Materials on the International Space Station - Forward Technology Solar Cell Experiment

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INTRODUCTION

This paper describes a space solar cell experiment currently being built by the Naval Research Laboratory (NRL) in collaboration with NASA Glenn Research Center (GRC), and the US Naval Academy (USNA). The experiment has been named the Forward Technology Solar Cell Experiment (FTSCE), and the purpose is to rapidly put current and future generation space solar cells on orbit and provide validation data for these technologies. The FTSCE is being fielded in response to recent on-orbit and ground test anomalies associated with space solar arrays that have raised concern over the survivability of new solar technologies in the space environment and the validity of present ground test protocols. The FTSCE is being built as part of the Fifth Materials on the International Space Station (MISSE) Experiment (MISSE-5), which is a NASA program to characterize the performance of new prospective spacecraft materials when subjected to the synergistic effects of the space environment. Telemetry, command, control, and communication (TNC) for the FTSCE will be achieved through the Amateur Satellite Service using the PCSat2 system, which is an Amateur Radio system designed and built by the USNA. In addition to providing an off-the-shelf solution for FTSCE TNC, PCSat2 will provide a communications node for the Amateur Radio satellite system. The FTSCE and PCSat2 will be housed within the passive experiment container (PEC), which is an approximately 2ft x2ft x 4in metal container built by NASA Langley Research Center (NASA LaRC) as part of the MISSE-5 program. NASA LaRC has also supplied a thin film materials experiment that will fly on the exterior of the thermal blanket covering the PCSat2. The PEC is planned to be transported to the ISS on a Shuttle flight. The PEC will be mounted on the exterior of the ISS by an astronaut during an extravehicular activity (EVA). After nominally one year, the PEC will be retrieved and returned to Earth. At the time of writing this paper, the subsystems of the experiment are being integrated at NRL, and we are preparing to commence environmental testing.

The Space Test Program (STP) is responsible for the integration of MISSE-5 with the Shuttle and the launch of MISSE-5. All public release of information concerning the Spaceflight of the MISSE5 payload will be coordinated and approved by STP and NRL. This includes the release of any information associated with MISSE-5 space flight experiment integration or operations.

MATERIALS ON THE INTERNATIONAL SPACE STATION EXPERIMENTS

The Materials on the International Space Station Experiments (MISSE) is a NASA program designed to provide access to space for new materials and devices being considered for use in space (http://misse5.larc.nasa.gov/index.html). This is accomplished by placing experiments into the Passive Experiment Container (PEC) which is a metal box approximately 2 ft x 2ft x 4 inches fabricated by NASA Langley Research Center (Figure 1). As shown in Figure 1, the experiments are mounted on custom designed trays that mount within the PEC. When closed, the PEC provides the container for the experiments for launch and transfer to the ISS on the Shuttle. For deployment, the PEC is clamped to a handrail on the exterior of the ISS by an astronaut who then opens the PEC to expose the experiments (Figure 2). The FTSCE will be the primary experiment on the 5th MISSE project.

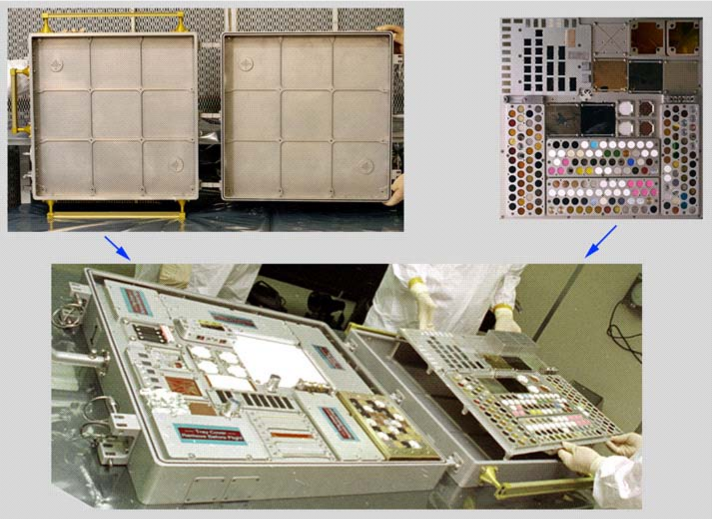

Figure 1: This is a photograph of a Passive Experiment Container (PEC). The PEC is built by NASA and is designed to hold experiments mounted on trays as shown. The PEC is closed to protect the experimental samples during transport on the Shuttle and deployment on the ISS. Once deployed, the PEC is opened to expose the experiments to the space environment. At the end of the mission, the PEC is closed and returned to Earth.

