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Space Exploration

***Discovery* to Transport Last U.S., Boeing-built Starboard Truss Segment to Space Station**



In the Space Station Processing Facility at NASA's Kennedy Space Center, Boeing workers stand ready as the starboard integrated truss, known as S6, is rotated in order to remove and replace lower deck batteries.

The delivery of the International Space Station's (ISS) final, major U.S. and Boeing-built truss segment, Starboard 6 (S6), by Space Shuttle *Discovery* during the STS-119 mission will not only signal the station's readiness to house a six-member crew for conducting increased science activities on-orbit but will also be another great example of American ingenuity. With its two Solar Array Wings (SAWs) for converting solar energy into electrical power and a radiator for

rejecting heat away from electrical components, the S6 is the final truss element and completes the station's 11-segment integrated truss structure (ITS). Also called a Photovoltaic Module (PVM) because of its ability to generate, store and distribute electrical power to the station, the Starboard 6 segment will ensure the outpost is powered to its intended maximum potential.

A unique feature about the segment is that it will carry two spare Battery Charge/Discharge Units (BCDUs) used for controlling the charge and discharge of spare batteries on the outpost. The S6 segment was modified to carry the additional payload of the BCDUs, attached the segment's Long Spacer Truss structure, to increase the amount of payload equipment that can be transported to the space station during shuttle missions.

The ISS solar arrays are the largest deployable space assemblies ever built and the most powerful electricity-producing arrays in orbit. Until deployed following on-orbit installation, each SAW remains folded in a special canister called a Solar Array Assembly (SAA) that is located at the end of S6 element. In the canister, each wing is equipped with an expandable mast. Two solar array blanket boxes, containing a total of

32,800 solar cells, are connected to the ends of each canister and are restrained to the element frame for launch. The addition of S6 brings the station's total SAWs to eight. Each wing is 115 by 38-feet wide and, when all eight are fully deployed, will encompass an area of 32,528 square feet, minus the masts.

The 310-foot integrated truss structure that the S6 will be attached to forms the backbone of the space station with mountings for unpressurized logistics carriers, radiators, solar arrays, and the various elements. The 45-foot-long skeletal S6 edifice is *Discovery's* primary payload and began as an operations test

item for its twin sister, the Port 6 Truss Segment that was launched during Space Shuttle *Endeavour's* STS-97 on Nov. 30, 2000. The starboard element was delivered to Kennedy Space Center in Florida on Dec. 17, 2002.

The space station is the greatest construction project of humankind, and as the prime contractor for the ISS, Boeing designed the S6 and worked with major subcontractors Lockheed Martin, Honeywell, Space Systems/Loral, and Hamilton Sundstrand to build it. Pratt and Whitney Rocketdyne (which was a part of Boeing at the time) provided most of the electrical power system components.

Middeck Payload

In addition to S6, Space Shuttle *Discovery* will carry in its middeck several insulating sleeves to protect some ungrounded connectors already on-orbit, Crew Health Care System (CHeCS) hardware items and Crew

provisioning items, Environmental Control and Life Support System (ECLSS) hardware items for coolant sampling and water recovery, special Extravehicular Activity (EVA) tools to support assembly operations, and other resupply hardware.

Also, hardware for two experiments will be

carried in the middeck:

- 1). The Middeck powered General Laboratory Active Cryogenic and ISS Experiment Refrigeration (GLACIER), GLACIER ISS Utilization Payload, will be swapped with a similar GLACIER being returned from the ISS. GLACIER GLACIER is a double locker cryogenic freezer for transporting and preserving science experiments that will remain on-

S6 Specifications	
Dimensions:	Width: 16.3 feet; 195.48 inches Length: 45.4 feet; 545.16 inches Height: 14.7 feet; 176.54 inches
On-Orbit Weight:	31,060 lbs
Cost	\$297,918,471

orbit at the end of the mission. The freezer provides thermal control between +4° Celsius and -160° Celsius and can operate in both the space shuttle's Middeck and the EXPRESS Rack on-orbit.

