, resulting in lower SOCs.

Members of the SPACE team coauthored a paper with staff from Hamilton Sunstrand and Deep Space Systems on adapting and reusing spacecraft power system models for NASA's Constellation Program.[112]

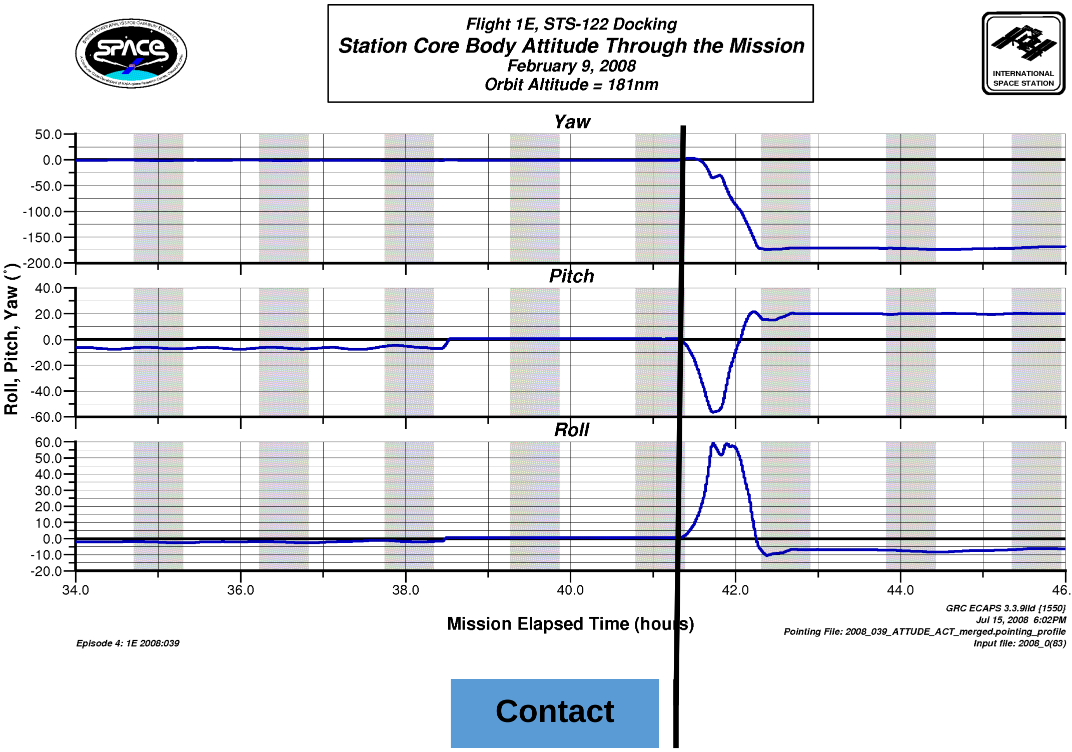


Figure 90.—Flight 1E space station attitude around shuttle docking.

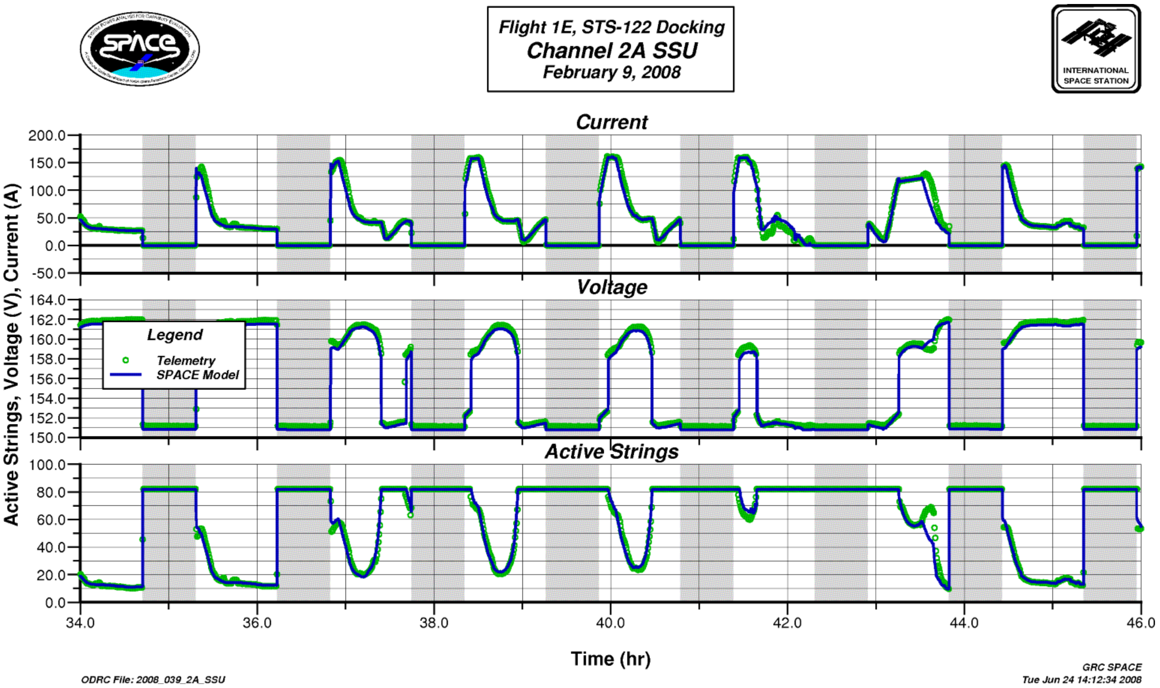


Figure 91.—Channel 2A sequential shunt unit (SSU) parameters for SPACE versus telemetry.

