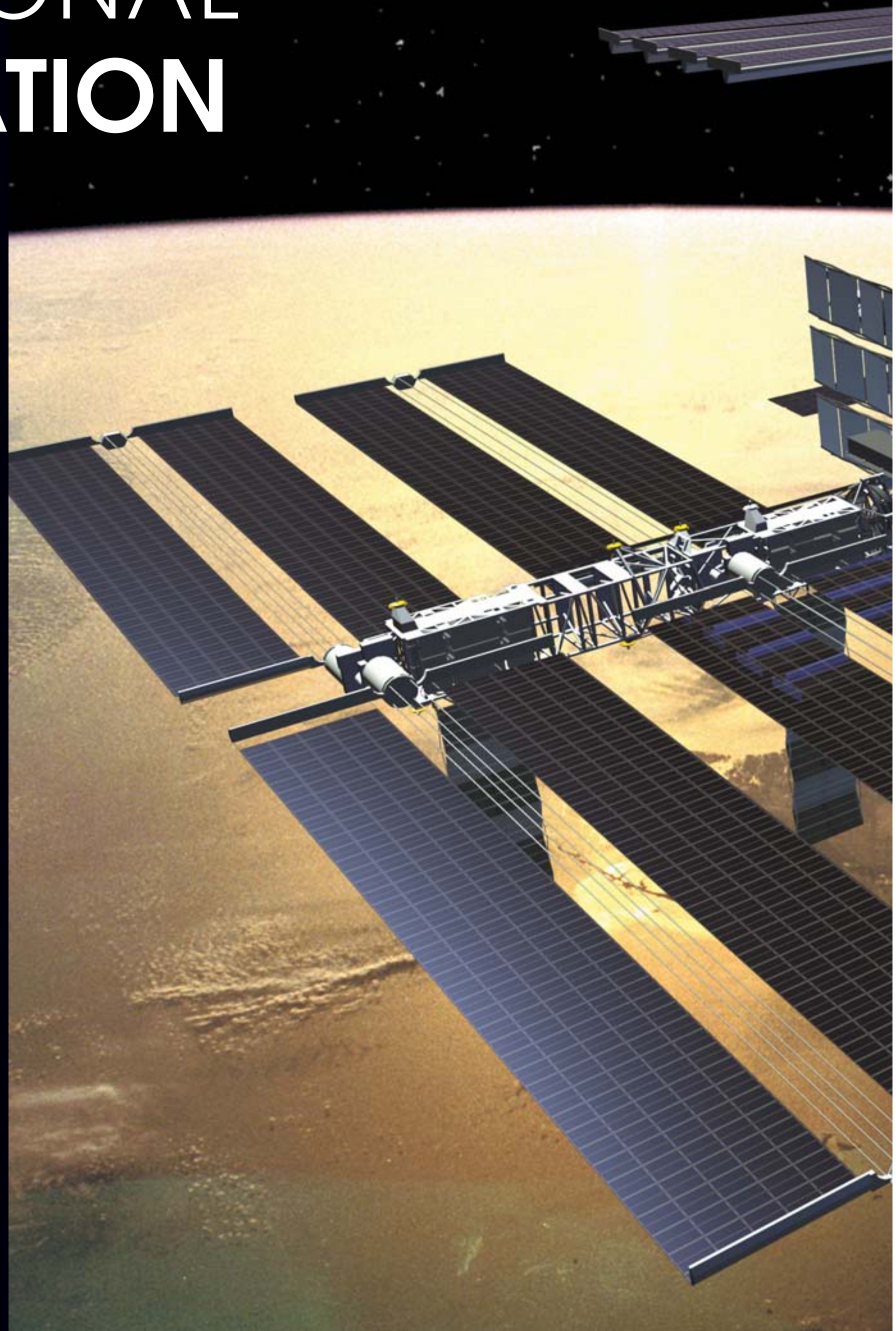
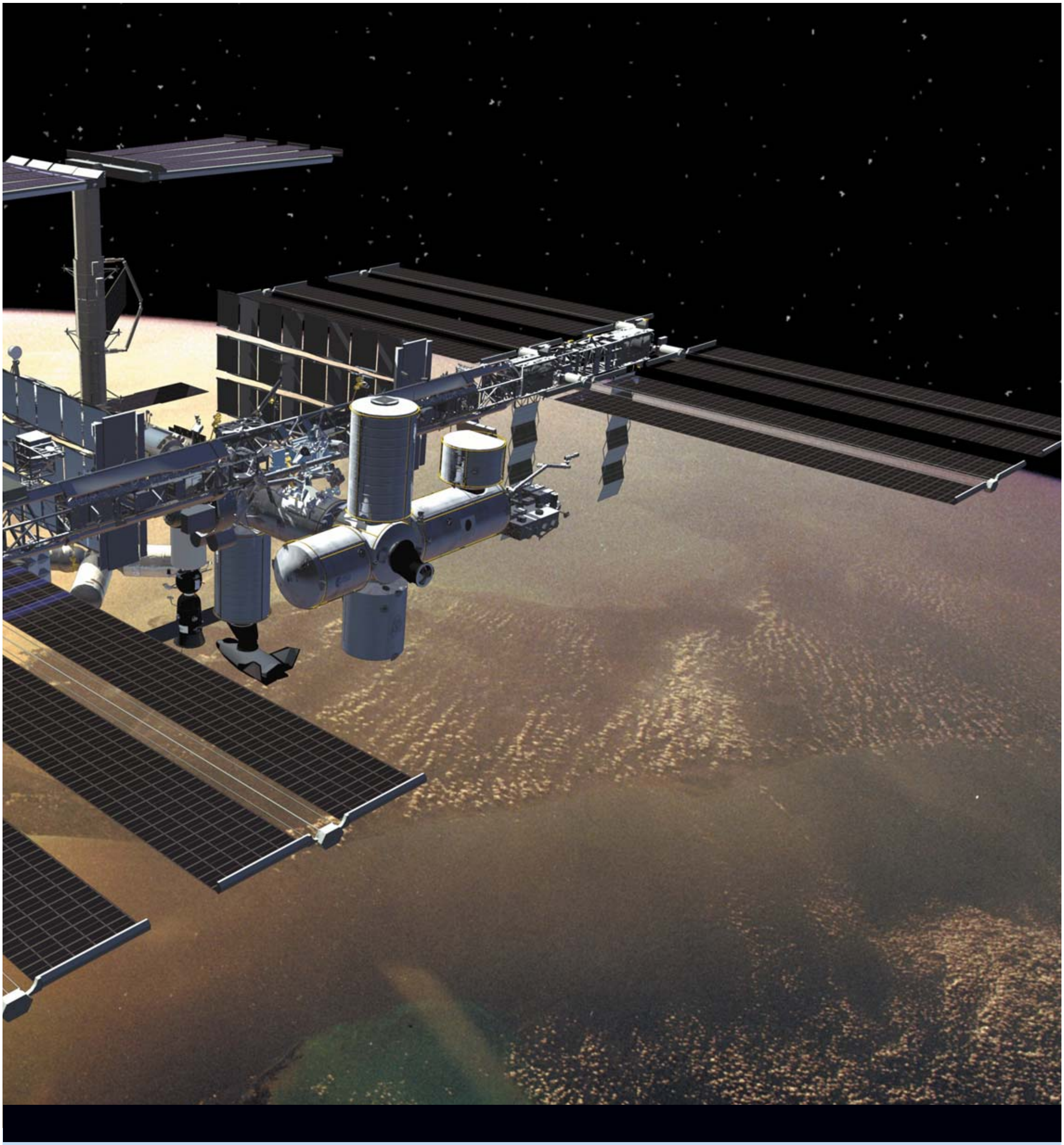
INTERNATIONAL **SPACE STATION**