2). The Middeck powered Protein Crystallization Diagnostic Facility – Processing Unit (PCDF-PU) is being flown up as an insert in an ISS locker. During docked ops, the PCDF-PU insert will be transferred to the ISS; for return, the remaining locker shell will be used for stowage of non-powered return items. PCDF-PU is a multi-user facility for the investigation of protein crystal growth and other biological macromolecules under microgravity.

Integrated Truss Segments and Payload Structure

The integrated truss segments started with Starboard zero (S0) as the center assignment and were numbered in ascending order outward to the port (P) and starboard (S) sides. Starboard is the right side and port is the left side of the truss structure. Zenith (Z) and is up, when the station is flying in its normal direction, in its normal orientation. At one time, there was an S2 and a P2 planned, but they were eliminated when the station design was scaled back. From S0, the truss segments are P1, P3, P4, P5 and P6 and S1, S3, S4, S5 and S6. P6 is attached to P5, and once on-orbit S6 will be attached to S5. The S6 primary structure is made of a hexagonal-shaped aluminum structure and includes four bulkheads and six longerons, which are beams that connect the bulkheads.

During the STS-119 mission, S6 will be removed from the payload bay with the Space Station Remote Manipulator System (SSRMS or station arm) because the shuttle's arm is unable to remove the element with the current

configuration of the ISS. The S6 element will then be handed to the Shuttle Remote Manipulator System (SRMS or shuttle arm) and maneuvered to another location while the SSRMS changes base points. The S6 will then be handed back to the SSRMS and then maneuvered to an overnight park position. The act of removing the element from the payload bay and maneuvering to an overnight park position takes an entire day. The following day the element will be installed during a planned spacewalk. Once the final truss segment is attached, S6 will support power generation and energy storage, utility routing, power distribution and spare Orbital Replacement Unit (ORU) storage.

Major Subsystems

Major subsystems of the S6 truss are the starboard outboard Photovoltaic Module (PVM), the Photovoltaic Radiator (PVR), the Long Spacer Truss (LST) and the Modified Rocketdyne Truss Attachment System (MRTAS). The S6 PVM includes all equipment outboard of Segment S5, namely the two Photovoltaic Array Assemblies (PVAAs) and the Integrated Equipment Assembly (IEA). The PVR provides thermal cooling for the IEA. The MRTAS is used to provide a structural interface to the S5 truss element. Each PVAA consists of a SAW and Beta Gimbal Assembly (BGA).

Major Elements

Photovoltaic Module (PVMs)

S6 will be the fourth and final of the four PVMs that convert sunlight to electricity on orbit. The primary functions of the power module are to collect, convert, store, and distribute electrical power to loads within the segment and to other station segments. Electrical power is the most critical resource for the station because it allows astronauts to live comfortably, safely operate the station and perform complex scientific

experiments. Since the only readily available source of energy for spacecraft is sunlight, technologies were developed



to efficiently convert solar energy to electrical power.

The PVMs use large numbers of solar cells assembled onto solar arrays to produce high power levels. NASA and Lockheed Martin developed a method of mounting the solar arrays on a "blanket" that can be folded like an accordion for delivery to space and then deployed to their full size once in orbit. The cells are made from purified crystal ingots of silicon that directly convert light to electricity for immediate use through a process called photovoltaics.

Gimbals are used to rotate the arrays so that they face the sun to provide maximum power to the space station. After the conversion process, the PVMs

also use the electricity to recharge onboard batteries for continuous sources of electricity while the station is in the Earth's shadow. Once complete, the station power system, consisting of U.S. and Russian hardware and four photovoltaic modules, will use between 80 - 100 kilowatts of power or about as much as 42 average houses (defined as 2,800-square-foot of floor space using 2 kilowatts each). Some of the electricity is needed to operate space station systems, but once that is figured in, the addition of the S6 will nearly double the amount of power available to perform scientific experiments on the station -- from 15 kilowatts to 30 kilowatts.

PVM components were assembled by The Boeing Company in Tulsa, Okla., and Lockheed Martin in Sunnyvale, Calif., before final assembly and testing by Boeing at Kennedy Space Center, Fla.