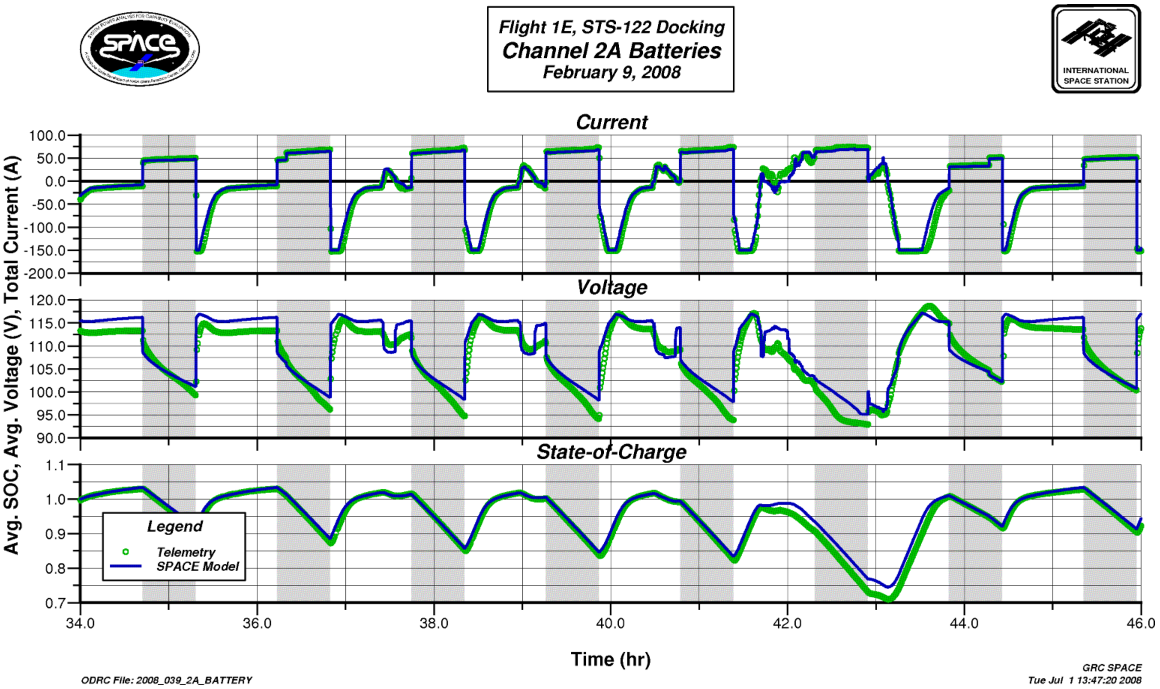
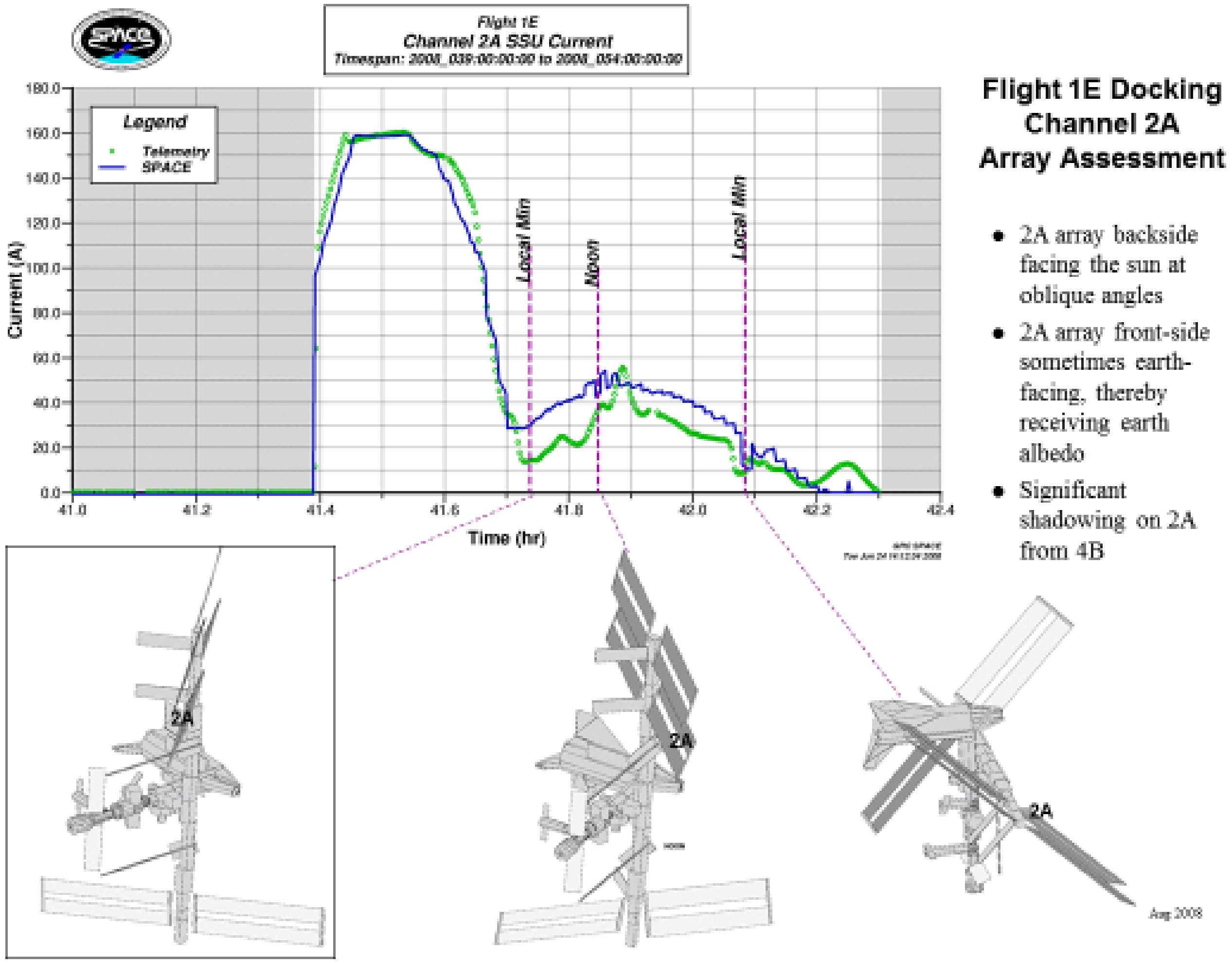


Figure 92.—Channel 2A battery parameters for SPACE versus telemetry.



