Student Space Systems Fabrication Laboratory

Field Emission Get-Away-Special Investigation

Final Technical Report[1]

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This document describes the design of and preparations undertaken to close out work on the Field Emission Get-Away-Special Investigation (FEGI) project. Due to the cancellation of the NASA Get Away Special Program (GAS) following the Columbia space shuttle accident, work on the FEGI project terminated with the fabrication and testing of the Engineering Design Unit (EDU).
Although FEGI did not fly as a GAS payload, the project has provided valuable personnel training, systems design, test data, and assembled prototypes for future S3FL projects, including mFEGI (Modular-FEGI), FENIX (Field Emission NanosatelIIte EXperiment), and TSATT (Tethered SATellite Testbed). FEGI will continue to be used to provide useful examples and lessons for students working on future S3FL projects.

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1. DOCUMENT PURPOSE & PROJECT IMPACT

This document describes the design of and preparations undertaken to close out work on the *F*ield *E*mission *G*et-Away-Special *I*nvestigation (FEGI) project. Due to the cancellation of the NASA Get Away Special Program (GAS) following the Columbia space shuttle accident, work on the FEGI project terminated with the fabrication and testing of the Engineering Design Unit (EDU).

Although FEGI did not fly as a GAS payload, the project has provided valuable personnel training, systems design, test data, and assembled prototypes for future S3FL projects, including mFEGI (*M*odular-*FEGI*), FENIX (*F*ield *E*mission *N*anosatell*I*te E*X*periment), and TSATT (*T*ethered *SAT*ellite *T*estbed). FEGI will continue to be used to provide useful examples and lessons for students working on future S3FL projects.

2. FEGI BACKGROUND AND HISTORY

FEGI, as GAS payload G-187, began development in early 2001 as a collaborative effort among three schools: the University of Michigan's (UM) Student Space Systems Fabrication Laboratory (S3FL) as the project lead, Pennsylvania State University (PSU), and the Air Force Academy. The project was intended to demonstrate the feasibility of operating field emitters (FE) in a low Earth orbit (LEO) environment. Rather than requiring heaters or consumables like thermionic or hollow cathodes, respectively, field emitters emit electrons via the field emission effect. By applying a modest voltage across small gap distances, electric fields on the order of 10^9 V/m are generated, thereby permitting electron emission via quantum mechanical tunneling. As field emitters require neither heaters nor consumables, they are attractive for a number of space applications ranging from spacecraft charge control to electrodynamic space tethers to electric propulsion.
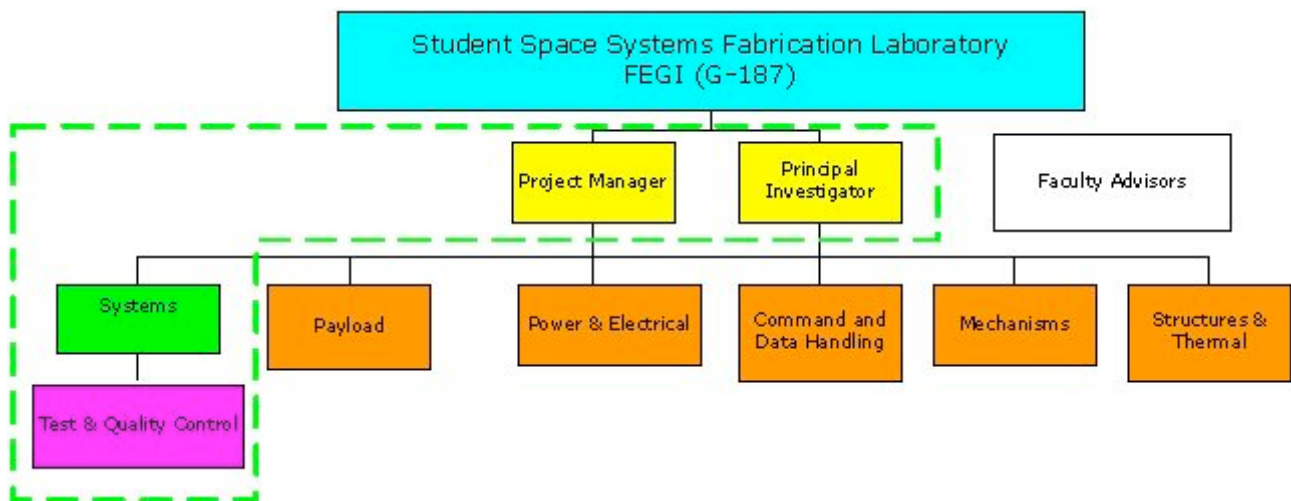

Figure 2.1: FEGI project organization at S3FL

As the project lead, S3FL was responsible for the program management and overall systems design, payload assembly and integration, systems qualification, and post-flight data analysis. Work on FEGI was organized along various subsystems, as shown in Figure 2.1, with student team leads heading each subsystem and systems position. PSU designed and fabricated the ground support system and the battery box assembly, while the Air Force Academy provided the Miniature Electrostatic Analyzer (MESA) as part of the experimental payload.

In 2003, FEGI became one of the entries in the Air Force Research Laboratory's University Nanosat 3 Program. While FEGI participated in the various program activities, its driving requirements continued to come from the GAS program. Unfortunately, the Columbia space shuttle accident in February 2003 caused a reorganization of the Shuttle Small Payload Project Office's priorities, leading to the official cancellation of the GAS program in spring 2005. Without the GAS program, the as-designed FEGI payload could not fly. S3FL thus decided to terminate the FEGI project following the fabrication and testing of the EDU such that test results and lessons learned could be passed on to and utilized by other S3FL projects derived from FEGI.

3. SYSTEMS OVERVIEW

The goal of the FEGI project is to provide a test bed to characterize the performance of cold cathode electron emitter devices in space.

3.1 Mission Objectives

FEGI's mission objectives are as follows:

3.1.1 Primary Mission Objectives

FEGI's primary mission objectives are to:

- Demonstrate cold cathode electron emission in a LEO environment.
- Measure electron emission sensitivity to spacecraft and space environment conditions.
- Demonstrate a handling technique and spacecraft integration procedure for safe delivery of emitters to orbit.

3.1.2 Secondary Mission Objectives

FEGI's secondary mission objectives are to:

- Identify emission current and return current behavior versus emission velocity, emitter current, and plasma density.
- Evaluate emission stability, durability, and reliability to variable LEO environment correlating with specific environmental measurements.
- Determine the extended time performance of one or more emitter types.
- Identify the effects of simultaneous, multiple emitter operation.