The digital artist's concept shows the ISS after assembly is completed in 2006. The completed station will be powered by almost an acre of solar panels and have a mass of almost 1 million pounds. The pressurized volume of the station will be roughly equivalent to the space inside two jumbo jets. Station modules are being provided by the U.S., Russia, Europe and Japan. Canada is providing a mechanical arm and "Canada hand." In total, 16 countries are cooperating to provide a state-of-the-art complex of laboratories in the weightless environment of Earth's orbit.



Excitement brews at NASA as Atlantis and its five-member crew prepare to deliver the American-made Destiny module to the International Space Station (ISS). Destiny is the first laboratory module to be delivered to the orbiting platform and will mark the beginning of a 2001 space science odyssey for the space station and its Expedition One crew. In a recent press release, Space Shuttle Program Manager Ron Dittemore said, “The Space Shuttle will see the 20th anniversary of its first launch this spring, and it is a fitting celebration that the year ahead holds some of the most challenging and spectacular tasks the Shuttle has ever been assigned.”

Johnson Space Center is the lead NASA center for the ISS program, providing technical, financial and operational direction and oversight. NASA Glenn Research Center serves in a supporting role to Johnson Space Center, providing significant expertise in the area of electrical power (generation, storage, conversion and distribution).



Boeing is the prime contractor and complete system integrator for the ISS. The company provides all system design, development, and production of most US modules, as well as associated hardware and software. The international partners provide modules and hardware, but Boeing maintains the charter to integrate the entire vehicle, with an active role in the on-orbit operation of the station. We interviewed the team of Boeing engineers and managers responsible for leading the design of the largest power system ever constructed in space.

Space power design is a very special field of expertise. It provides a tough environment, severe restrictions on parts selection, weight constraints, cooling difficulties, and the need for very high reliability.

Reliability is paramount. In commercial power supplies, reliability is achieved after several cycles of manufacturing, failure, failure analysis, and design improvement. This is not an option is space power. Only a handful of units are built, and reliability must be on target from the outset.