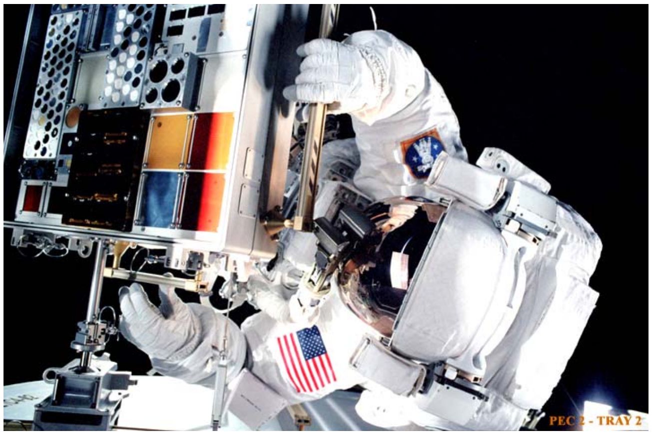

Figure 2: This is a photograph of an astronaut deploying the second PEC onto the exterior of the ISS.

DESCRIPTION OF THE FTSCE EXPERIMENTS

A total of 39 solar cells are included in the FTSCE. The technologies include state-of-the-art and next generation multijunction InGaP/GaAs/Ge, heteroepitaxial GaAs/GeSi/Ge, and amorphous Si and CuIn(Ga)Se_2 thin film solar cells. A photograph of the deck that holds the experiments is shown in Figure 3. This deck is designed as a heat shield to help keep the interior of the PEC warm and is referred to as the Thermal Deck. The experiments are identified in Table 1. The primary experiments are the triple-junction (3J) InGaP/GaAs/Ge based technologies from Spectrolab (SPL) and Emcore. In each case, the current state-of-the-art technology (ITJ for SPL and ATJM for Emcore) and the next generation technology (UTJ for SPL and BTJ for Emcore) are included. In addition, the Emcore ATJM devices include the new monolithic bypass diode. The SPL panel includes two DJ InGaP/GaAs/Ge solar cells that serve as control cells. The Emcore and SPL experiments were assembled by the manufacturer according to their standard practices on aluminum honeycomb rigid array substrates.

Laboratory development technologies are also included in the FTSCE. There are several single-junction (SJ) GaAs solar cells grown on Si substrates that are representative of the GaAs/SiGe/Si technology being developed jointly by NASA GRC, Ohio State University (OSU), and Massachusetts Institute of Technology (MIT). These cells, along with GaAs/Ge control cells, are mounted on a rigid Al honeycomb substrate. There are four 3J InGaP/InGaAs/Ge solar cells supplied by SPL. These are the metamorphic cells that employ a stoichiometry that results in a slightly lattice mismatched semiconductor stack, which, in turn, results in a bandgap combination more closely optimized for the air mass zero (AM0) spectrum. These solar cells are mounted on the SPL panel.

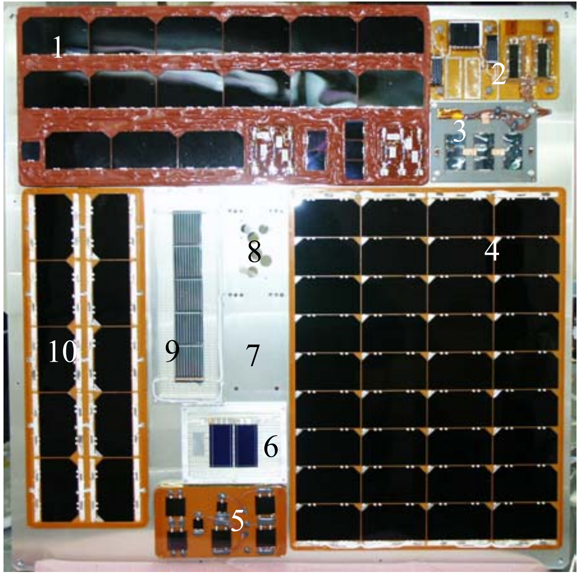

Figure 3: This is a photograph of the FTSCE experiment deck to be placed into the MISSE5 PEC. The experiments are numbered in the picture and described in **Table 1**. Note that the contamination monitor (6) and sun sensors (7) are not in this picture.