- Test additional protocols to initiate and maintain emitter operation in LEO spacecraft environment.

3.1.3 Tertiary Mission Objectives

FEGI's tertiary mission objectives are to:

- Test limits of emitter capabilities and survival limits.
- Measure the effect of Shuttle outgassing and effluents on emission.
- Test fast start capability of emitters.
- Measure the effect of the Earth's magnetic field on emission.
- Test procedures to recover from an emitter short circuit.

3.2 Mission Concept

The main components of the G-187 experiment are three small vacuum protective enclosures (SVPE) each housing four FEs. The NASA-provided motorized door assembly (MDA), while permitting payload exposure to the space environment while opened, does not provide a hermetic seal while closed; consequently, the SVPEs are necessary to minimize contamination of the FEs both before and after the duration of the experiment. Once in orbit, following sufficient outgassing time after MDA opening and the constraints of Shuttle operations, the SVPEs would open to expose the FEs to the local space plasma and to commence emission experimentation. A Langmuir probe, pressure sensors, current collectors, and MESA would monitor ambient plasma conditions to evaluate the effect of the plasma on FE emission and vice versa. The SVPEs would be closed after the completion of the experiment to protect the FEs from further contamination; this action would allow examination upon recovery of the flown contamination test coupons to determine operational and environmental effects on the structure and chemistry of FEs. All experiment components described above are mounted on a faceplate that would be exposed to the space plasma with the opening of the MDA. The remaining part of the GAS canister houses the battery box and supporting electronics stack.
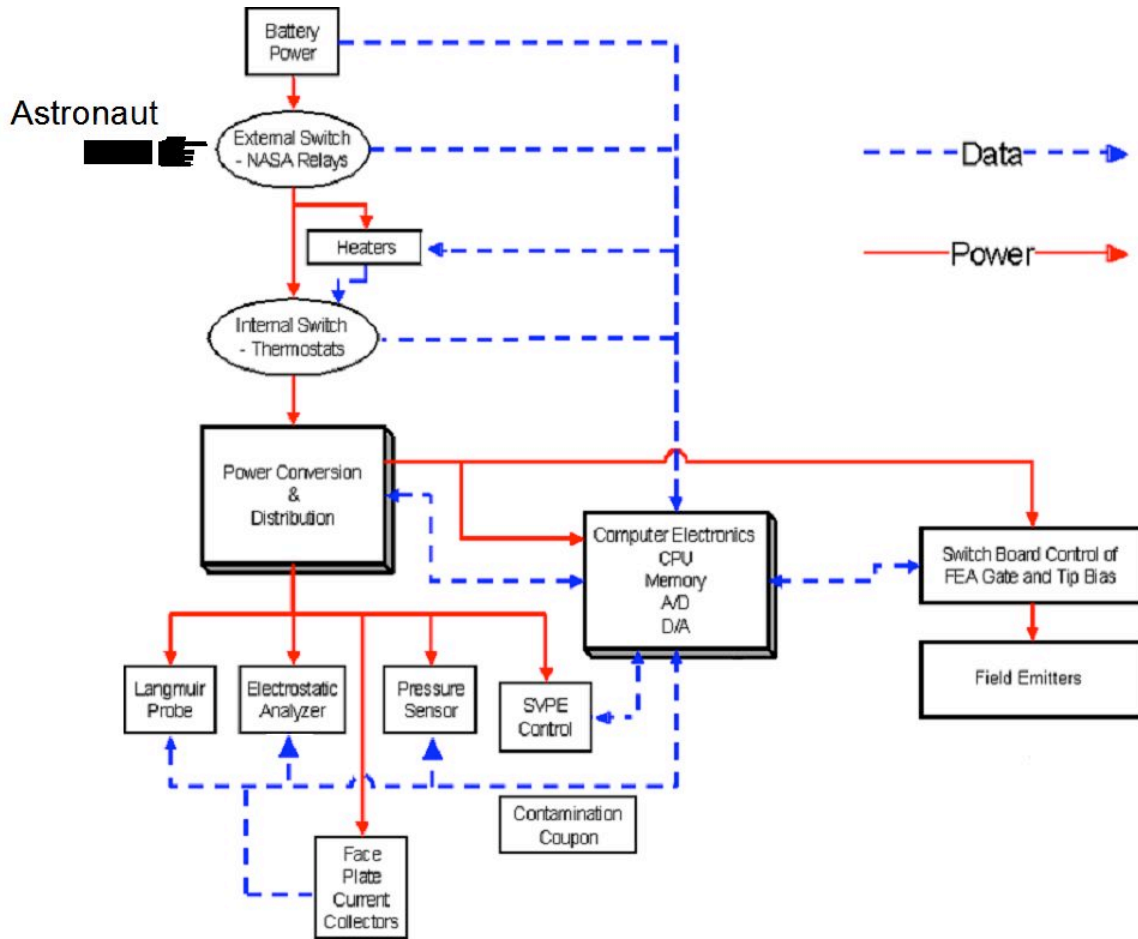
Figure 3.1: Block diagram of FEGI system

As a GAS payload utilizing a MDA, FEGI is mounted to the GAS canister via the NASA-provided Motorized Door Assembly Experiment Mounting Plate (MDAEMP). A battery vent system consisting of two 15-psid pressure relief valves connect FEGI's battery box to the MDAEMP. Bumpers on FEGI provide lateral support against the GAS canister wall. The electrical interface between FEGI and the GAS can consists of three relay signal lines from the Interface Equipment Plate that enable astronauts to control the FEGI experiment. Also, an electrical grounding strap connects FEGI to the GAS canister.