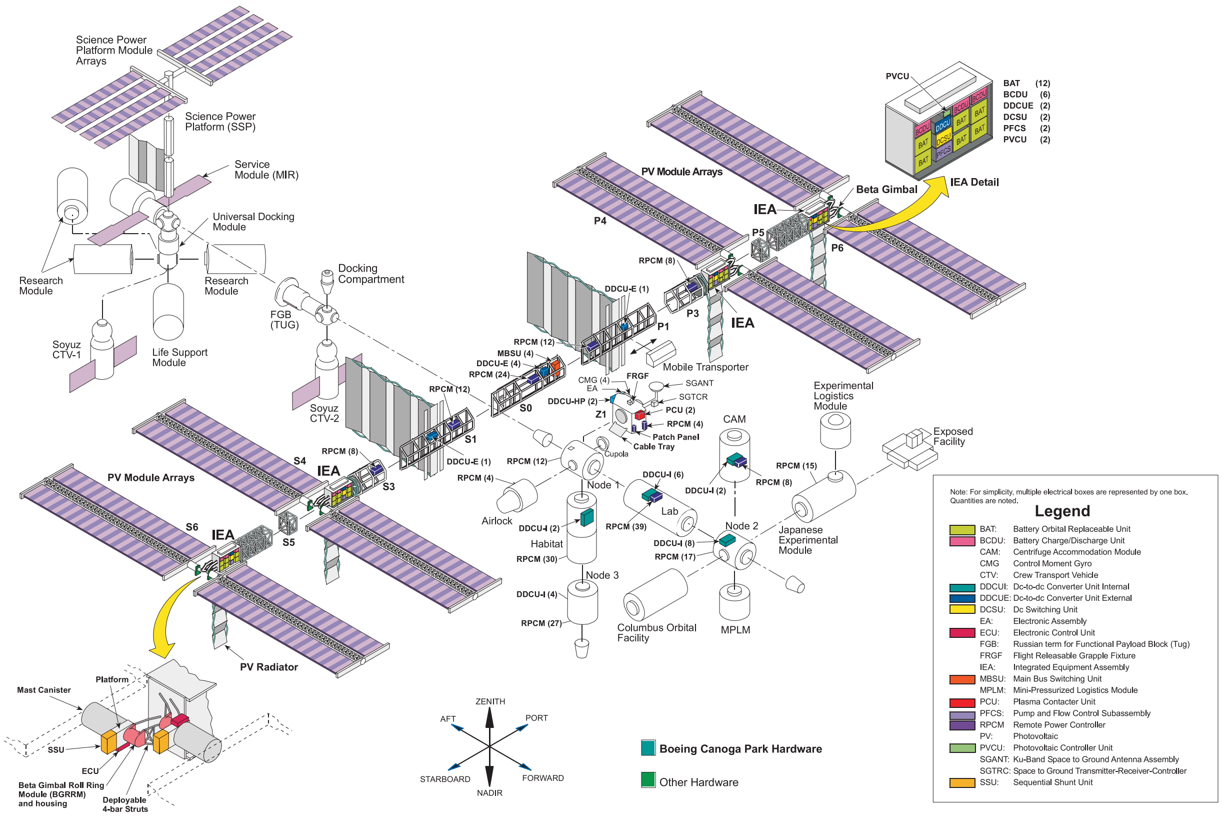


Figure 1. System diagram of the space station power system

Much of the space station structure is power related. *Figure 1* shows the block diagram of the electrical power system. The most important elements of this system are:

- Solar arrays
- Batteries
- Solar arrays preregulator (SSU)
- Bus switches and routers
- Battery chargers and dischargers (BCDU)
- DC-DC bus converters (DDCU)

Also shown in the system are interface converters between the different power systems on the ISS, and the downstream load converters provided for the various experiments and life support functions of the space station.

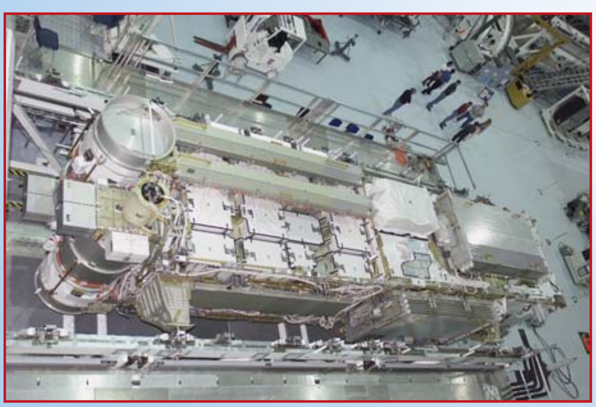


Figure 2. Power system module P6 preparing for loading

The total power requirement of the finished station will be about 110 kW. There are two separate power systems on the ISS– the Russian system, and the US system. The large solar arrays at the end of the space station (shown in illustration on previous page) are part of the US power system. The smaller arrays in the middle, perpendicular to these, are Russian.

The only available power in space is solar power. When the the solar arrays are in direct sunlight, the space station is in insolation mode and the batteries begin charging. When the space station is in the shadow of the earth, or eclipse mode, the batteries discharge.

The space station is positioned approximately 240 miles above the earth. The time of each orbit is roughly 90 minutes. Of this, typically 58 minutes are in sunlight and 32 minutes are in eclipse. This defines the needed overhead on the power generation requirements, and how much energy storage is necessary on the space station.

The U.S. solar arrays are launched and delivered exclusively by the shuttle, about a year apart. "Everything within is packaged like a Chinese fan," explains Chuck Clark, Technical Fellow, Electronics Design & Analysis at Boeing. "It expands and deploys from blanket boxes to about 240 feet

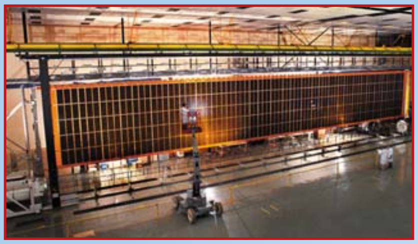


Figure 3: Solar array blanket with mast deployed.

from tip to tip." When the ISS is complete, four units will join together to form the main power and distribution system.