The FTSCE also includes flexible, thin-film solar cell (TFSC) technologies. Because the flexible TFSC experiments represent not only a shift in solar cell technology but also a potential dramatic change in future solar blanket and array technology designs, the FTSCE TFSC experiments were fabricated to mimic as closely as possible functional "first-generation" thin-film blanket technology. Each experiment includes multiple, interconnected cells mounted on a light weight array substrate. Two of the experiments incorporate amorphous silicon (a-Si) photovoltaic technology. One a-Si sample utilizes monolithically-interconnected cells grown by Iowa Thin Film (ITF) on a Kapton substrate. This unit was provided by Lockheed Martin and the Aerospace Corporation and represents a variety of interconnect, laydown and coating techniques developed for their thin-film program. The other a-Si experiment consists of a-Si material from UniSolar grown on a stainless steel (SS) substrate using their commercial production process. The cells for this experiment were integrated by AEC-Able Engineering using an adaptation of their UltraFlex blanket design and represents a near-term attempt to "space-qualify" thin-film cell technology when integrated into a viable light weight solar array design. This sample consists of two interconnected a-Si on SS cells affixed to a Vectran gore weave, which simulates the deployed conditions on the UltraFlex array design. It will test cell-to-cell interconnects, cell-to-array attachments and coating technology under long-term space environmental conditions. AEC-Able/NASA Glenn also supplied a $CuIn(Ga)Se_2$ (CIGS) experiment integrated into the same UltraFlex blanket design as described above. This experiment consists of five CIGS cells interconnected in series using a "shingled" approach. The CIGS cells were provided by ITN/Global Solar. It is important to note that the three FTSCE thin film experiments are primarily thin-film blanket technology durability tests. As noted in Table 1, the efficiency of some of the thin-film devices being flown do not represent the current achievable performance of that technology and were selected because of availability or adaptability to specific thin-film blanket technologies.

The FTSCE includes an experiment to test the environmental durability and long-term transmittance of silicone materials. Certain silicones, such as DC 93-500 that is currently used as a transparent adhesive to affix a coverglass to crystalline solar cells, are being considered for use as concentrator lens materials or coatings for advanced photovoltaic devices. It is critical to quantitatively understand the long-term performance of these materials, specifically optical transmittance degradation due to UV darkening, for such applications. The Silicone Degradation Experiment consists of films of silicone (DC 93-500) attached to two different solar cell coverglasses. These two samples are placed over multijunction solar cells so that optical transmission (relative to the response of the MJ cells) can be monitored throughout the duration of the flight experiment. Two other bare silicone samples are being flown as passive experiments and will be evaluated upon return to earth at the completion of the mission.

A passive contamination monitor will fly on the FTSCE. The monitor consists of a piece of CMX coverglass mounted such that a large surface area of the glass is exposed to the space environment. Transmission and reflectance measurements were made on the glass prior to integration, and these measurements will be repeated upon return to Earth. Comparison of the pre- and post-flight data will enable an evaluation of the effect of contamination on the output of the experimental solar cells. The theory is that any loss in transmission due to contamination will be observed in the coverglass data, and assuming uniform contamination of the FTSCE surface, this will translate into a decrease in photocurrent of all of the experimental cells.

DESCRIPTION OF THE THIN FILM MATERIALS EXPERIMENT

As described more fully below, one half of the MISSE 5 PEC will hold the PCSat2 system which is the RF communications subsystem. This half of the PEC is covered by a thermal blanket, and the PEC will be oriented on orbit so that this side is always facing away from the sun. The NASA Langley team has transformed the outer layer of the thermal blanket into a three and one half ounce experiment to evaluate the in space survivability of 200 advanced materials that are being developed to enable future US space missions. The survivability of these materials will be established by comparing pre and post flight characterization test data. The exposure conditions anticipated for this experiment are unprecedented in previous space exposure experiments. Since these specimens will be facing the anti-solar direction when mounted on the ISS, they will receive no UV radiation that can rupture chemical bonds and provide reactive free-radical sites. They will be subjected to thermal cycling, particulate radiation and atomic oxygen bombardment. With no UV exposure, all reactions that do occur will be essentially chemically driven oxidation. A photograph of the experiment package is shown in Figure 4.