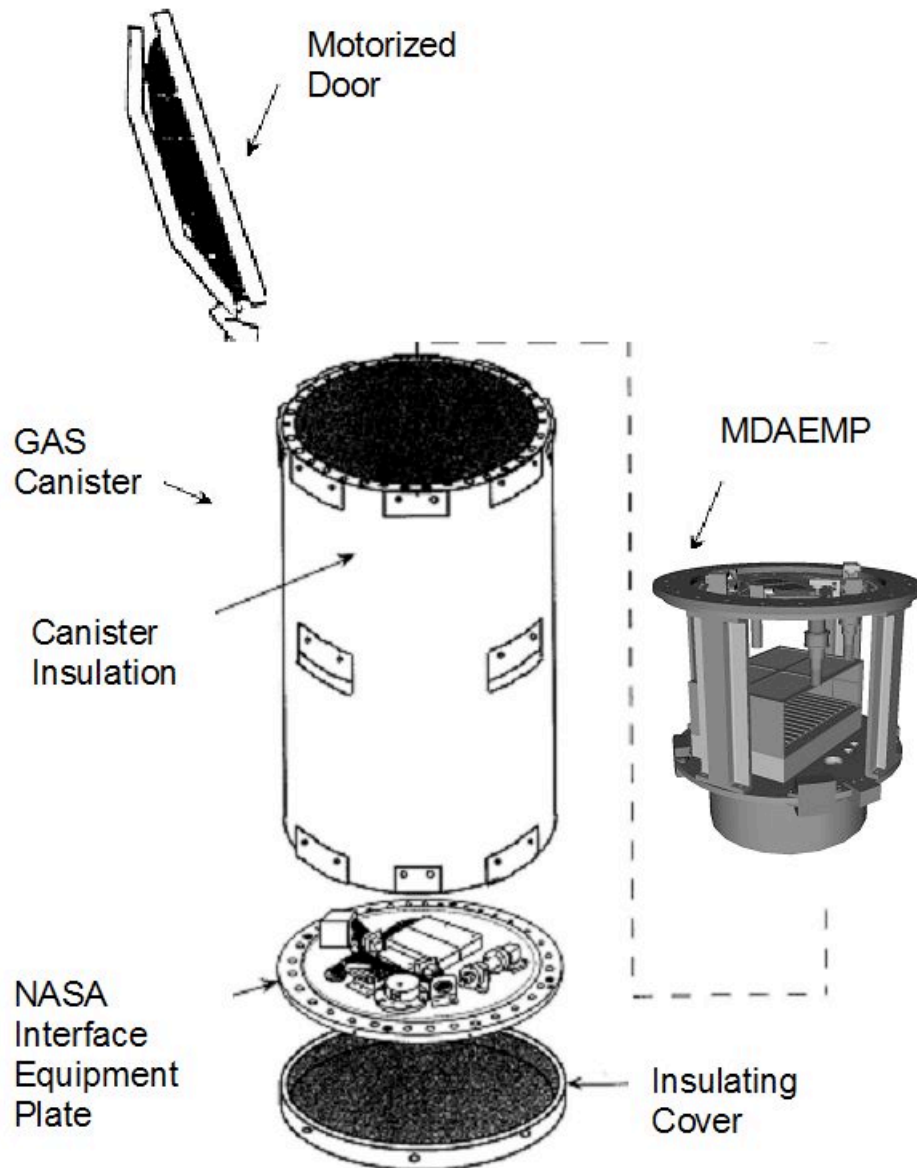Figure 3.2: GAS canister

3.3 Project Requirements

Systems-level requirements for FEGI are shown below with driving requirements in italics. The FEGI Requirements Document lists the complete set of project requirements.

Parameter	Requirement
Field emitter performance	Emission on multiple types for ≥ 30 min. (or stable) at > 10% nominal capability on ground
Experiment activation time	36 ± 2 hr after launch or ≥ 12 hr prior to International Space Station (ISS) rendezvous
Orbit	≥ 5 orbits of emission spread over ≥ 10 hr Shuttle outgassing
Mission duration	*≥ 12 hr operation*
Autonomy	Fully autonomous; can tolerate mission interruptions
Emitter redundancy	> 1 emitter of each technology
Mass	*≤ 160 lbm (72.7 kg)*
Volume	≤ 5.0 cubic feet (0.14 cubic meters)
Envelope	≤ 19.75 in (50.16 cm) diameter; ≤ 28.25 in (71.75 cm) height
Height above MDAEMP	≤ 1.5 in (3.8 cm) above lower surface of MDAEMP
Flight loads	Survive ±10 g's in three orthogonal axes simultaneously
Fundamental frequency	*≥ 35 Hz (need additional 1.5 factor of safety in analysis)*
Random vibration	Shuttle random vibration spectrum
Thermal environment	*Operate continuously in Shuttle bay-to-Earth attitude; survive 30 min solar excursions and 90 min deep space viewing*
Usage life	≥ 4 mission lifetimes for not easily swappable components
Vacuum compatibility	*≤ 1% TML (Total Mass Loss); ≤ 0.1% CVCM (Collected Volatile Condensable Material)*
Fracture control	GSFC 731-005-83

Figure 3.3: Systems-level requirements (driving requirements in italics)

3.4 System Budgets

The following system budgets are from FEGI's Critical Design Review (CDR). Wherever possible, the EDU sought to adhere to these system budgets; exact matching of the systems budgets was unnecessary because the EDU was not intended for flight.

3.4.1 Mass

To fly as a GAS payload with a MDA, FEGI is limited to a mass of 160 lbm (72.7 kg).

	Mass (kg)	% Contingency	% Total Mass	
Payload	2.56	11.86%	3.81%	
PE	6.60	6.46%	9.81%	
CDH	0.88	10.39%	1.31%	
Mechanisms	9.25	13.75%	13.75%	
Structures	32.86	10.21%	48.86%	
Faceplate	5.16	10.00%	7.67%	
Lower Mounting Plate	6.97	10.00%	10.36%	
Struts	6.20	10.00%	9.22%	
Electronics Housing (Empty)	2.70	16.67%	4.01%	
Battery Box (Empty)	9.18	9.14%	13.65%	
Battery Vent Assembly	0.51	50.00%	0.76%	
Fasteners	0.46	20.00%	0.68%	
Bumpers	1.69	9.09%	2.51%	
Batteries	12.79	4.76%	19.01%	
Wiring	2.32	50.00%	3.45%	
Total	67.27			
Total Available	72.73			
Systems Level Contingency	5.09		7.00%	of total available
Component Contingency	7.57		10.41%	of total available
Total Contingency	12.66		17.41%	of total available
Margin	0.37		0.51%	of total available

Figure 3.4: Mass budget

3.4.2 Power

Since FEGI is not drawing any power from the Space Shuttle, all payload power comes from the onboard batteries.