On November 30, 2000, the Integrated Truss Structure P6 (*Figure 2*) was launched. This hardware comprised the first US photovoltaic (PV) module, including solar arrays, batteries and other power system electronics. There are currently three astronauts on board– two Russian and one American. "The ISS will ultimately house a permanent crew of seven people," says Clark..

The next launch is Destiny, the US Lab Module, scheduled for early February 2001. It is the centerpiece of the ISS, where unprecedented science experiments will be performed in microgravity.

The entire space station will be delivered in 20-30 flights over the course of several years. The present shuttle launch plan calls for approximately eight flights per year with three or four of those dedicated to space station assembly and support. With four shuttles presently operating, this give four months to prepare and load after each flight. The total payload for each shuttle flight is approximately 40,000 lbs.

Each load requires years to package and prepare for launch. The packaged unit is transported to NASA Kennedy Space Center, FL, where it is thoroughly tested. The latest launch package was tested for over a year, powering up and implementing as much of the system as is possible on the ground. The only part of the system not fully tested was the solar panel unfolding system, as it is not possible in earth's gravity without damaging the array.

One of the arrays encountered a problem when deployed in space. "Mechanical oscillations in the structure caused some cables to displace from their pulleys on one of the arrays. An EVA (a space walk) was required to fix the problem– which was done with ease," says Dr. Ed Gholdston, Deputy EPS Subsystem Manager at Boeing.

Solar Arrays

The solar arrays, one of which is shown in *Figure 3*, have the capacity of 193 kW– depending on solar conditions and array age. Approximately half of this is used to charge the batteries. Panel life is about 15 years, and NASA anticipates replacement of the panels after seven years. The source of degradation of the panels is micrometeorites and radiation which eventually dull the coating and reduce the conversion efficiency. Solar cells are approximately 15% efficient, which means that 1300 kW of solar energy must impinge on the solar panels. Four hundred solar cells are connected in series to form a "string", providing an open-circuit voltage of up to 250 V, and a current source of about 2.6 A. In order to maximize the incident solar flux on the panels, two computer controlled rotary gimbals are used to continuously point the arrays at the sun during each orbit.

Sequential Switching Unit

The solar panels may provide more power than is needed by the power system. Power electronics circuitry in the sequential shunt unit (SSU) is used to either connect or short out strings on the solar array panels. Solar cells act as current sources, and MOSFET switches are provided directly across 400 stacked cells of the solar array to either short them, or allow them to feed the primary power bus. There are 82 strings of solar cells, each with MOSFET shunt switches. Most of them are either fully on or fully off, providing coarse regulation. One or sometimes more shunt units are PWM modulated at 20 kHz to fine tune the required current feeding the primary bus.

The choice of the shunt switching regulation was determined by the need for maximum efficiency at full power. Even when the load current is unswitched, and the heat dissipation in the SSU is very small for the power processed, requiring no active cooling.

The output of this part of the system is 126 – 173 VDC. This is a relatively large range for a solar generator, but is intended to accommodate the changing loads and deterioration of the solar panels over their full lifetime. This voltage determines the range of operation of the subsequent DC-DC converters that process the main power of the ISS.

Figure 4 shows the final SSU flight hardware developed for the ISS by engineers at Loral. Shown is a 36 kW unit, weighing 186 lbs. Fault protection, EMI filtering, and monitoring are incorporated in this unit.

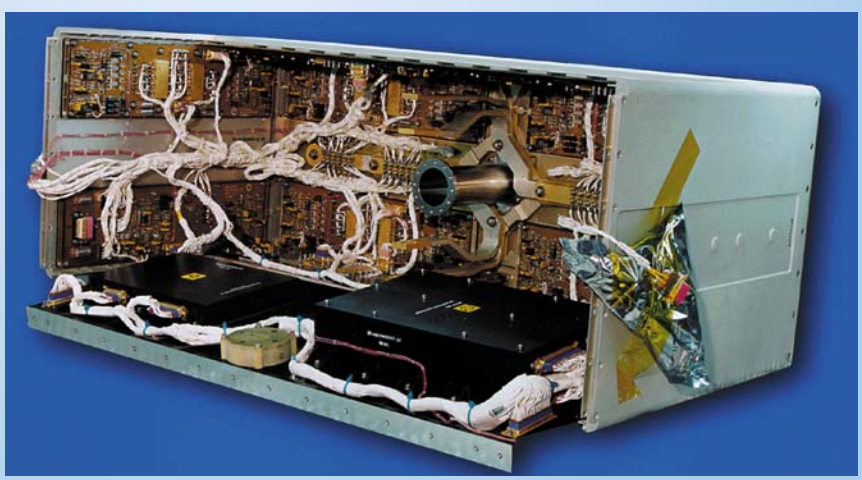


Figure 4. Sequential Shunt Unit (SSU)

The package enclosure shows the ruggedness and simplicity of the exterior of this power system building block. A major requirement of the design of the space station is that it must be easy to put together, service if necessary, and be mechanically extremely rugged.

Battery Charge and Discharge Units

For the lightest weight, Ni-H_2 batteries are used, pressurized inside each cell. During eclipse mode, the batteries are discharged by 34%, leaving plenty of reserve power. The batteries consist of two units in series, each with 38 cells, for a total storage capacity of 189 kWh. The battery voltage ranges from 70 to 125 V, depending on the state of charge and current flow into or out of the batteries.