Flight 1E Docking Channel 2A Array Assessment

- 2A array backside facing the sun at oblique angles
- 2A array front-side sometimes earth-facing, thereby receiving earth albedo
- Significant shadowing on 2A from 4B

Figure 93.—Channel 2A docking and detailed solar array assessment.

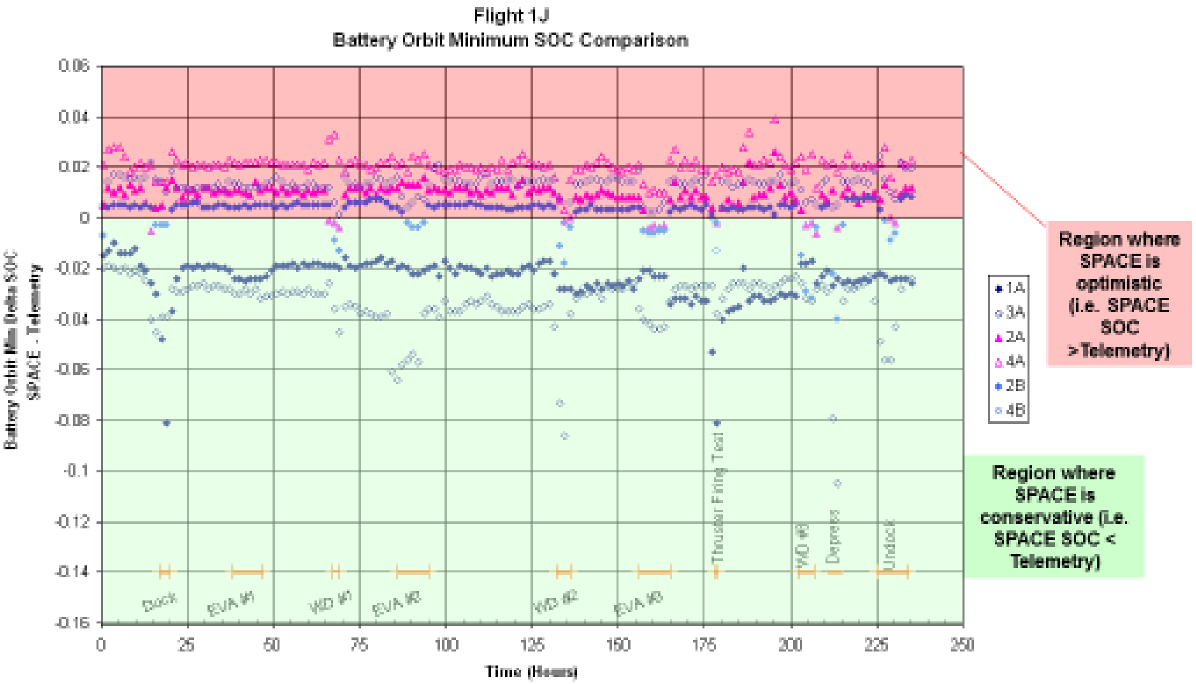


Figure 94.—Flight 1J orbit minimum state of charge (SOC) comparison.

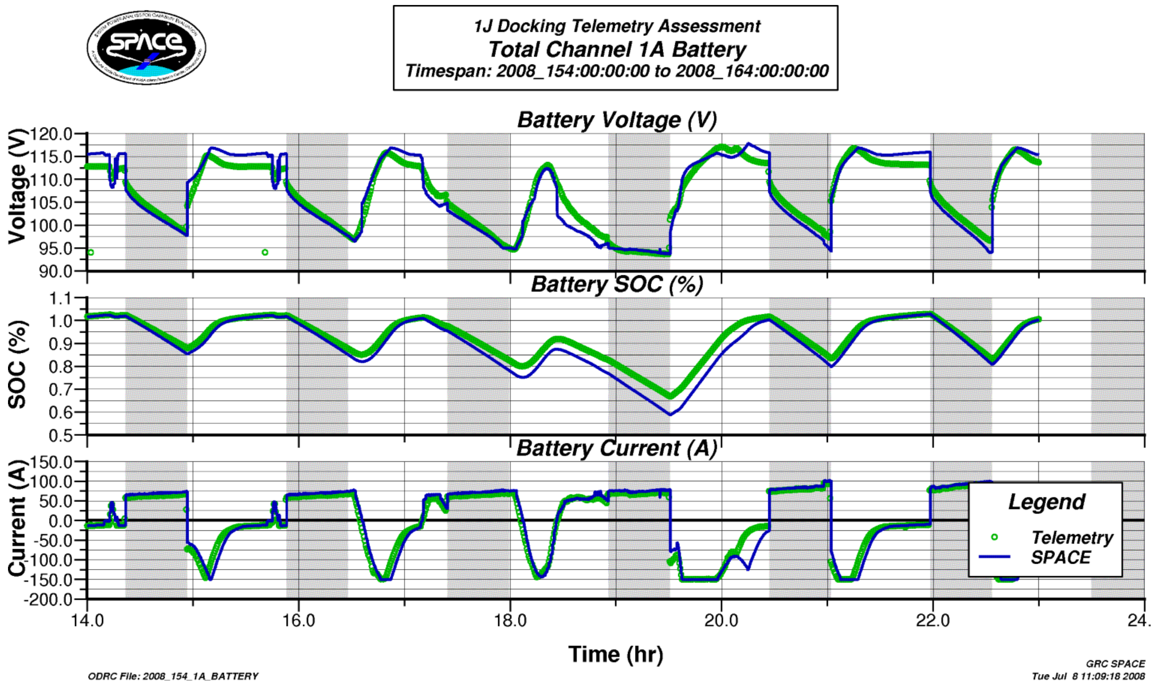


Figure 95.—Flight 1J channel 1A battery parameters during docking.