Device	Power (peak)	Power (avg)	Contingency	Conversion Loss	Duty Cycle	Total (pk)	Total (avg)	Unit
Payload Total	12.76	4.34	7%			13.48	4.94	W
Mechanisms Total	0.94	0.72	8%			0.50	0.39	W
C&DH Total	4.64	2.46	9%			6.20	3.28	W
P/E Total	95.41	73.27	9%			14.07	10.70	W
System Contingency	11.37	8.08	10%	-	-	3.37	1.93	W
Total	125.11	88.87				37.62	21.24	W
Total (No Heaters)	40.61	23.87				34.55	18.87	W
Battery current draw with heaters	6.26	3.70				1.57	0.86	A
Battery current draw w/out heaters	2.03	0.99				1.44	0.77	A

Figure 3.5: Power budget

3.4.3 Data

With no downlink capability, FEGI must store all experimental data onboard for post-mission recovery and processing.

Size of Sample General (bits)	16	thermistors	10.00	MESA	14
Total Mission Time (hours)	48				
contingency factor	2				

Device	Number	Sampling (Hz)	Duty Cycle (%)	Data Rate (Bits/s)	Data Rate (Bytes/sec)
Face-Plate Current Collectors	24	1	100.0%	384	48
MESA	5	200	50.0%	7000	875
Langmuir Probe (LPSP)	1	RS-422	50.0%	1800	225
Pressure Sensor	1	1	100.0%	16	2
FEA Voltage/Current Sensors	36	1	100.0%	576	72
Thermistors	11	1	100.0%	110	13.75
Photodiode	1	1	100.0%	16	2
Health Sensors	102	1	100.0%	1632	204
Switch voltage/current sensors	15	1	100.0%	240	30
Motor voltage/current sensors	3	1	100.0%	48	6
HV supplies	4	1	100.0%	64	8
Motor voltage/current sensors	1	1	10.0%	1.6	0.2
Thermal Sensors	52	1	100.0%	832	104
Proximity Sensor	9	1	100.0%	144	18
Total Devices	265		Total Bits/Sec	12863.6	
Total Storage (bits)	2E+09		Total Bytes/Sec	1607.95	
Total Storage(Megabytes)	264.98	MB			
After contingency factor	529.96	MB			

Figure 3.5: Data budget

3.4.4 Cost

As part of the NanoSatellite-3 program funded by the Air Force, the FEGI project received $100,000 USD to be distributed according to the following table:

	5/1/03 - 10/31/03	11/1/03 - 10/31/04	11/1/04 - 4/30/05	Total
	Cost	Cost	Cost	Cost
1. Systems and Design Analsis	$3,878	$5,764	$2,179	$11,821
2. Electron Emission System	$14,576	$17,494	$1,500	$33,570
3. LP and Surface Curr Sensor	$0	$1,000	$0	$1,000
4. MESA (USAFA)	$250	$5,929	$0	$6,179
5. Pressure Sensor	$500	$2,000	$0	$2,500
6. Contamination Testing	$0	$1,000	$0	$1,000
7. C&DH	$3,750	$14,572	$0	$18,322
8. Power and Distribution	$2,500	$7,000	$0	$9,500
9. Structure and Thermal	$4,047	$7,592	$0	$11,639
10. Integration and Testing	$0	$4,460	$0	$4,460
11. Mission Ops & Data Analysis	$0	$0	$0	$0
Sponsor Budget	$29,501	$66,811	$3,679	$99,991

Table 1: FEGI Cost Summary

3.5 Operational Scenario

When flying on the Space Shuttle, FEGI is activated via three astronaut-controlled relays (named A, B, and C with states LATENT and HOT). Relay A is a hard cutoff switch that connects (HOT) or disconnects (LATENT) all experiment power (including heaters, etc.). Relays B and C control signal lines that tell the flight computer whether to run, or if already running, tell the computer when to shut down experiments. Normal operation is for all three relay switches to be activated in rapid sequential secession (A, B, C) at experiment activation. This activation following MDA opening occurs either 36 hours +/- 2 hours after launch but no later than 12 hours before rendezvous with the ISS in order to permit the payload to outgas sufficiently.

At the end of the experiment operations (when the window for FEGI operations ends), normal operation is to turn relay B and C off, wait five minutes, then turn relay A off. This procedure would allow FEGI time to shut down normally (closing SVPE doors, etc.). If necessary, however, a quick turnoff can be achieved by switching relay A off (or relays A, B, and C simultaneously). In this case, the cost would be that the SVPE doors would remain open and that some state and contamination information may be lost. FEGI can be re-activated after either turnoff procedure by switching on relays A, B, and C, and it would continue the experimentation sequence where it left off.
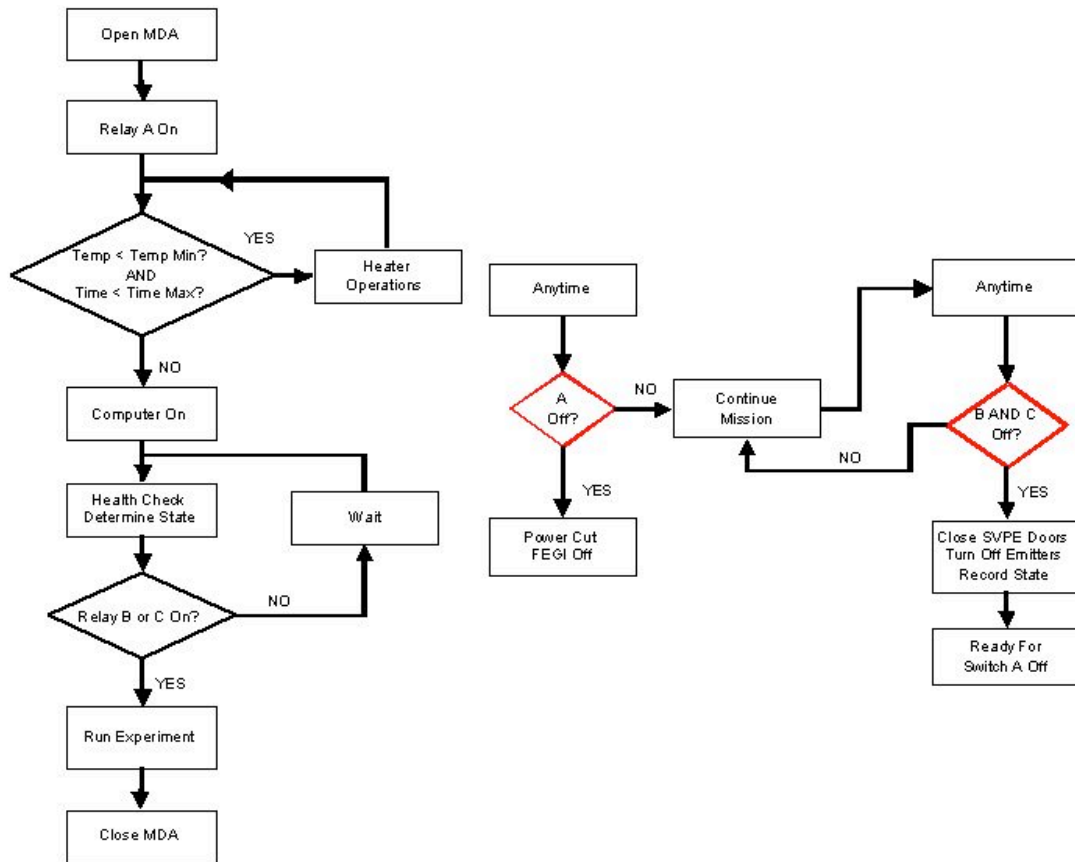
Figure 3.6: FEGI response to astronaut relays