Solar Array Wings (SAW)

There are two SAWs on the S6 module, each deployed in the opposite direction of the other. Each SAW is made up of two solar blankets mounted to a common mast. Before deployment, each panel is folded accordion style into a Solar Array Blanket Box (SABB) measuring 20 inches high and 15 feet in length. Each blanket is only about 20 inches thick while in this stored position. The mast consists of interlocking battens that are stowed for launch inside a Mast Canister Assembly (MCA).

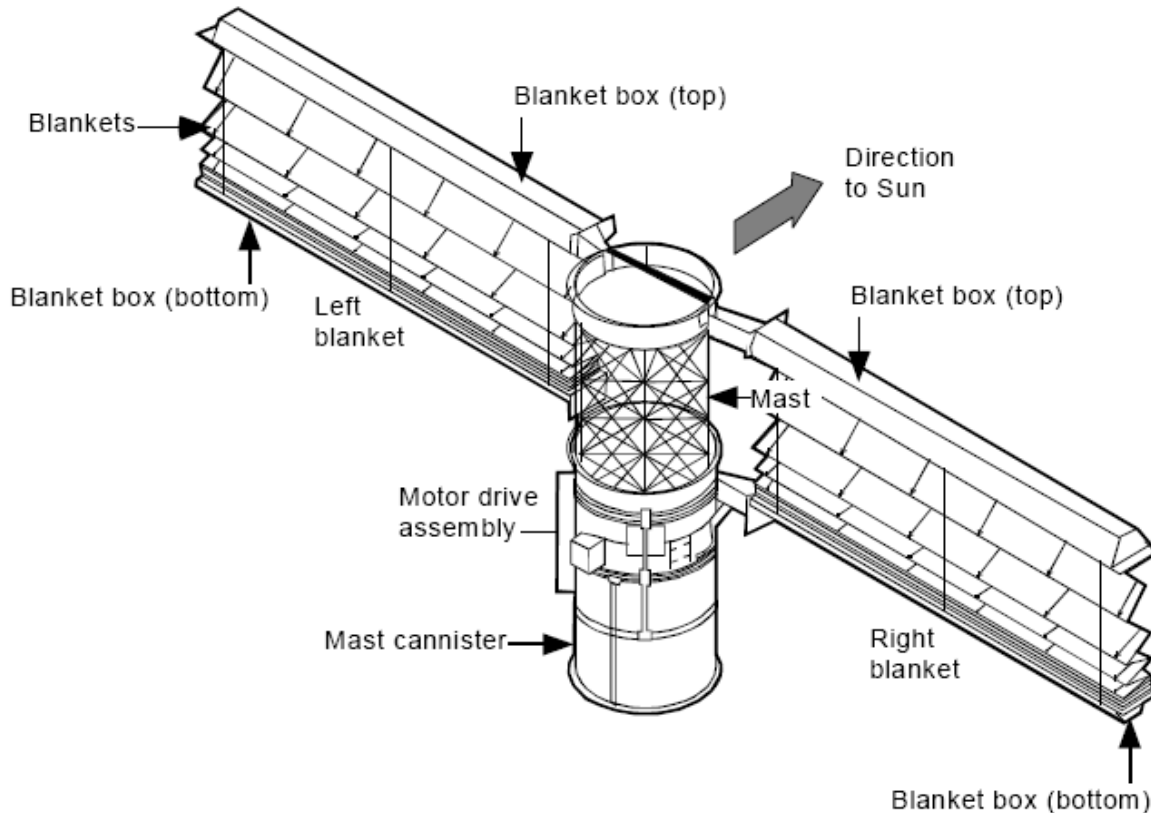
When deployed by the astronauts, the SAW unfolds like an erector set. Like a human torso, it has two arms when mounted on S6, and they are rotated outwards by astronauts during a spacewalk so they can be fully deployed. Because these blankets were stored for such a long time, extensive testing was conducted to ensure they would unfold

properly in orbit so the blankets would not stick together.

power per PVM with a total of four PVMs on the station.

When fully deployed, the SAW extends

The solar arrays produce more power



115 feet and spans 38 feet across and extends to each side of the Integrated Equipment Assembly. Since the second SAW is deployed in the opposite direction, the total wing span is more than 240 feet.