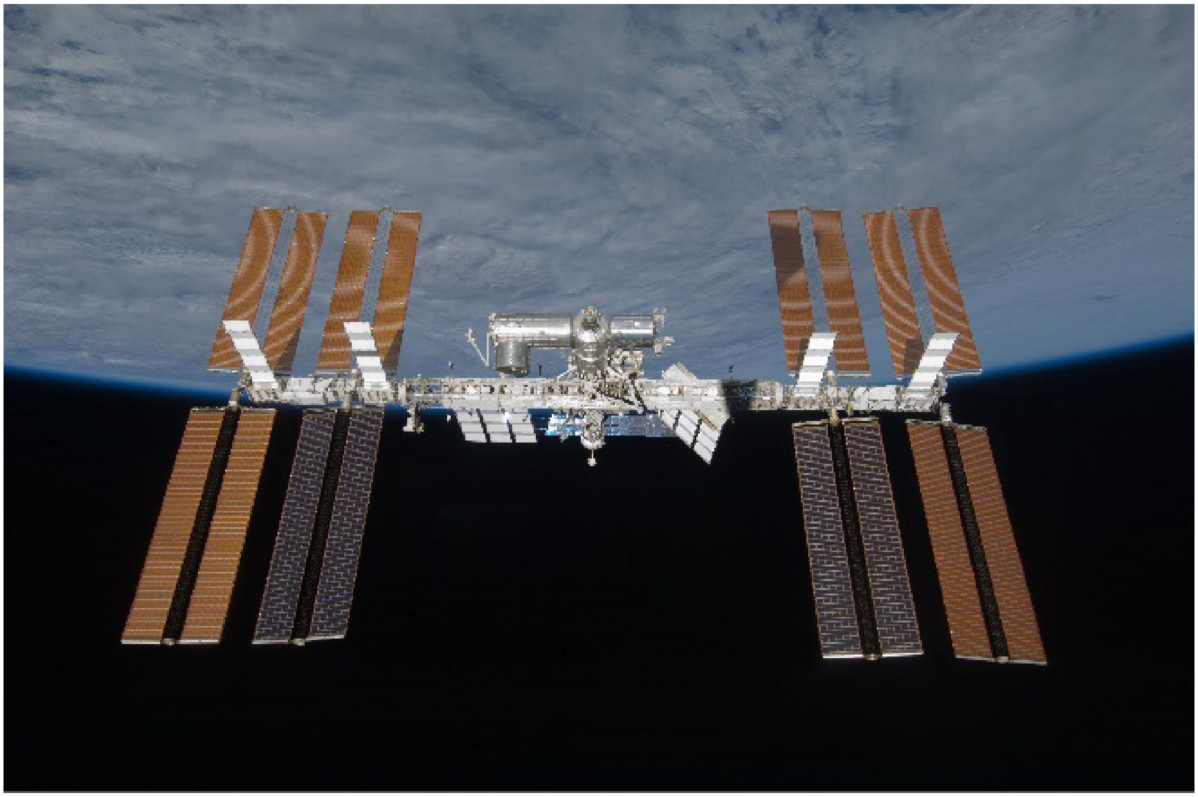


Figure 96.—International Space Station configuration with S6 installed and eight channels online (S119E008332).

Figure 97.—Astronauts removing old 2B NiH$_2$ battery (S127E008440).

S6 Launch and Replace 2B NiH_2 Batteries (2009)

Activation of International Space Station (ISS) Element S6 (Channels 1B and 3B)

In March 2009, STS–119 delivered the final power module (S6) to ISS (Figure 96). In this figure, the ISS is seen from Space Shuttle Discovery after separation. The Sun is behind the space shuttle and off to the left, as evidenced by the shadow patterns of the four PVM radiators on the solar arrays. The shadow pattern on the top inboard SAW on the right side is from a wing of the space shuttle. The two lower inboard solar arrays have their frontsides oriented toward the Sun, while the other six solar arrays have their rear sides facing the Sun.

Replace 2B NiH_2 Batteries

STS–127 delivered six NiH_2 replacement batteries for channel 2B in July 2009, which the crew installed on two EVAs (Figure 97).

SPACE Validation Episode #5, Replace 4B NiH_2 Batteries (2010)

SPACE Validation Episode #5

This validation episode provided a first look at S6 on-orbit performance when solar array shunt tests were being performed on days 86 and 89 of 2009. RMS errors between SPACE predictions and on-orbit data were comparable to earlier validation episodes.

Replace 4B NiH_2 Batteries

Similar to STS–127 (which provided replacement batteries for 2B), STS–132 provided replacement NiH_2 batteries for channel 4B in May 2010. This was the last set of NiH_2 batteries launched to the ISS, as future battery replacements utilized new Li-Ion batteries.

Initiated Development of Solar Electric Propulsion Simulation (SEPSim) (2011)

This new software combines solar array performance modules of SPACE with the rigid body simulation code Mission Analysis Simulation Tool in Fortran (MASTIF). This software allows modeling of low-thrust solar electric propulsion during its transfer from a selected initial orbit to a selected final orbit in the vicinity of Earth.[113]

SPACE Validation Episode #7 (2012)[i]

The berthing of the SpaceX demonstration mission on day 147 of 2012 at solar beta +16° was the focus of this validation episode. The overall RMS errors were higher than for previous validation episodes (6 to 12 percent compared with less than 5 percent for prior episodes).