3.6 Mission Timeline

The nominal FEGI mission timeline is as follows:

T-3mo[2]	Final University of Michigan checkout. Ship FEGI to Cape Canaveral. FEGI test at Cape.
T-1mo	Final load of emitters in SVPEs. Ship emitters to Cape. Install SVPEs at Cape.
T-5? d	Final installation/ system check of FEGI in Shuttle.
T-0	Launch!
T+0 to T+36? h	Outgassing of the Shuttle bay; MDA opened if possible, but experiment not yet activated.
T+36? h = M0	Astronauts activate all three relays. This activates the heater control circuit, which begins warming the critical components (computer, batteries, etc.).
M+h1	Computer is activated when it reaches a safe temperature or heater time limit passes. It takes over control of heating other components and performs other health checks and startup procedures.
M+h1+h2	Components warmed to safe temperatures and health check completed.
M+h1+h2+15	Open SVPE1. Begin initial field emission experiments.
M+h1+h2+45m	Completed baseline experiments on emitters in SVPE1. Open SVPE 2; begin additional baseline experiments
M+h1+h2+75m	Completed baseline experiments on emitters in SVPE1&2. Begin secondary objectives and long-term experiments. Mid-mission: When interesting environmental conditions are observed, adjust timeline to perform testing of all emitters in all environmental conditions as much as possible. Otherwise follow experiment objective timeline.
M+h1+h2+10h	Completed longer duration experiments, many secondary experiments, and some tertiary experiments. Have made environmental variance observations. Open SVPE3. Begin baseline experiments of emitters in SVPE3 for post-additional-outgassing experiments.
M+h1+h2+10.5h	Completed baseline experiments on SVPE3 emitters. Continue with secondary and tertiary objectives on SVPE1-3 emitters.
End -15m (>M+12h)	Computer observes battery life has dropped to reserve level. Discontinue experimentation. Shut down science instruments (emitters and environmental monitors). Close SVPE doors one at a time.
End	Rest in quiescent state until battery life runs out, or astronauts switch off experiment power and close MDA.

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[2] mo = Month, d = days, h = hours, m = minutes, h1: initial heating time to warm computer (15m?), h2: heating time controlled by computer to warm additional components (15m?)

The tests would be conducted in the order of decreasing importance, so that if the mission were prematurely terminated by Shuttle operations, the most important results would have been obtained.

4. SUBSYSTEM OVERVIEW

This section provides an overview of the FEGI subsystem design.

4.1 Payload

The payload subsystem is made up of the information collecting devices located in Figure 4.1 and associated hardware. Additionally, the payload subsystem is also responsible for the handling and testing of field emission technology.
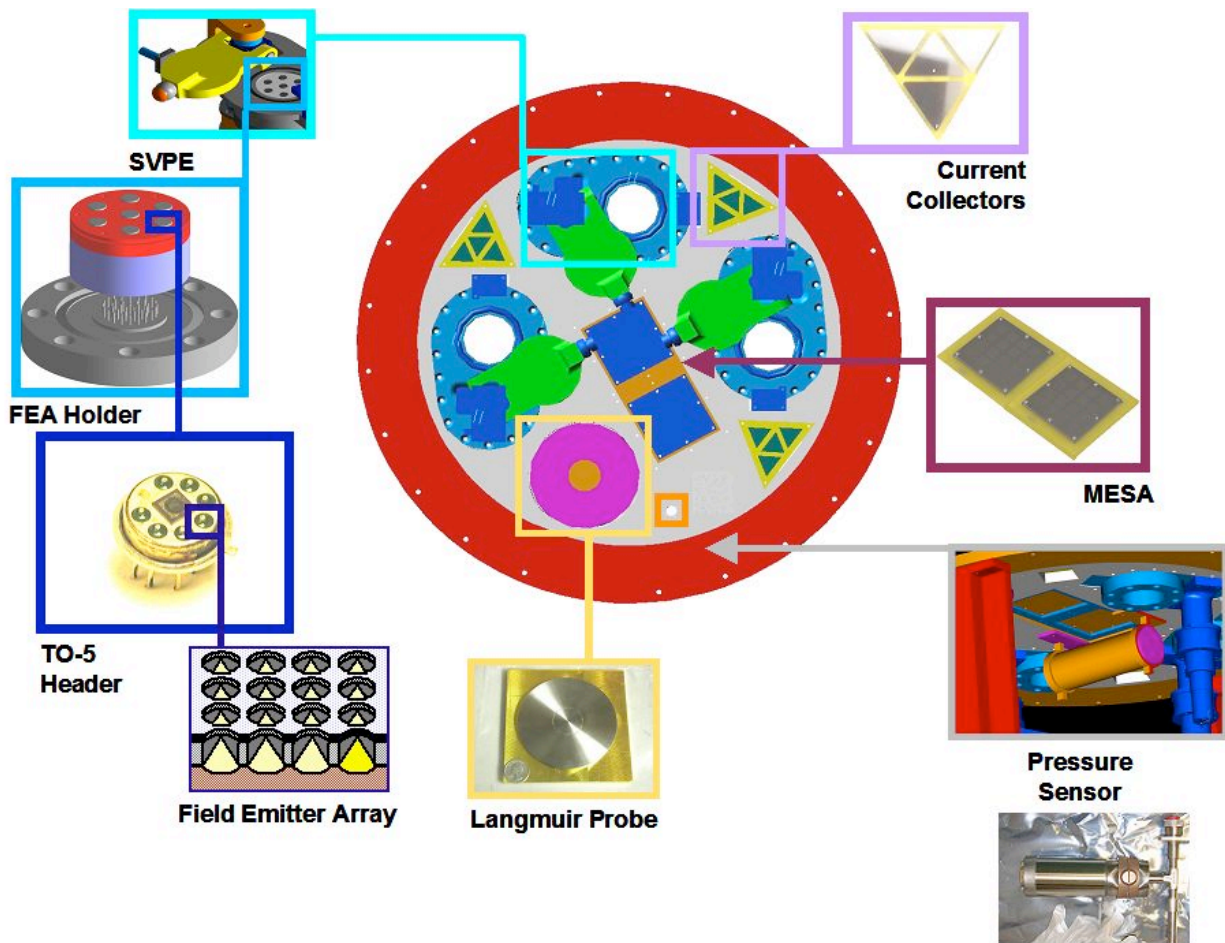