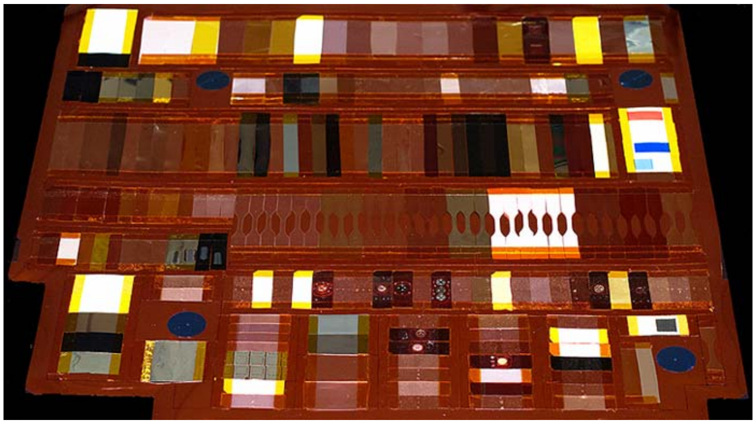

Figure 4: This is the Thin Film Materials Experiment fielded by NASA Langley Research Center. This 3 & 1/2 ounce experiment will evaluate in-space survivability of 200 advanced space materials. Specimens are attached to thermal blanket outer layer. Specimen survivability determined from comparisons of pre and post flight laboratory characterization tests data

DATA ACQUISITION ELECTRONICS AND SOFTWARE

The data acquisition electronics were designed and built by the NASA GRC team. A photograph of the electronics is shown in Figure 6. In Figure 6, the electronics are shown mounted to the deck (named the Electronics Deck) that will hold the boards within the PEC. The Thermal Deck holding the solar cell experiments (Figure 3) is mounted on stand-offs on the opposite side of the Electronics Deck. The two layer unit will be mounted in one half of the PEC. The electronics consists of one “main” microprocessor board and nine data acquisition (DAC) boards. The main microprocessor board provides the communications link with the TNC of PCSat2, serves as the command interpreter, and controls the DAC boards. In addition, the main microprocessor includes dual redundant flash memory so that not only is data transmitted to ground, but is also archived on board. Upon return to Earth, and in the event of communication downlink failure, the mission will still have data available.

Each DAC board is approximately 4x6 in^2 and is capable of measuring a 32 point IV curve on four individual solar cells, making two temperature measurements using AD590 temperature sensors, and taking data from one sun angle sensor. The two temperature channels on a board can be combined to measure temperature using a resistance temperature device (RTD), which provides a wider operating range than the AD590. A single temperature channel on a board can also be configured to make a single IV point measurement on a cell. The IV curve is created by using a FET as a variable resistor and thereby sweeping the load resistance while measuring the solar cell current and cell voltage. Considering that most solar cell experiments employ a bank of switched load resistors for making the IV measurement, which requires much more space and weight, these measurement boards are a significant improvement. A comparison of data measured by one of the DAC boards on a 3J InGaP/GaAs/Ge solar cell under illumination by the X-25 solar simulator in the NRL Solar Cell Characterization Laboratory with data measured by laboratory equipment under illumination by the same simulator is shown in Figure 6, and the agreement can be seen to be excellent.