SPACE Validation Episode #8 (2015)

This episode assessed nominal day 332 of 2014, as well as SpaceX–5 capture on day 12 of 2015. To best match on-orbit data, the solar array degradation model was adjusted with the radiation fluence factor increased by three times for channel 4B and one and one-half times for 2B. The micrometeoroid and orbital debris factors were increased by two times for both 2B and 4B. The battery degradation model was updated to use a Weibayes method, resulting in lower battery degradation.

The resulting RMS errors were about 8 percent.

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[i] Due to an error in numbering, SPACE validation episode #6 was inadvertently skipped.

Figure 98.—Composite images of Cleveland, Ohio, taken from the International Space Station in 2016 (image range from ISS047-E-61433 to ISS047-E-61442).

Li-ion Battery Replacement; SPACE Validation Episodes #9 and #10 (2017)

Replaced NiH_2 Batteries With Li-ion on 1A/3A

The NiH_2 batteries were replaced with Li-ion batteries on channel 1A (January 13, 2017) and 3A (January 6, 2017). This necessitated updating the SPACE model to incorporate Li-ion batteries. Details of this new model are described in a paper published in 2018.[114]

SPACE Validation Episodes #9 and #10

These two validation episodes were grouped together due to unique circumstances. Episode #9 was started in December 2015, assessing day 65 of 2013, which included SpaceX–2 berthing. This included high negative solar beta operations, which identified a deficiency in the SPACE code SAW geometry model (the flat conductor cable on both sides of the solar array was not included in the initial model). After updating the geometry, SPACE better matched the on-orbit telemetry. The team discussed including a trending analysis in episode #9 and reviewing RMS error trends across all the validation episodes.

The degradation trending assessment was temporarily put on hold while the team conducted validation episode #10. This episode consisted of 11 days of ISS operations in 2016 at various solar beta angles and 1 day in 2017 with new Li-ion batteries for channels 1A and 3A. Following these assessments in episode #10, 30 cases from episodes #1 to #10 were rerun as part of the episode #9 trending analyses. The SPACE solar array degradation model was modified to better match the trends in the solar array maximum power on-orbit tests.

Further details on validation episodes #9 and #10, as well as information about other recent model changes and the future of the SPACE code, may be found in Reference 114.

Figure 99.—International Space Station Expedition 30 Space Flight Awareness Poster (jsc2012e054037).

♦ Chapter 3 ♦

Key SPACE Code Development Participants

The individuals listed in Table V played an important role in the development and use of the SPACE code. They are shown in approximately chronological order of their initial involvement with SPACE. Figure 101 and Table VI list the WP–04 team members from the 1987 roster.

TABLE V.—KEY PARTICIPANTS IN SPACE CODE DEVELOPMENT AND USE

Name	Role
Ron Thomas	Thomas was the manager of the Lewis Space Systems Office in the early 1980s. Because of Thomas's outstanding leadership, Lewis was selected to lead the development of the International Space Station (ISS) Electrical Power System (EPS). Thomas went on to become the head of the Lewis space station directorate. He always had an interest in SPACE results, and he reviewed major analysis reports prior to their delivery outside of Lewis.
Raymond Burns	Burns served as the manager of the analysis group within the Space Systems Office. He was a strong proponent of the development of the SPACE code and nurtured the group in the key early years of writing SPACE.
Peter Staiger	As the author of the ENERGY code (which served as a foundation for SPACE), Staiger helped set the initial direction for SPACE.
Jeff Hojnicki	Without Hojnicki, there would not be a SPACE code. A highly talented engineer with strong coding skills, he successfully led the team in the initial development of SPACE. He is the owner of 37 percent of the SPACE subroutines and has been involved with almost the entire code. He developed many of the scripts that were used as follows—to execute the code, manipulate graphical results, and provide code configuration management. Hojnicki continued to lead the SPACE team in the early ISS years and through the numerous redesign activities and fire-drill requests from Level II. Hojnicki was also instrumental in preparing the paperwork for the NASA Software-of-the-Year (SOY) Award application. Hojnicki led the effort to modify SPACE to predict the performance of the Orion Multi-Purpose Crew Vehicle (MPCV).
Jeff Trudell	A thermal expert, Trudell helped develop the first SPACE models to predict solar cell temperature. Trudell improved the gimbal pointing algorithms to reflect on-orbit operations of any attitude. Trudell also added rapid environmental heating rate algorithms versus orbital position to more accurately predict solar cell temperature and backside power capability through an entire orbit.
Bob Green	Green was the SPACE battery expert. He coded the first battery model in SPACE, and then led the effort to integrate a battery model developed by the ISS battery manufacturer into SPACE. Green also led several Design Analysis Cycle assessments.
James Fincannon	Fincannon is the SPACE expert in shadowing analysis. He developed spacecraft geometry models and the SPACE code to use these models to predict shadow patterns on ISS and Mir solar panels as well as for the Mir solar dynamic (SD) collectors (for the Mir SD project).[115] Using the SPACE shadowing analysis background, Fincannon supported the Constellation program by developing an analytical tool to assess lunar polar solar array illumination and shadowing.[116] A spinoff of this work was to use recent Lunar Reconnaissance Orbiter imagery to discover that three Apollo landing site flags were still flying (based on the shadows cast by the flag itself) and had not disintegrated as many had speculated.[117]
Dave Hoffman	Hoffman developed the initial view factor subroutines in SPACE. He also ran SPACE to generate shadow patterns for the solar arrays on the Russian modules launched early in the ISS assembly. He famously summarized the Glenn recommendation to Johnson for an upcoming flight as "Sit back, Relax, and Enjoy the Flight." Hoffman became chief of the Glenn Power Architecture and Analysis branch, which includes all of the current SPACE team members.