Figure 4.1: Faceplate payload instrumentation

4.1.1 Electron Field Emitter Arrays

The five field emitter technologies being considered to fly on FEGI are:

- Basic Spindt type emitters with molybdenum tips and gate.
- Coated Spindt emitter, to be provided by NASA's Jet Propulsion Laboratory.
- Busek carbon nanotube emitter.
- University of Michigan Cubic Boron Nitride (cBN) emitter.
- Air Force (Dave Cooke) triple point emitter.

Two emitters of each technology will be flown for redundancy. They will be housed in one of three SVPEs located on the faceplate. See figure 4.1 and figure 4.2.
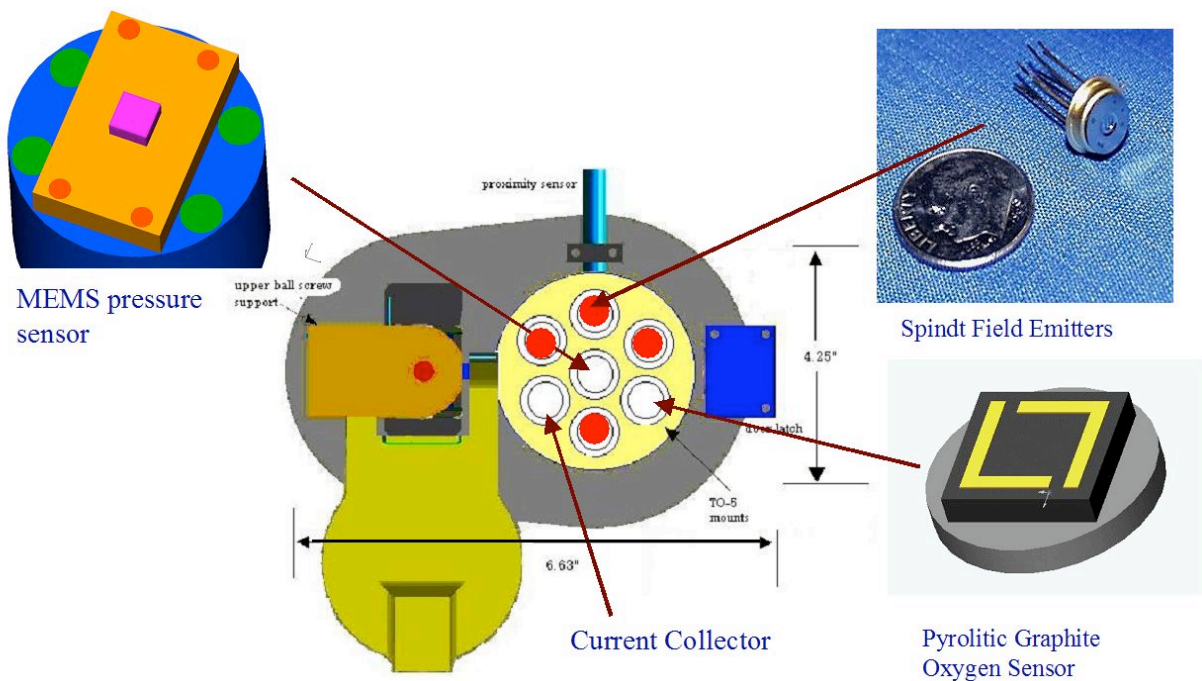

Figure 4.2: SVPE payload suite

4.1.2 Pressure Sensors

The main pressure sensor is designed to measure neutral gas pressure at the FEGI faceplate. Neutral gas pressure is an important measurement for this mission because it directly affects the operation of the FEs; neutral gas particles lead to contamination and decreased emission due to the desorbed gas particles on emitter tips. FEGI is using a Kernco Modion vacuum gauge/ pump, which was donated by Marshall Space Flight Center. This device has heritage on the Wake Shield vacuum facility, which was a LEO vacuum measurement mission. The Kernco pressure sensor is located directly under the faceplate.

MEMS (micro-electro-mechanical systems) pressure sensors are housed within each SVPE. These MEMS pressure sensors can measure pressure to the millitorr levels and are used to monitor the sealed nature of the SVPEs prior to opening. Proper seal knowledge is essential to validation of pristine field emitters prior to emission in LEO environment.

4.1.3 Graphite Atomic Oxygen Coupon

The graphite atomic oxygen coupon, in coordination with the contamination test coupons, help determine what environment the field emitters were exposed to during the mission. The sensor detects atomic oxygen flux in the vicinity of the FEs by exposing a piece of single crystal Highly Oriented Pyrolytic Graphite (HOPG) inside the small vacuum protective enclosure (SVPE). Since HOPG is very non-reactive to most substances, with the exception of oxygen, and since HOPG reacts with atomic oxygen present in the LEO environment by etching at a known rate, this material can be used to approximate the total atomic oxygen flux seen by the field emitters. The design is based on a sensor flown by Eric Snyder *et. al* on STS-46, a mission to determine the atomic oxygen flux seen in the Shuttle ram during orbit.

4.1.4 Langmuir Probe

The Langmuir Probe (LP) is the primary measurement instrument designed to characterize the local plasma environment at the faceplate. The LP is an important supporting instrument because in the space charge limited regime (which occurs with low plasma densities), the performance of the emitters will be directly dependant upon the local plasma density; thus, it is important to know if the performance is due to emitter issues or local plasma conditions. I-V (current-voltage) responses of the local plasma are measured by the LP. The electronics to provide a Langmuir probe I-V sweep (ProSEDS LPSP) are already available to us. This is flight equipment from a previous mission, the Propulsive Small Expendable Deployer System (ProSEDS).