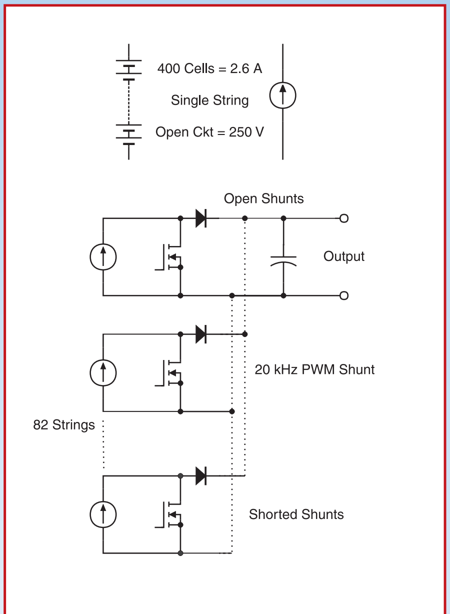


Figure 5 . SSU Schematic

The battery charge and discharge unit (BCDU), shown in *Figure 6*, is a bi-directional converter. It runs as a buck converter from the bus into the battery, and as a boost converter from the battery to the bus. There are some unique challenges with such converters. The magnetics components are halved since they are used in both directions– a major advantage. The switching must be bi-directional and able to carry current both ways.

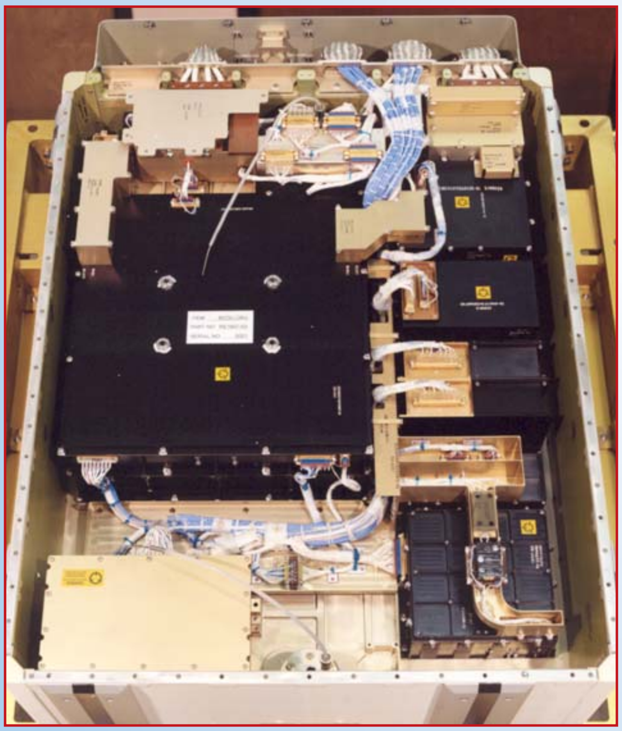


Figure 6. Battery Charge Discharge Unit (BCDU) Hardware

The control loop design itself is a fascinating challenge. It's a single converter, with the same input and output voltages. Depending on the direction of the current, it can take on the characteristics of either a buck or boost converter. compensation of the control loops, a topic beyond the scope of this article, is another exciting challenge.

The buck converter charger operates at up to 8.4 kW with an efficiency of approximately 90%. The boost converter (or, in this case, the same buck converter running with negative current) operates at 6.6 kW. The total packaged unit weighs 235 lbs. This seems heavy for the power level of a flight-ready unit, but hold your opinions until after the section on special test requirements of these converters.

Power Distribution Bus

The main Russian power distribution bus is 28 V as compared to the 124 V for the US power distribution bus. Russia's participation in the space program was crucial because of both their technical expertise and experience in space, as well as the political contribution of the joint program. To stay on schedule, it was necessary to operate the Russian system at their existing 28 V hardware, which had a long history of development and deployment. The US system was able to select a more optimal, higher, DC voltage since their designs were newly built. DC-DC converters are used to interface between the US power system and the Russian power system.

Until around 1988, NASA investigated the concept of an AC power system at 20 kHz, 440 VAC. They hoped that the high voltage system would minimize the amount of copper needed in the distribution system, and that the AC distribution would offer the same kinds of advantages as AC distribution on ground-based utility grids. End users could simply hook a transformer to the bus and step down without further switching devices. The high frequency would minimize the size of the step down transformers.

The system seemed attractive at first glance, but was abandoned after much research. Reasons for this include technical issues with the inverters, rectification processes, and loads generating harmonics on the line. The deciding factor was the driving need of the science experiments. The distribution bus had to be quiet, and this would have been very difficult with an AC system.