Name	Role
Tom Kerslake	Kerslake is one of the top NASA experts on solar arrays, supporting solar array development activities in a multitude of projects. He authored many subroutines in SPACE for computing solar cell performance, including enhancements to the solar cell temperature models. He has expanded SPACE beyond the ISS to model Mars surface power systems.[118] Kerslake prepared Figure 101 and Table VI, which show the Work Package-04 (WP–04) team from 1987 and the names of the team members, respectively.
Ann Delleur	Delleur currently serves as the SPACE team lead. She worked with Kerslake on adding bifacial power generation to the solar cell code, has helped mentor many summer interns with their tasks on SPACE, and has led many of the key SPACE analyses.
Tony Jannette	Starting as a support service contractor, Jannette helped the SPACE team conduct many analyses during the key flights in the ISS assembly sequence. He later became a civil servant and continued to support the team in many model validation activities.
Carlos Rodriguez	Rodriguez paid attention to the details in his analyses. This characteristic was very useful in his SPACE assessments.
Jeff Follo	Follo played a key role in the development and updates to the ECAPS main program and 37 subroutines. His updates added the capability to model dynamic changes in the EPS architecture occurring during an analysis run (such as adding a new DDCU to the architecture).
Terrian Nowden	Nowden joined the branch without extensive experience with coding or conducting analyses. During her time with the SPACE team, Nowden has become an integral part of the team. She has led many SPACE–ISS and SPACE–MPCV analyses and has also assisted with new code development.
Penni Dalton	Dalton is the project lead for all ISS work performed at Glenn. She also serves as the lead for the batteries on the ISS (first NiH_2, then Li-ion). In both roles, Dalton has been very helpful to the SPACE team by serving as a reviewer for internal Engineering Review Boards and passing information related to recent data on ISS batteries along to the SPACE team.
Tim Propp	Propp was the SPACE team point-of-contact for the Johnson Vehicle Integrated Performance, Environment and Resources (VIPER) Team. He worked very closely with Ann Delleur during the Beta Gimbal Assembly (BGA) Anomaly Resolution Team (ART) activities.
Steven Korn	Korn quickly became an expert at running SPACE after joining the branch in 2013. He developed the inputs for the Li-ion battery model in the SPACE code and new scripts that allow the team to quickly execute multiple SPACE runs. Korn is leading the SPACE–Next Generation (NextGen) team.
Kristen Bury	Bury supported SPACE–MPCV development and performed many analyses requested by the project using this new code.
Sara Miller	As a pathways intern, Miller recently conducted an assessment of the impact of changing thermal environments on ISS EPS performance. Miller is the lead author of a paper on recent SPACE code activities.
Sarah Tipler	Also a pathways intern, Tipler was instrumental in assisting with validation episode #9. She is a member of the SPACE–NextGen team.
Brandon Klefman	The latest addition to the SPACE team, Klefman is focusing on modifying SPACE to model the EPS for NASA’s new initiative dubbed Gateway (a space station in a lunar orbit). He is also a member of the SPACE-NextGen team.

Figure 100.—View of Aurora Australis with Soyuz and Progress in the foreground taken by Expedition 29 crew (iss029e008433).

Figure 101.—Space Station WP–04 team circa 1987.

TABLE VI.—WORK PACKAGE-04 (WP–04) TEAM MEMBERS

No.	Name	No.	Name	No.	Name	No.	Name
1	Ron Thomas	32	Bonnie Kaltenstein	63	Bob Finkelstein	94	Tom Irvine
2	Erwin “Pete” Kempke	33	Bill Goette	64	Bob Corrigan	95	Mary Lester
3	Roger Slutz	34	Tom Cochran	65	Clint Ensworth	96	Jack Cassidy
4	Ken Mellot	35	Paul Asmondy	66	Dick DeLombard	97	Carl Daniele
5	Frank Gati	36	Eli Naffah	67	Mike Skor	98	Shirley Anderson
6	Mark Hoberecht	37	Dave Namkoong	68	Nick Samonich	99	Bob Green
7	Bob Manly	38	Harvey Schabes	69	Dick Secunde	100	Mike Bur
8	Frank Gourash	39	Frank Hrach	70	John Taylor	101	Mia Akers
9	Rudy Spagnuolo	40	Myron Hill	71	Caroline Rist	102	Steve Cohen
10	Bob English	41	Ray Sizemore	72	Dick Puthoff	103	Dean Miller
11	Gary Horsham	42	John Ewashinka	73	Larry Viterna	104	Harold Neustadter
12	Dan Briehl	43	Bob Corban	74	Marsha Nall	105	Dale Stalnaker
13	Todd Peterson	44	Dave Hoffman	75	Juan Rivera	106	Robert Seidel
14	Steve Alexander	45	Mike Zernic	76	Gerald Barna	107	Larry Gordon
15	Steven Winegar	46	Bob Tacina	77	Lois Wolf	108	Bill Pack
16	Dick Schuh	47	Michael Ciancone	78	Marton Forkosh	109	Rodger Rachul
17	Tony Long	48	Jack Estes	79	Fred Teren	110	Jim Soeder
18	Vern Weyers	49	Balazs “Bob” Hatvani	80	Jim Calogeras	111	Pete Staiger
19	Don Schultz	50	Dick Lancashire	81	Gordon MacKay	112	Bob Stochl
20	John Dunning	51	Henry Speier	82	Larry Trase	113	Pat Gedeon
21	Ed Braunscheidel	52	Don Nored	83	Jim Dolce	114	Mike Mackin
22	Justine Hamm	53	Larry Scudder	84	Carl Richter	115	Stacy Corban
23	Tom Kerslake	54	Pat Finnegan	85	Donna Mantinieks	116	Dave McKissock
24	Kent Jeffries	55	John Kobak	86	Gerald Sadler	117	Dan Chrulski
25	Laura Rieker	56	George Kopasakis	87	Jose Davis	118	Will Knapp
26	Monica Hoffman	57	Tony Hoffman	88	Geralyn Neely	119	Jim Faddoul
27	Barb Ercegovic	58	Dan Bernatowicz	89	Terry O’Malley	120	Debbie Burak
28	Sandy Reehorst	59	Karen Hughes	90	Steve Johnson	121	Yoland Bowser
29	Dory Sharp	60	Henry Nahra	91	Vanessa Stygles	122	Steve Simons
30	Karen Faloon	61	Bob Stubbs	92	Lorraine Yost	123	Ray Burns
31	Phyllis Mongulo	62	Bob Hyland	93	Kathy Schubert		

Figure 102.—Expedition 48 crew poster (jsc2015e089462).