4.1.5 Current Collectors

The faceplate current collectors provide sufficient information to determine if current is returning from the FEs to the faceplate and if so where. Three distinct designs are to be flown on FEGI: triangular faceplate current collectors, circular SVPE door current collectors, and TO-5 mounted SVPE current collectors. The first two designs each include four large conducting zones to give a spatial distribution of electron beam current returning over the faceplate during experiments. Integrated current measurement circuitry performs local current-to-voltage conversion. The third design, consisting of a simple TO-5 header used to collect current, is too small to include current-to-voltage circuitry directly on the device. This current-to-voltage conversion is done inside the main electronics box. Prior to electron beam emission, an ambient current signature will be taken; current measurements will then be taken during emission experiments.

4.1.6 Contamination Test Coupons (CTC)

The CTCs are used to determine what environment the field emitters are being exposed to and how they are being contaminated during the mission. The idea is to use a surface that is exposed

to the same environment in as many ways as possible as the emitters are exposed to. The CTC will collect on its surface the same contaminates the fields emitters collect. This surface can be analyzed upon FEGI's return to earth for residual contamination effects. Contaminates will most likely come from organic outgassing, either in the SVPE or in the Shuttle cargo bay. The coupon will also collect contaminants that fall on the emitters during construction. The top surface of the FE holder in the SVPE is currently being designed as a contamination test coupon. The thickness of any acquired contaminate layer will be determined using ellipsometry.

4.1.7 Miniature Electrostatic Analyzer (MESA)

MESA is an electrostatic analyzer designed to measure flux of electrons with energy from zero up to greater than 100 eV by using a grid of three plates, two with fixed biases and one with a bias sweep. It is manufactured using photolithography so that the analyzer consists of a stack of thin, patterned metal plates that make up an array of miniature analyzers. The reason for employing MESA on the FEGI payload is to determine whether or not the electrons emitted experience the space charge limit phenomenon. This can be determined by analyzing the amount of current read by the MESA for various energy levels. MESA can also be used in a low-voltage regime to record the temperature of ambient thermal plasma. Density measurements can also be determined by the magnitude of the current response.

4.2 Mechanisms

The SVPEs are mounted to the FEGI faceplate and houses the field emitters as the primary payload as well as current collectors, MEMS pressure sensors, and contamination test coupons as secondary payloads. Each SVPE is actuated via a motor-driven, gearbox-coupled, ballscrew driveline. When being opened, the fail-safe brake is disengaged, and the motor is activated. As the ballscrew turns, the stainless steel SVPE door lifts off and breaks the o-ring seal. After breaking seal, the turning ball screw swings the door open, thus exposing the SVPE internals directly to the space environment. The door continues to open until proximity sensors signal motor cutoff. At this point, power is cut to the fail-safe brake, which clamps and prevents the driveline from turning anymore. A double torsion spring acts to keep the SVPE door in constant contact with the faceplate, and a door tether exists to keep the door tied down as a redundant measure.

When the door is ready to be closed, power is supplied to the fail-safe brake, which unclamps the driveline. A single torsion spring pulls the door closed, and the motor, operating with reversed polarity, actuates the driveline and reseals the SVPE door.
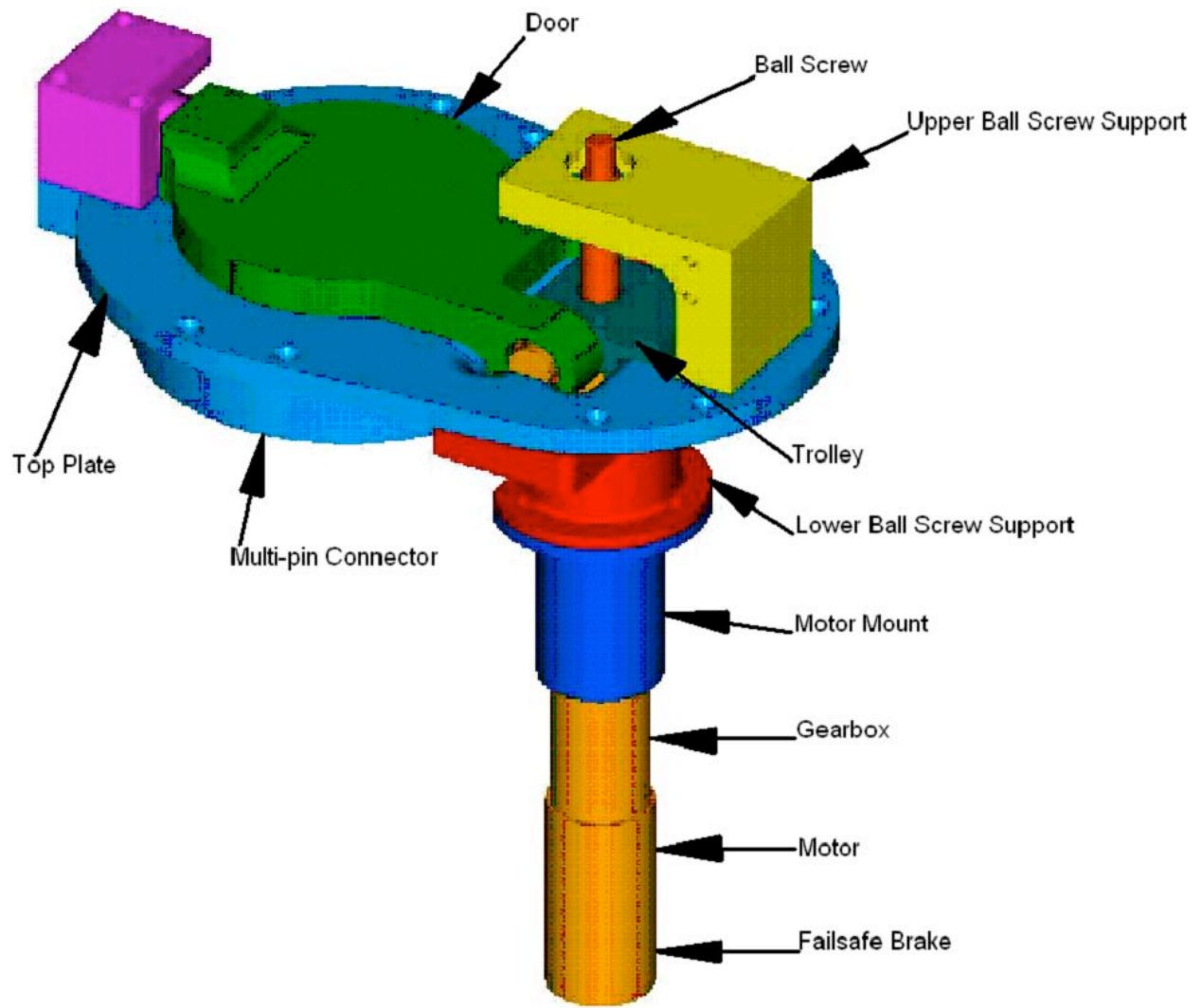
Figure 4.3: SVPE Configuration