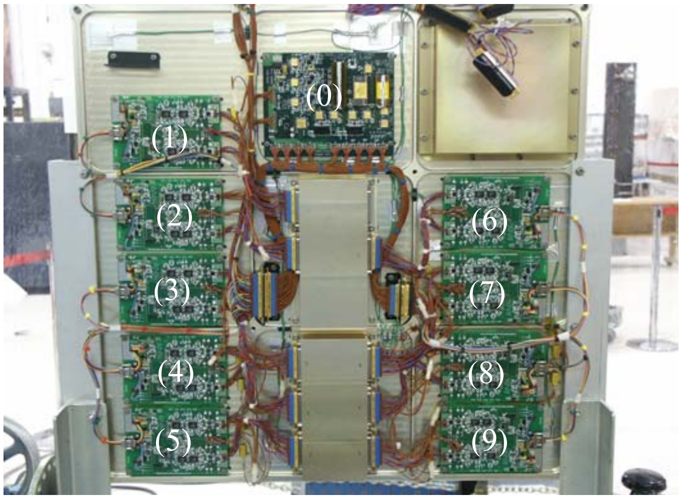

Figure 6: This is a photograph of the data acquisition electronics mounted on the electronics deck. There is a single "main" microprocessor board (0) that controls nine "daughter" boards (1-9), which measure the IV curve, temperature, and sun angle data. The metal box in the upper right of the photograph is the power control unit (PCU). The metal boxes in the center are feed-throughs that route the wires from the solar cells that are mounted on the opposite side. These boxes serve to maintain a Faraday cage around the measurement electronics.

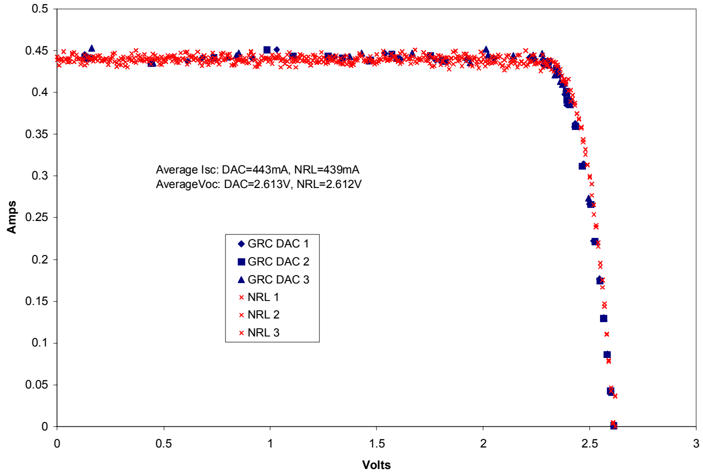

Figure 6: This graph compares IV data measured on one of the FTSCE 3J InGaP/GaAs/Ge solar cells by a flight DAC board and flight software compared to data measured on the same cell by laboratory equipment. In each case, three data sets were measured in succession, and the three curves are shown. All measurements were made under the same X-25 solar simulator in the NRL Solar Cell Characterization Laboratory.

The data acquisition software was also designed and written by the NASA GRC team. Portions of the software reside on each of the DAC boards and the main microprocessor. The DAC board software is responsible for taking commands from the main microprocessor, returning data to the main microprocessor, and performing the IV curve, temperature, and sun angle measurements. The software is designed to autonomously take data when user defined conditions of sun angle and temperature are met. Also, the experiment can be commanded to measure on demand. In addition, each DAC board can be commanded individually with a specific set of measurement criteria. This grants the scientists on the ground flexibility in creating experimental data sets. For example, the DAC boards can be commanded to measure data once the sun angle is below a set threshold, which allows IV data vs angle of incidence data to be generated. Alternatively, the DAC boards can be commanded to measure once the temperature has exceeded a set threshold value, which allows IV data vs. temperature to be generated.

The software resident on the main microprocessor board is responsible for receiving command from the TNC of PCSat2, decoding the commands, and passing the appropriate commands to the DAC boards. The main microprocessor software must also take the data from the 9 DAC boards, translate it into printable ASCII characters and pass it to the TNC for down-linking by PCSat2. The main microprocessor software must also "oversee" the autonomous operation of the experiment, which consists of periodically recording readings from all of the temperature sensors to give a temperature profile for the PEC during each orbit and monitoring the temperature and sun angle data and determining if the measurement conditions have been reached.