Each SAW weighs more than 2,400 pounds and uses 32,800 solar array cells, each measuring 8 centimeters square with 4,100 diodes. The individual cells were made by Boeing's Spectrolab and Aviation Systems Engineering Co. There are 400 solar array cells to a string and there are 82 strings per wing. Each SAW is capable of generating 32.8 kilowatts, or about 10.5 to 15 kilowatts of usable power. There are two SAWs on the S6 module capable of delivering a combined 21 to 30 kilowatts of usable

than can be made available to the station's systems and experiments. Because all or part of the solar arrays are eclipsed by the Earth or station structure at times, batteries are used to store electricity for use during those periods. About 60 percent of the electricity generated is used to recharge the batteries. During long eclipse periods, power availability is limited to about 10.5 kilowatts from each SAW, or 30 kilowatts per PVM. During shorter eclipse periods more power is available to station systems and experiments. Circuit breakers also regulate the flow of electricity to prevent overheating of the Utility Transfer Assembly (UTA) that allows power to flow through the rotating SARJ.

Space Station Power

	Current (3 PVMs)	Starboard 6	Total (Post STS-119)
Power Generation Capability	198 kilowatts	66 kilowatts	264 kilowatts
Usable Power Capability*	63-90 kilowatts	21-30 kilowatts	84-120 kilowatts
Power for Science**	15 kilowatts	15 kilowatts	30 kilowatts

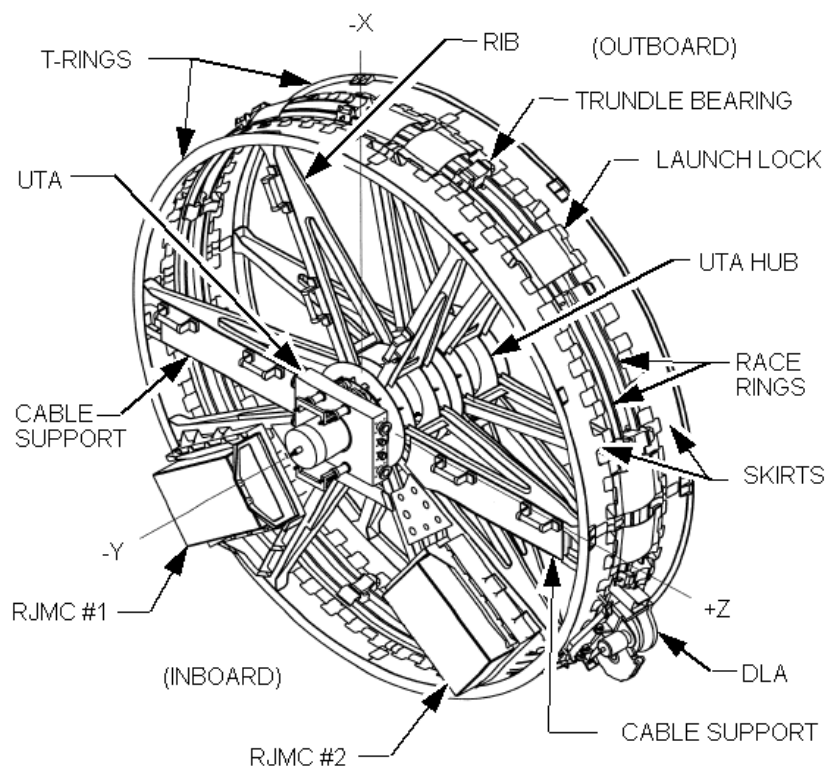
* The amount of usable power varies depending on the time of year and the orientation of the station relative to the Earth and sun.

** A greater fraction of power from the first three photovoltaic modules (PVMs) currently installed is needed to support day-to-day station systems operation.