High voltage was a good idea in terms of the power distribution, and there is a penalty for the final choice of the lower voltage. The present system uses 1/0 cables, each supply generates an output of 50 A or so at 124.5V. A lot of copper weight is used, counter to the goals of the space station. 124 V was a compromise voltage, taking into consideration the problem of corona on the insulation of the distribution bus. At

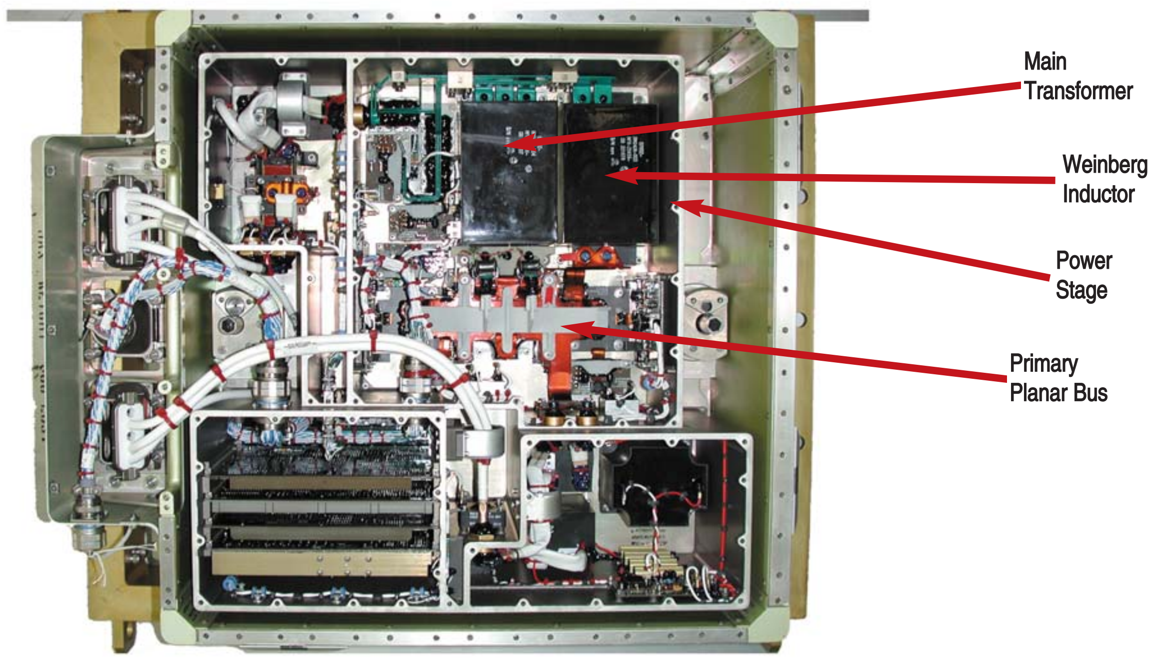


Figure 7. DC to DC Converter Unit (DDCU)

higher voltages, capacitors would also be a problem and series MLC capacitors would have to be used for derating purposes.

Switching big DC currents was a sizeable challenge for the engineers, as was the management of power system transients, which must be very carefully controlled. DCSU and MBSU units are routing switches. Seemingly trivial, just steering DC currents and connecting and disconnecting them can be frustrating. (The IBM power system in Issue 1 of switching power magazine also learned this the hard way. Interrupting large DC currents is not an easy task.)

DC Bus Regulators

The DC converters (DDCUs), shown in *Figure 7*, are used to regulate the final US power distribution bus to 124.5 +/-1.5 VDC. Improved Weinberg converters are used, operating at 40 kHz, with an 80 kHz output ripple. An improved Weinberg schematic is shown in *Figure 8*. The choice of the Weinberg converter is unusual. Its improved immunity to a single power switch failure was an influential factor. This does not create an instantaneous hard short across its input if the main power switches are shorted. The current-driven Weinberg topology has the inductor on the primary side, and this gives time for auxiliary protection mechanisms to disconnect a failed converter. Over 35-40 of these will eventually be used, and the first four are already in orbit. The DDCU peak efficiency is 95%. While this is impressive, it still translates into 300 W of heat to be removed from each converter at full load.

Space Power Components

No electrolytic capacitors are allowed in space applications. Evaporation of electrolyte is the main failure mechanism of electrolytics. Tantalums are still a contentious issue for space use. Sometimes they are acceptable, but using solid tantalum only, seriously derated. Tantalums fail as a short, typically a destructive mode for the rest of the system. A single shorted tantalum out of a bank of many creates a fire hazard, and may still draw enough current when the power supply controller goes into protection mode to be hazardous. Some space customers require each tantalum capacitor to be in series with a resistor for protection.

Multilayer ceramics are the capacitors of choice for these space power supplies. They are available as standard parts up to 200 V, and for custom designs 300 V. Above this voltage, devices must be used in series, and some method must be used to balance the voltage on series capacitors. Space standards typically require 50% derating, or higher. Four-leaded devices are used. The main problem is in packaging– high impedance connection faults can sometimes cause excessive heating, hence the need for extensive testing.

Efficiency is crucial on the space station, due to the large weight penalty of cooling structures. For this reason, far

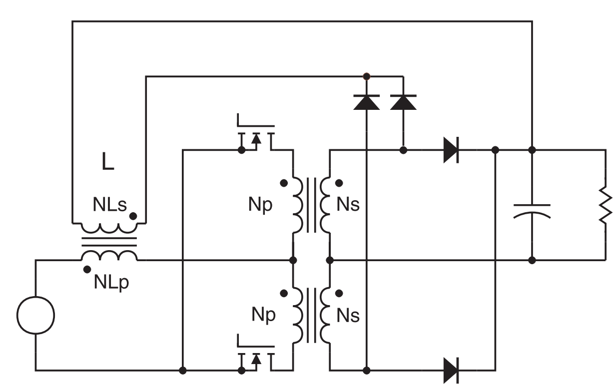


Figure 8. Improved Weinberg Schematic

more silicon is used for the converters that would ever be contemplated for earth-bound systems. They would be simply too expensive for any but the most esoteric applications. The main power MOSFETs are referred to affectionately at Boeing as “MOOSE-FETS”.