POWER SUBSYSTEM

In sunlight the experiment is powered by an array of 4 strings of Emcore ATJ solar cells (the power array is pictured in Figure 3). Each string has 9 cells wired electrically in series to produce an open circuit voltage (Voc) of approximately 23.09 Volts. Power from the 4 strings is fed into the Power Control Unit (PCU). The PCU distributes power to the GRC data acquisition electronics and the PCSat2 communications system and regulates charge current to the battery. When the experiment power array is shadowed, by either the ISS itself or normal orbit eclipses, the experiment is powered by 4 high capacity (55 A-hr) prismatic Lithium Ion (Li-ion) batteries. This will be the first flight of this battery technology and one of the first flights of a Li-Ion battery system in a low Earth orbit (LEO) space environment. Lithion of Pawcatuck, Connecticut, manufactured the battery cells. The cells are wired together in series to provide a bus voltage of 12.0 to 16.0 volts. The PCU uses a shunt regulator to reduce the charge current to the battery when the battery voltage reaches 16.0 volts. The thin film shunt resistors are taped to the inside of the PEC. An under-voltage detection circuit sheds all non-critical loads when the battery voltage drops below 11.5 volts.

It was determined that RF emissions from the PCSat2 transmitters could cause electromagnetic interference with the astronauts' EVA suit, so a multiple inhibit scheme has been implemented to prevent RF transmission when the astronauts are in the vicinity of the PEC. The power system is inactive for launch and EVA transportation to the experiment site on the ISS. Solar array power and battery connection to the experiment are only enabled after an astronaut installs a turn-on plug and toggles a power switch. Power to the transmitters, however, remains delayed by an 8 hour timer circuit to allow sufficient time for the astronauts to exit the area around the PEC.

PCSAT2 – RF COMMUNICATIONS SUBSYSTEM

The RF communications subsystem is called PCSat2. PCSat2 is an Amateur Satellite Communications system similar to what it is flying on PCsat as an external Amateur Radio on the ISS (ARISS) payload. The PCSat2 subsystem will operate in the ITU Amateur Satellite Service in cooperation with ARISS and provide a PSK-31 multi-user transponder, an FM voice repeater for possible use with ISS Crew communications and an AX.25 packet system for use as a UI digipeater and for telemetry, command, control. PCSAT2 will use the same dual redundant AX.25 command and control system as used on PCsat (NO-44) offering 8 on/off commands, 5 telemetry channels and a serial port for the solar cell experiment telemetry. It also supports the Digital Comms Relay support of the PCsat2/APRS mission. The packet uplink is on 145.825 MHz and the default downlinks are in the 435 MHz band to avoid any possible interference with existing ARISS missions. PCSAT2 will have quad redundant transmit inhibits for EVA safety issues, thus, it is also easy to turn off to avoid any issues with other UHF ARISS experiments that may be activated in the future.

One of the key issues with any Amateur Radio experiments on ISS is the requirement to avoid any mutual interference between systems. For this reason, ARISS will need to eventually move all uplinks and downlinks into separate bands. This is so that multiple uplinks and multiple downlinks can be going on simultaneously. As it is, with both uplinks and downlinks on 2m, that band cannot be shared without mutual interference. Thus

PCSat2 is designed as mode J to avoid transmitting on 2m, even though mode B (downlinks on 2m) is far superior to reaching schools and low-tech stations and meeting our mission objectives. There is much UHF equipment being planned for ISS, but until it is operational and ARISS has a long range plan, mode J must be used.

DEPLOYMENT ON ISS

In the MISSE Program, experiments are packaged inside a PEC which is then transported to the ISS via the Shuttle. Once aboard the ISS, the PEC is taken outside the Station by an astronaut during an EVA and clamped onto an external handrail. For MISSE-5, the requirement for favorable sun exposure for the experiments and for power generation made the choice of the location of the PEC critical. After several iterations of lighting, thermal, and power budget analysis, the P4 trunion handrail was chosen. This handrail is located on the port-side solar array truss section between the solar arrays. This section of the ISS is scheduled to be installed on ISS Mission 12A.1/STS Flight 116, and MISSE-5 was scheduled to be installed at the same time. The original STS-116 launch date was July 14, 2003, but the loss of the Space Shuttle Columbia has delayed this date. In an effort to be deployed sooner, alternate locations are being investigated. In particular, a handrail on the crew airlock, which is the current site of MISSE-2, has been identified as a viable alternative. Another possible alternative is on the P6 truss section between the existing solar arrays. The important point gained from the analysis of possible locations is that the amount of sun that the experiment will see during a given orbit and the incident solar angle will vary significantly over the duration of the mission depending on the ISS orbital attitude. Furthermore, certain locations may experience extended periods of shadow during Shuttle docking. This proved to be the major driver in the design of our thermal management system, power subsystem, and experimental data acquisition protocols.