Solar Alpha Rotary Joint (SARJ)

When the S6 truss becomes attached to the S5 short spacer, S6 will be positioned by the starboard SARJ, which, when fully operational, will continuously rotate to keep the solar array wings on S4 and S6 oriented toward the sun as the station orbits the Earth. Located between S3 and S4, the starboard SARJ is a 10.5-foot diameter rotary joint designed to track the sun in the alpha axis that turns the entire S4/S5/S6 module assembly. The starboard SARJ race ring has been damaged from inadequate lubrication from the gold rollers on the Trundle Bearing

Assemblies that attach to the ring. The race ring has a triangular cross-section that 12 TBA bearings roll on. As a result of cleaning and lubrication, the starboard SARJ can perform automated continuous tracking mode when needed. Extensive simulated wear testing of the race ring with lubricant is now being performed to determine further actions, if



required. The SARJ weighs approximately 2,500 pounds. The SARJ can spin 360 degrees using bearing assemblies and a servo control system to turn. All of the power flows through the Utility Transfer Assembly (UTA) in the SARJ. Roll ring assemblies allow transmission of data and power across the rotating interface so it never has to

unwind. Under contract to Boeing, the SARJ was designed, built and tested by Lockheed Martin in Sunnyvale, Calif.

Beta Gimbal Assembly (BGA)

The solar array wings also are oriented by the BGA, which can change the pitch of the wings by spinning the solar array. The BGA measures 3 x 3 x 3 feet and provides a structural link to the Integrated Equipment Assembly (IEA.) The BGA's most visual functions are to deploy and retract the SAW and rotate it about its longitudinal axis. The BGA consists of three major components: the Bearing, Motor and Roll Ring Module (BMRRM), the Electronics Control Unit (ECU) and the Beta Gimbal Transition Structure, mounted on the BGA Platform. The BGA was designed by Boeing Rocketdyne in Canoga Park, Calif., which has since been acquired by Pratt and Whitney. The Sequential Shunt Unit (SSU) that serves to manage and distribute the power generated from the arrays and is also mounted on each BGA platform. The SSU was designed and manufactured by Space Systems/Loral.

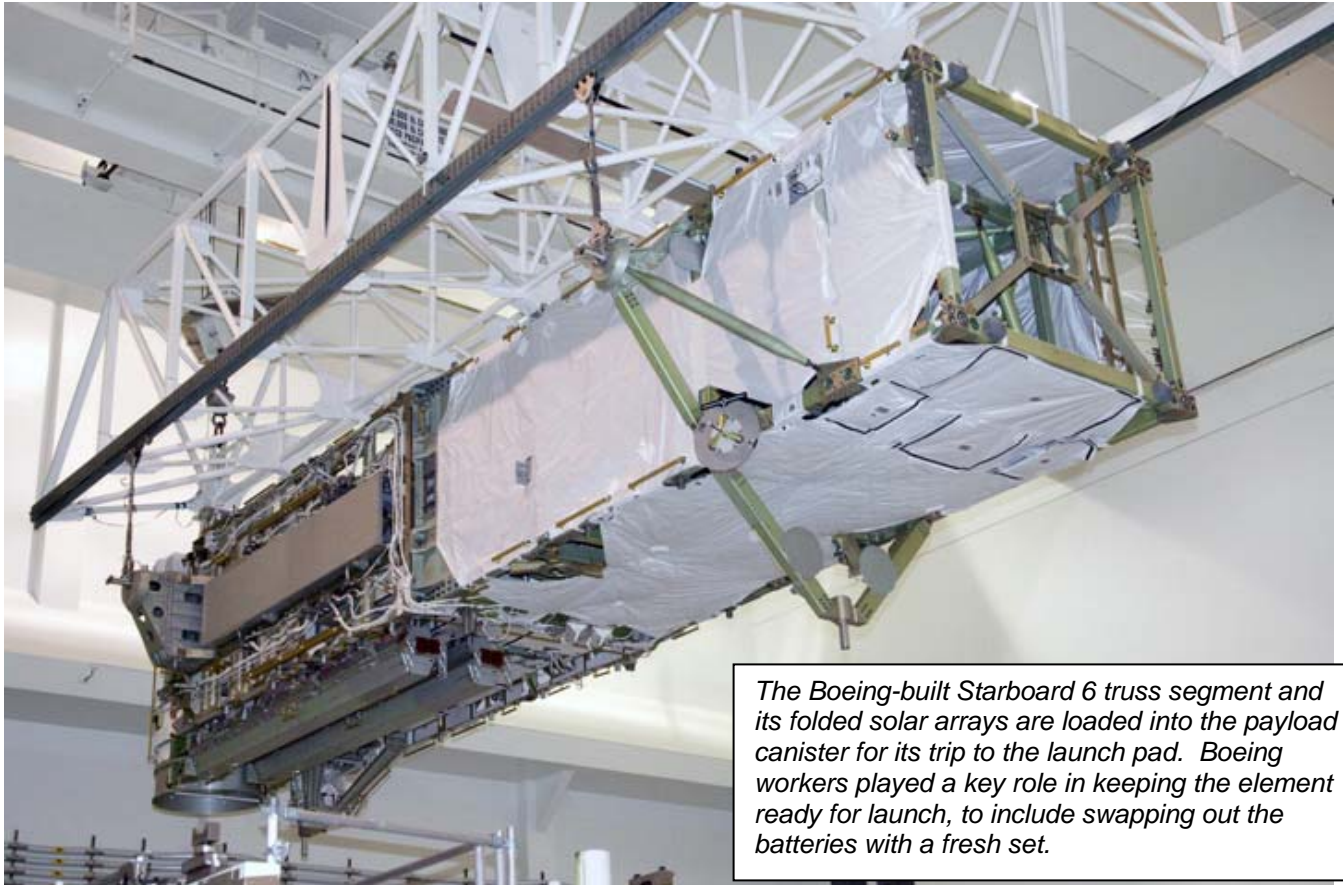
Both the SARJ and BGA are pointing mechanisms and mechanical devices used to point the arrays toward the sun. They can follow an angle target and rotate to that target in the direction toward the sun. On-orbit controllers continuously update those targets so they keep moving continuously as the station orbits the Earth every 90 minutes, maintaining contact with the sun at the same orbital rate. The SARJ mechanism