Relatively low switching frequencies are used for the same reason. Heatsink weight is substantial. The size of the converter elements must be balanced to offset the amount of cooling needed to remove excess heat from switching loss. Despite the large size of the MOSFETs, they are turned on extremely fast, with gate rise times of 0.6 V/ns achieved with very low impedance drivers and stripline technology.

The temperature of the semiconductors can be extreme, ranging from –55 degrees to 125 degrees C. This puts stringent requirements on the ruggedness of the packaging. Silicon die are easily able to operate over this temperature range, but problems are usually encountered with the mechanical stress imposed by the packaging technology.

It is often difficult for commercial designers to appreciate the reason for the high cost of the Class S components needed for space power. Harris Semiconductor (now Intersil) worked closely with NASA during this program to develop special devices and packages suitable for the application. Every space program company faces this type of issue. Special hermetic packages are required for space, and these can easily cost $1000 for a single power FET package.

Magnetics are similarly expensive. A price point from $3,000-4,000 per magnetic is not uncommon, or unreasonable for the amount of testing and documentation that is required for space power. Accelerated life testing is done on the flight components to get them past infant mortality, and x-rays are used to assure proper construction of the finished components.

A large portion of the cost of parts is the exhaustive documentation and tracking needed to ensure high quality. The finished parts may not look so very different from commercial parts, but they are guaranteed to be far more reliable and rugged.

Space Power Cooling

Ultimately, all heat generated on the space station must be sent out into space as radiation. The space station illustration on page 8 shows radiative panels attached to each PV module pointing downwards. These are used exclusively to cool the power system, which is a daunting task when there is no air.

Some of the converters are mounted externally to the space station, and interface directly to radiators which remove the heat. Others are internal to the space station, and can use heat pipes for transferring the excess heat to the external radiators.

Surprising effects can impact the efficiency of the radiative cooling. Cloud cover on earth can have a big impact on how well the radiators work. Dense cover can change the amount of reflected sunlight coming from earth, increasing the power from the solar arrays, and thus heating the radiative coolers.

Two of the externally located converters (DDCU-HPs) have integral heat-pipe radiators attached to their baseplate. By means of this two-phased passive system, waste heat is directly sent to space. All other externally mounted converters (DDCU-Es) are cooled by an active thermal control system as part of the PV element. Inside the pressurized volumes the internal converters (DDCU-Is) attach to a coldplate, part of a second, but water-based, active cooling system.

Efficiency, or thermal impedance of the radiators is quite different from what we are used to as commercial designers with air around. The effectiveness of a radiator depends on its temperature (radiation goes by temperature to the 4th power) and the temperature and type of surface of the environment to which it is radiating. For the typical space station deployment, engineers count on about 100 W of effective heat removal per square meter of radiator.

Unique Design Requirements

When we asked what the most difficult challenge was in the ISS project, the room echoed in unison with the response “packaging”. Electrical engineering challenges were a good part of the difficulty encountered, but every facet of the project was wracked with packaging problems to solve. Surviving shock, high g-forces, controlling parasitics, making units easy to hook up reliably, and packing into a flight-ready container are truly marvelous feats of engineering that were achieved.

Fitch R. Williams, Associate Technical Fellow, Electrical Systems, Boeing, summarized the philosophy of the power system: “It goes into space and doesn’t come back. The goal is to be so reliable that it isn’t of concern to the users,”

The 6.25 kW DDCU will actually run at 160% power indefinitely, as long as adequate cooling is provided. Full isolation and protection is provided in the design. The units are subjected to what is referred to internally as “MOAT” testing– the mother of all tests.”

Commercial designers would do well to take some notes from these tests and learn about pushing the envelope of a converter to identify sources of obscure failures.

The output of the 6.25 kW can be hard-shorted repeatedly, with no ill effects. As soon as the short is removed, the converter restores its output voltage as if nothing happened. And during this test, the input impedance specification of the converter is still met. It must operate from 30 W to 9,000 W with fully predictable operation. All converters must look alike under all conditions and must match performance– down to the waveforms across snubber components. These are severe tests that would cause failure in most commercial power supplies.

Worst case analysis is essential, and a very time consuming and costly part of the development program. Plenty of margin in the design is a key lesson learned. For almost all parts of the system, this margin was constantly eroded by increasing power needs. The thermal design margins were severely tested as well, as the space station design requirements evolved.

Power Supply Impedance Specs

Impedance interactions are a big part of the converter designs. All designers deal with the issue of converter output impedance, either as a direct specification of a maximum allowed value, or indirectly as a step load requirement. The ISS goes beyond this, and imposes an input impedance specification on each load converter. The intent is to ensure, as the space station system grows, that converters do not overload the system in a small-signal sense, and create stability issues for the upstream bus converters.