CONCEPT OF OPERATIONS

The plan is for MISSE-5 to remain on orbit for one year. At the end of the mission, the PEC will be closed and returned to Earth. Once returned, the FTSCE will be disassembled to allow for full characterization of the individual experiments. While on orbit, the FTSCE will experience the LEO orbital environment of the ISS. The orbit has a 90 minute period with typically 60 minutes of sunlight and a thirty minute eclipse. The experiment is designed to track the illumination conditions on the face of the FTSCE and the temperature. As the illumination and temperature approach the user-defined set points, the main microprocessor board energizes the DAC boards. When the measurement conditions have been met, the main microprocessor initiates the data measurement, and the DAC boards measure all 36 IV curves within one minute. When complete, the DAC boards pass the data to the main microprocessor, which, in turn converts the data into Automatic Position Reporting System (APRS) format and passes it to the TNC via a serial port. PCSat2 telemeters the data to the ground as AX.25 packets at 9600 bps. To maximize probability of reception, the data is transmitted as a beacon, repeating approximately every 3 minutes. The primary ground station is the USNA where the data will be received and transferred to NRL for analysis. The back-up ground station is NASA GRC. In addition, the data can be received by any amateur radio station operating in AX.25 mode. Once received, the data is placed on the Internet from which it will be received by NRL.

Table 1: This table identifies and gives a brief description of the individual solar cell technologies included in the FTSCE . The approximate solar cell size is given and the number of individual cells is given in parentheses. The beginning of life (BOL) efficiency is the average of the data measured by the responsible organization and given to NRL with the experiments. * - Denotes atypical cell efficiency due to available selection/modification of cells for flight experiment.

#	Experiment Name	Responsible Organization	Description	BOL Eff (%)
1	ITJ	Spectrolab	3J commercial ITJ cells, 26.6 cm^2 (10)	27.0
	UTJ	Spectrolab	3J commercial UTJ cells, 26.6 cm^2 (5)	28.6
	Metamorphic	Spectrolab	3J lattice-mismatched cells, 4 cm^2 (4)	28.5
	Control	Spectrolab	DJ InGaP/GaAs/Ge control cells, 27 cm^2 (2)	22.9
2	Si Degradation	NASA GRC/Entech	Films of DC 93-500 silicone mounted on coverglass superstrate over MJ cell to measure the transmittance degradation of silicone material, 4 cm^2, (2 active, 2 passive)	N/A
	USNA Solar Cells	USNA/NASA GRC	Commercial-off-the-shelf terrestrial solar cells, passive experiment, 2 are ~3.5 cm^2 and the third is ~7.75cm^2, (3)	7.0*
3	Amorphous Si on Kapton	NASA GRC/LM/Iowa Thin Films	Blanket-level test of interconnected thin film amorphous silicon cells on Kapton substrate (3 monolithically-interconnected cells for 1 active sample, 2 passive samples)	0.24*
4	Power Panel	Emcore	Primary power panel for mission, ATJ cells	N/A
5	GaAs on Si	NASA GRC/OSU/MIT	SJ GaAs cells grown on SiGe/Si substrates with one GaAs/GaAs control, 1 & 4 cm^2, (7)	12.2
6	Amorphous Si on Stainless Steel	NASA GRC/AEC Able/UniSolar	Blanket-level test of interconnected thin film amorphous silicon cells on stainless steel substrate affixed to a Vectran gore sheet (simulating UltraFlex array design), ~20.5cm^2 (2 series-interconnected cells)	10.4
7	Contamination Monitor	NRL	Thales 5 mil CMX coverglass, passive witness plate for contamination effects, Not shown in figure	N/A
8	Sun Angle Sensors	NRL	Two orthogonal sun angle sensors. Not shown in figure	N/A
9	CIGS	NASA GRC/AEC-Able/ITN	Blanket-level test of interconnected CIGS cells on stainless steel affixed to a Vectran gore sheet simulating UltraFlex array, ~20cm^2 (5 series-connected cells)	~3.5*
10	ATJM	Emcore	3J commercial ATJM cells, includes monolithic bypass diode, 26.6cm^2 (5)	27.1
	BTJ	Emcore	3J commercial BTJ cells, 26.6cm^2 (5)	27.8