moves much more than the BGA, which moves about four or five degrees per day, whereas the SARJ rotates 360 degrees every orbit or about 4 degrees per minute.

S6 Integrated Equipment Assembly (IEA)

The IEA has many components: 12 battery subassembly Orbital Replacement Units (ORUs), Battery Charge/Discharge Units (BCDU) ORUs, two Direct Current Switching Units (DCSUs), two Direct Current to Direct Current Converter Units (DDCUs), and two Photovoltaic Controller Units (PVCUs). The IEA integrates the Thermal Control Subsystem that consists of one Photovoltaic Radiator (PVR) ORU and two Pump Flow Control Subassembly (PFCS) ORUs, which are used to transfer and dissipate heat generated by the IEA ORU boxes.

In addition, the IEA provides accommodation for ammonia servicing of the outboard PV modules as well as pass through of power and data to and from the outboard truss elements. The IEA measures 16 x 16 x 16 feet, weighs nearly 17,000 pounds and is designed to condition and store the electrical power collected by the photovoltaic arrays for use on board the station. The IEA integrates the energy storage subsystem, the electrical distribution equipment, the thermal control system and structural framework. The IEA consists of three major elements:



The Boeing-built Starboard 6 truss segment and its folded solar arrays are loaded into the payload canister for its trip to the launch pad. Boeing workers played a key role in keeping the element ready for launch, to include swapping out the batteries with a fresh set.

1. The power system electronics consisting of the Direct Current Switching Unit (DCSU) used for primary power distribution; the Direct Current to Direct Current Converter Unit (DDCU) used to produce regulated secondary power; the Battery Charge/Discharge Unit (BCDU) used to control the charging and discharging of the storage batteries; and the batteries used to store power.

2. The Photovoltaic Thermal Control System (PVTCS) consisting of: the coldplate subassemblies used to transfer heat from electronic boxes to the coolant; the Pump Flow Control Subassembly (PFCS) used to pump and control the flow of ammonia coolant; and the Photovoltaic Radiator (PVR) used to dissipate the heat into deep space. Ammonia, unlike other chemical coolants, has significantly greater heat transfer properties.