The effect of this on the power supply designer is to restrict the design of the input filter components used in the converter. Typically, we use more capacitive than inductive elements in power supply design. If you do that for the ISS loads, the input capacitance will load the upstream converters to the extent that the control loops will interact with each other, and possibly cause instability. To avoid this, the input impedance of the converters is intentionally raised using more inductive filters, which poses a challenging task for the designers.

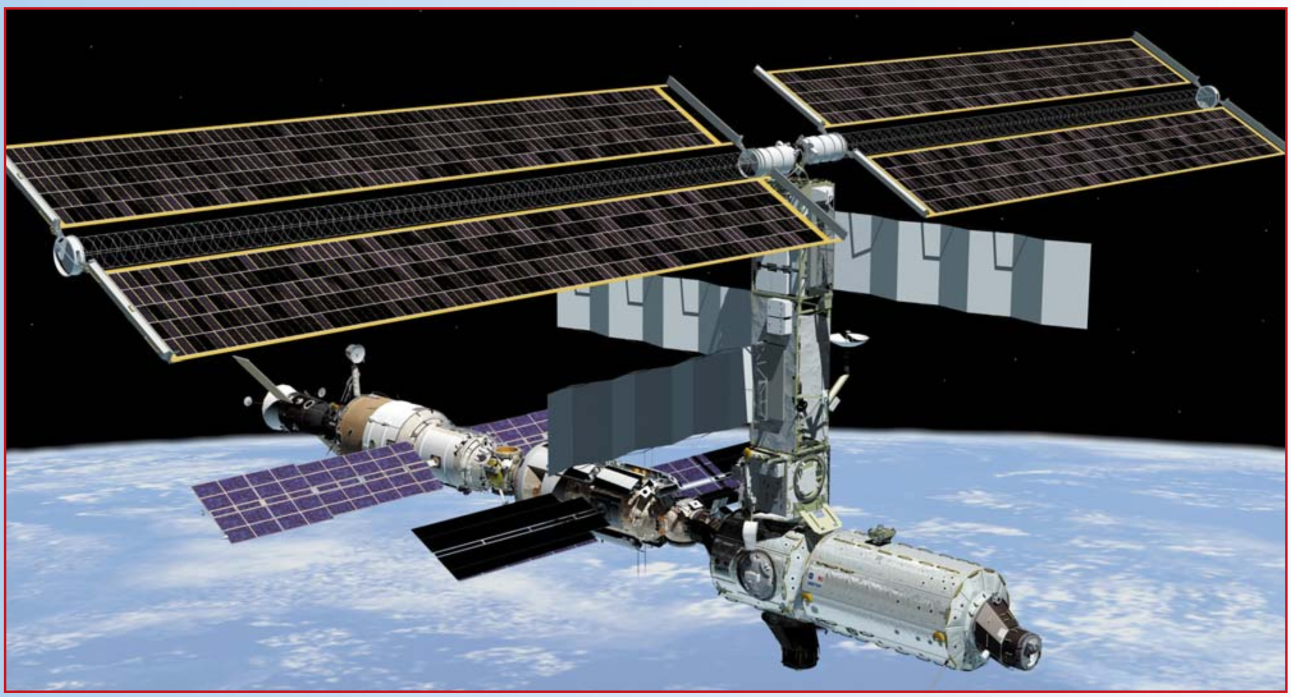
The Design Team Contribution

Despite the rigid requirements– seemingly impossible at times– the Boeing team executed successful designs. It's a very emotional and satisfying finale to see a project of this magnitude launch into space and come on line. And it is more than just an engineering project when it contributes to furthering human knowledge, international cooperation and world peace.

"NASA talked to us recently about the contribution we were making to world peace," says Dr. Gholdston. "We have worked shoulder-to-shoulder with scientists from Russia, Europe and other International Partners and forged friendships with amazing long-term consequences."

Development of this type of power system has a major impact on every individual involved. Fitch Williams, Associate Technical Fellow, Electrical Systems at Boeing, describes his experience with the design from concept to launch, "Ed Gholdston and I were involved in the space station many years ago when it was just a dream. I have to admit that when they finally launched the two DDCUs, I cried." Ed Gholdston added, "The people involved in this took daunting design challenges with overwhelming enthusiasm and really enjoyed it. It's a thrill to see it go."

We would like to thank the team of people responsible for their cooperation and time involved in this feature:
Dr. Ed Gholdston, Deputy EPS Subsystem Manager, Boeing **Fitch R. Williams**, Associate Technical Fellow, Electrical Systems, Boeing; **Chuck Clark**, Technical Fellow, Electronics Design & Analysis, Boeing; **Joel Bruemmer**, DDCU Tech Lead, EPS Electrical Engineer, Boeing; **Donald L. Bartosch**, Development Electronic Technician, Boeing; **Rob Wilde, Sr.** Power Systems Engineer, Boeing; **Ken Whalen**, Sr. Power Systems Engineer, Boeing; **Greg Schmitz**, Acting Deputy EPS System Manager, NASA Glenn Research Center; **Bruce Manners**, Chief of Analysis and Management Branch, NASA Glenn Research Center; **Dan Beck**, Media Relations Manager, Boeing; **Stacy L. Koller**, ISS Program Support, Boeing; **Chris A. Weimer**, EPS Support, Boeing



Artist's rendering in January 2001 of the International Space Station (ISS) following the undocking of the Space Shuttle Atlantis, representing the completion of 5A. Note new position of U.S. Laboratory Destiny.