♦ Chapter 4 ♦

Concluding Remarks

The SPACE code has had a long and robust use at Glenn in support of the ISS program. The code is also satisfying the Orion project office requests for assessments of the Orion EPS capabilities. While the SPACE code is a key to the success of the ISS and Orion programs, perhaps more important than the actual code itself are the capabilities of the analysts using the code. Glenn not only develops performance models, but also uses these models to assess the EPS performance under a variety of operating conditions (some foreseen and built into the code, others requiring code modifications to accommodate unforeseen circumstances). Newer members of the Glenn space power organizations will utilize updated versions of SPACE to support future NASA projects such as a lunar-orbiting outpost and missions to Mars.

Figure 103.—Wearing a Santa Claus hat, NASA astronaut Scott Kelly, Expedition 26 commander, poses for a holiday photo near Christmas decorations in the Unity Node of International Space Station in December 2010 (ISS026-E-009371).

Figure 104.—The Roll-Out Solar Array experiment attached to the SSRMS, with the Dragon vehicle in the background (iss052e086009).

♦ Appendix ♦
Acronyms and Abbreviations

ARCU	American-Russian Converter Unit
ART	Anomaly Resolution Team
ATV	Autonomous Transfer Vehicle
BCDU	battery charge discharge unit
BGA	Beta Gimbal Assembly
BOL	beginning of life
BRM	Baseline Reference Mission
BSAM	Battery/Solar Array Model
CDR	Critical Design Review
DCSU	DC Switching Unit
DDCU	DC-to-DC converter unit
DDCU-E	DC-to-DC converter unit-external
DDCU-I	DC-to-DC converter unit-internal
DFI	Development Flight Instrumentation
DOD	depth of discharge
DOE	Department of Energy
ECAS	Energy Conversion Alternatives Study
ECLSS	Environmental Control and Life Support Systems
EFT	Electrical Functional Test
EMTC	Early Man-Tended Capability
EOD	end of discharge
EODV	end-of-discharge voltage
EOL	end of life
EPSOP	Rocketdyne EPS performance tool
EPS	Electrical Power System
ERDA	Energy Research and Development Administration
ESA	European Space Agency
EVA	Extravehicular Activity
FGB	Functional Cargo Block
FY	fiscal year
GRC	Glenn Research Center
IBR	Internal Branch Report
ICM	Interim Control Module
IEA	Integrated Equipment Assembly
IOC	Initial Operating Capability
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KhSC	Khrunichev State Research and Production Space Center
LCC	life cycle cost
LILT	low-intensity low-temperature
Li-ion	lithium-ion

LVLH	local-vertical, local-horizontal
MASTIF	Mission Analysis Simulation Tool in Fortran
MBSU	Main Bus Switching Unit
MCSA	Mir Cooperative Solar Array
MET	mission elapsed time
MISSE	Materials International Space Station Experiment
MPLM	Multi-Purpose Logistics Module
MPCV	Multi-Purpose Crew Vehicle
NextGen	Next Generation
NiH_2	nickel-hydrogen
ODRC	Operational Data Reduction Complex
OMV	orbital maneuver vehicle
ORU	orbital replacement unit
P/L	payload
PCCU	power conditioning and control unit
PDR	Preliminary Design Review
PEACE	Power and Energy Analysis for Capability Evaluation
PIR	Preliminary Information Report
PMA	Pressurized Mating Adapter
PMAD	Power Management and Distribution
PMR	Program Management Review
PSDD	Power System Description Document
PSE	payload support equipment
PSF	Power System Test Facility
PUI	Program Unique Identifier
PV	photovoltaic
PVM	photovoltaic module
RFP	Request for Proposal
RMS	root mean square
SARJ	solar alpha rotary joint
SAW	solar array wing
SD	solar dynamic
SDFD	solar dynamic flight demonstration
SEPSim	Solar Electric Propulsion Simulation
SOC	state of charge
SOY	Software-of-the-Year
SPACE	System Power Analysis for Capability Evaluation
SRT	Station Redesign Team
SSF	Space Station Freedom
SSRMS	Space Station Remote Manipulator System
SSU	sequential shunt unit
STELAR	Spacecraft Time-phased Electrical Loads Analysis and Resources
STS	Space Transportation System
VIPER	Vehicle Integrated Performance, Environments and Resources
WP	Work Package

Symbols

I_{sc}	short circuit current
V_{oc}	open-circuit voltage
Xpop	x-axis perpendicular to the orbit plane
Xvv	x-axis in the velocity vector
Xnadir	x-axis pointing nadir
Xnadir spin	x-axis pointing nadir with vehicle spinning
Znadir	z-axis pointing nadir
Zvv	z-axis in the velocity vector

Figure 105.—Expedition 52 crew took this picture of part of a solar array and docked Soyuz spacecraft with Earth in the background (iss052e081327).

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Figure 106.—Russian support personnel work to help get crew members out of the Soyuz spacecraft shortly after the capsule landed in Kazakhstan in March 2011. Scott Kelly and two Russian cosmonauts returned from almost 6 months onboard the ISS (201103160036hq).