3. The computers used to control the S6 module ORUs consisting of two Photovoltaic Controller Unit (PVCU) Multiplexer/Demultiplexers (MDMs).

The IEA power system is divided into two independent and nearly identical channels. Each channel is capable of control (fine regulation), storage and distribution of power to the station. The two SAWs are attached to the outboard end of the IEA.

Direct Current Switching Unit (DCSU)

Power received from each SAW is fed directly into the appropriate DCSU, a high-power, multi-path remotely controlled unit used for primary and secondary power distribution, protection and fault isolation within the IEA. During periods of insolation ("insolation" means during periods of sunlight), the DCSU routes primary power directly to the station from its SAW and also routes power to the power storage system for

battery charging. During periods of eclipse, the DCSU routes power from the power storage system to the station. The DCSU measures 25" x 40" x 14" and weighs 218 lbs.

Direct Current to Direct Current Converter Unit (DDCU)

Primary power from the DCSU also is distributed to the DDCU, a power processing system that conditions the coarsely regulated power from the SAW and BCDUs to 124.5 +/- 1.5 VDC. It has a maximum power output of 6.25 kW. This power is used for all S6 operations employing secondary power. By transmitting power at higher voltages and stepping it down to lower voltages where the power is to be used, much like municipal power systems, the station can use smaller wires to transmit this electrical power and thus reduce launch loads. The converters also isolate the secondary system from the primary system and maintain uniform power quality throughout the station. The DDCU measures 27.25" by 23" by 12" and weighs 129 pounds.

Primary power from the DCSU also is distributed to the three power storage systems within each channel of the IEA. The power storage system consists of a Battery Charge/Discharge Unit (BCDU) and two battery subassembly ORUs. The BCDU serves a dual function of charging the batteries during solar collection periods and providing conditioned battery power to the primary power busses (via the DCSU) during eclipse periods. The BCDU has a battery charging capability of 8.4 kW and a discharge capability of 6.6 kW. The BCDU also includes provisions for battery status monitoring and protection from power circuit faults. Commanding of the BCDU is from the PVCU. The BCDU measures 28" by 40" by 12" and weighs 235 pounds.

Each battery subassembly ORU consists of 38 lightweight nickel hydrogen cells and associated electrical and mechanical equipment. Two battery subassembly ORUs connected in series are capable of storing 8 kWh (kilowatt-hours) of electrical power. This power is fed to the station via the BCDU and DCSU respectively. The batteries have a design life of 6.5 years and can exceed 38,000 charge/discharge cycles at 35 percent depth of discharge. Each battery measures 41" by 37" by 19" and weighs 372 pounds.

Photovoltaic Thermal Control System (PVTCS)

To maintain the IEA electronics and batteries at safe operating temperatures in the harsh space environment, a PVTCS is used. The PVTCS consist of ammonia coolant, 11 coldplates, two Pump Flow Control Subassemblies (PFCS) and one Photovoltaic Radiator (PVR).

The coldplate subassemblies are an integral part of the IEA structural framework. Heat is transferred from the IEA orbital replacement unit (ORU) electronic boxes to the coldplates via fine interweaving fins located on both the coldplate and the electronic boxes. The fins add lateral structural stiffness to the coldplates in addition to increasing the available heat transfer area.

Pump Flow Control Subassemblies (PFCS)

The PFCS is the heart of the thermal system, consisting of all the pumping capacity, valves and controls required to pump the heat transfer fluid to the heat exchangers and radiator, and regulate the temperature of the thermal control system ammonia coolant. The PVTCS is designed to dissipate and average of 6,000 Watts of heat and communicates

with the PVCUs. Each PFCS consumes 275 Watts during normal operations and measures approximately 40 x 29 x 19 inches, weighing 235 pounds.

Photovoltaic Radiator (PVR)

The PVR – the radiator – is deployable on orbit and comprised of two separate

flow paths through seven panels. Each flow path is independent and is connected to one of the two PFCSs on the IEA. In total, the PVR can reject up to 14 kW of heat into deep space. The PVR weighs 1,633 pounds and when deployed measures 44 x 12 x 7 feet.

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