♦ About the Author ♦

David B. McKissock joined the NASA Glenn Research Center staff in May 1983. He began his NASA career supporting the development of the Electrical Power System (EPS) for the International Space Station (ISS). He spent a year working at NASA Headquarters in Washington, DC, where he helped negotiate with the Russians when they became a partner in the Space Station program. McKissock also served a 1-year detail at NASA Johnson Space Center, supporting NASA's Exploration program, which was developing new launch vehicles and crew vehicles to replace the space shuttle and return astronauts to the Moon.

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Figure 107.—View of the Moon taken by Expedition 22 crew (iss022e017568).

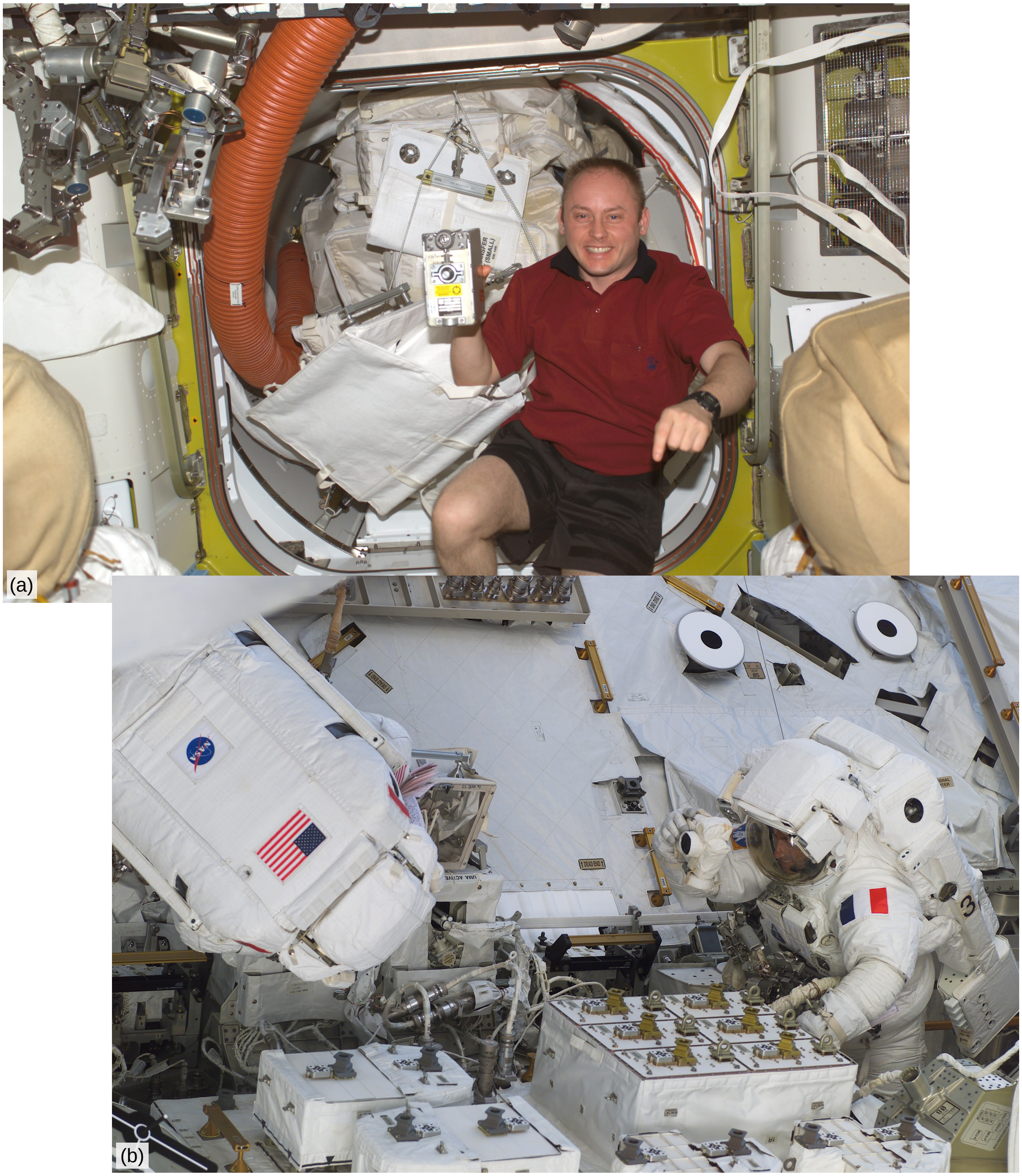

Figure 108.—(a) Astronaut Edward M. (Mike) Fincke, Expedition 9 NASA ISS science officer and flight engineer, holding a spare Remote Power Controller Module (RPCM), and then (b) during an EVA to replace a failed RPCM with the spare (iss009e10554 and S111E5183).

In the early 1980s, the System Power Analysis for Capability Evaluation (SPACE) computer code was developed by staff at the NASA Glenn Research Center to assess the performance capability of proposed power system designs for NASA's space station. As the space station program progressed from design to fabrication, the computer code grew in complexity. During the space station on-orbit assembly, SPACE was repeatedly used to assess the viability of key space shuttle assembly flights as well as to conduct special studies for unusual station operating conditions. Currently, the SPACE code is used to assess the station power system performance during the docking of visiting vehicles, such as SpaceX and Soyuz. SPACE has been modified to predict the performance of the Orion electrical power system, and Glenn's SPACE team is using this new version of the code to assess various Orion mission profiles. This report tells the story of the development and use of the SPACE computer code.

Front cover: The International Space Station (ISS) soars into a sunrise every 90 minutes, each and every day. This image, taken on July 20, 2018, shows one of four basketball-court-sized main solar arrays that power the space station, in contrast to the bright blue glow of Earth's limb in the background as the orbital complex flew over eastern China. Overlaid in green and blue are actual data from the SPACE code.