4.3 Command and Data Handling

The Command and Data Handling (C&DH) subsystem is responsible for executing the flight plan that is preprogrammed into the computer, monitoring the system health, acting on failures, and recording data in real-time.

C&DH serves two main purposes. First, the system automates the experiment, controlling the entire operation of the device through its mission, including opening the SVPE doors, deciding which emitters to run, how much to bias them, for how long, etc. There is no telemetry involved, and the system uses simple control algorithms.   Second, the C&DH system controls the collection and transfer of data for storage and post-mission retrieval.
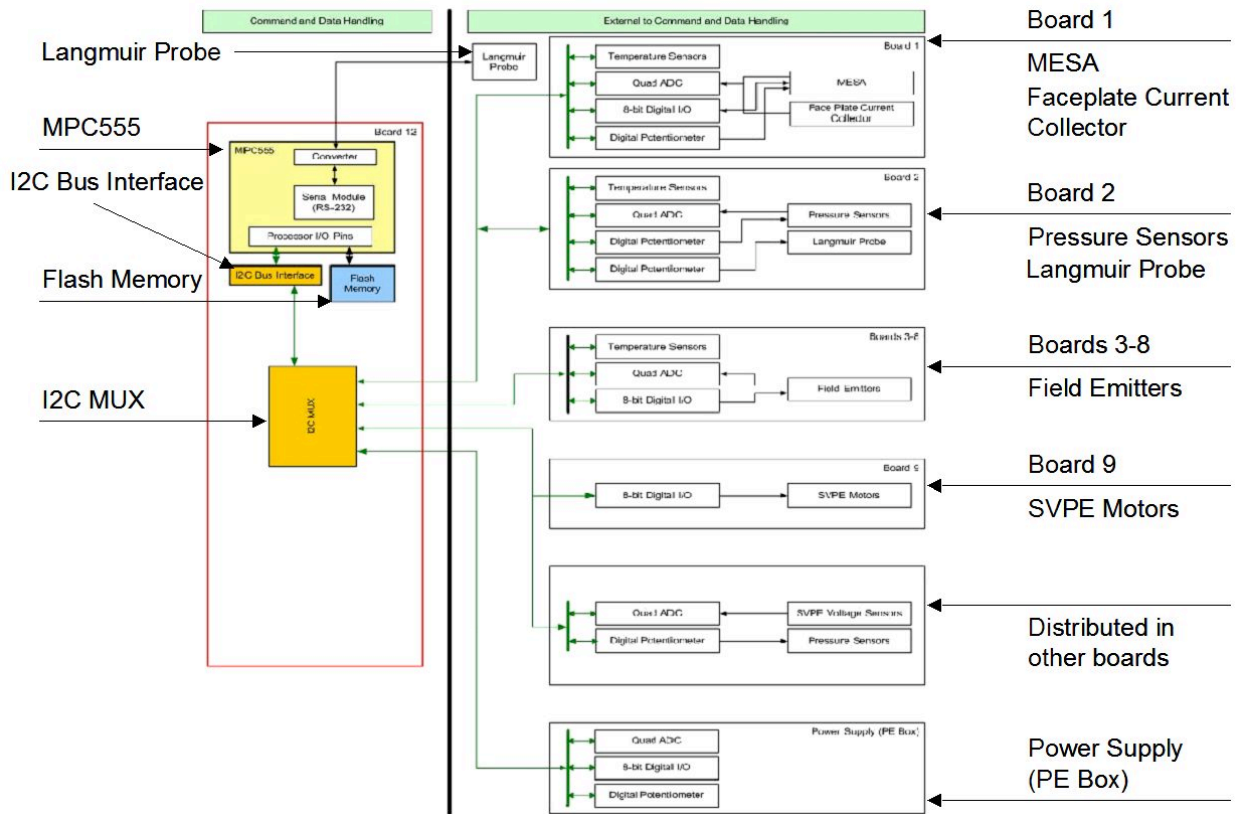

Figure 4.4: Command and data handling subsystem block diagram

4.3.1 Microprocessor

The microprocessor is the Motorola PowerPC MPC555 embedded, RISC processor. It is low-power, clocked at 40 MHz, and contains many useful peripherals. It is also rated to at least 5 krads. The MPC555 has a 448 Kbytes internal flash for storing program data and internal SRAM for caching and running programs.

4.3.2 Data Storage Unit

Experiment data will be stored via four Samsung 128 MByte (1 Gbit) NAND FLASH cards. These cards offer high density, low power draw, no moving parts, and good thermal tolerance. Error correction in software will be used, and buffering will be implemented to alleviate access latency. Since the mission is mainly collecting and storing data, the write case should be optimized over other reading.

4.3.3 Communication Protocol

FEGI will be using the I2C protocol for command and data I/O. The I2C suite includes temperature sensors, I/O switches, A/D converters, D/A converters, and data line extenders.

4.4 Power and Electrical

The Power and Electrical (P&E) subsystem is divided into the following sections: Batteries, Power Supplies, Measurement Sensors, Health Sensors, Electronics Box Interfacing, and electronics boards. Figure 4.5 shows a detailed diagram of the P&E subsystem.

The power and electrical subsystem must supply power to the following subsystem:

- Payload: FEs, Langmuir probe, MESA, Kernco pressure sensor, MEMS pressure sensor, support circuitry
- Computer and Data Handling (C&DH): microcontroller, microdrive, C&DH Support Hardware, reliable and accurate power for data acquisition and transmission
- Power and Electrical (P&E): housekeeping and heating system.
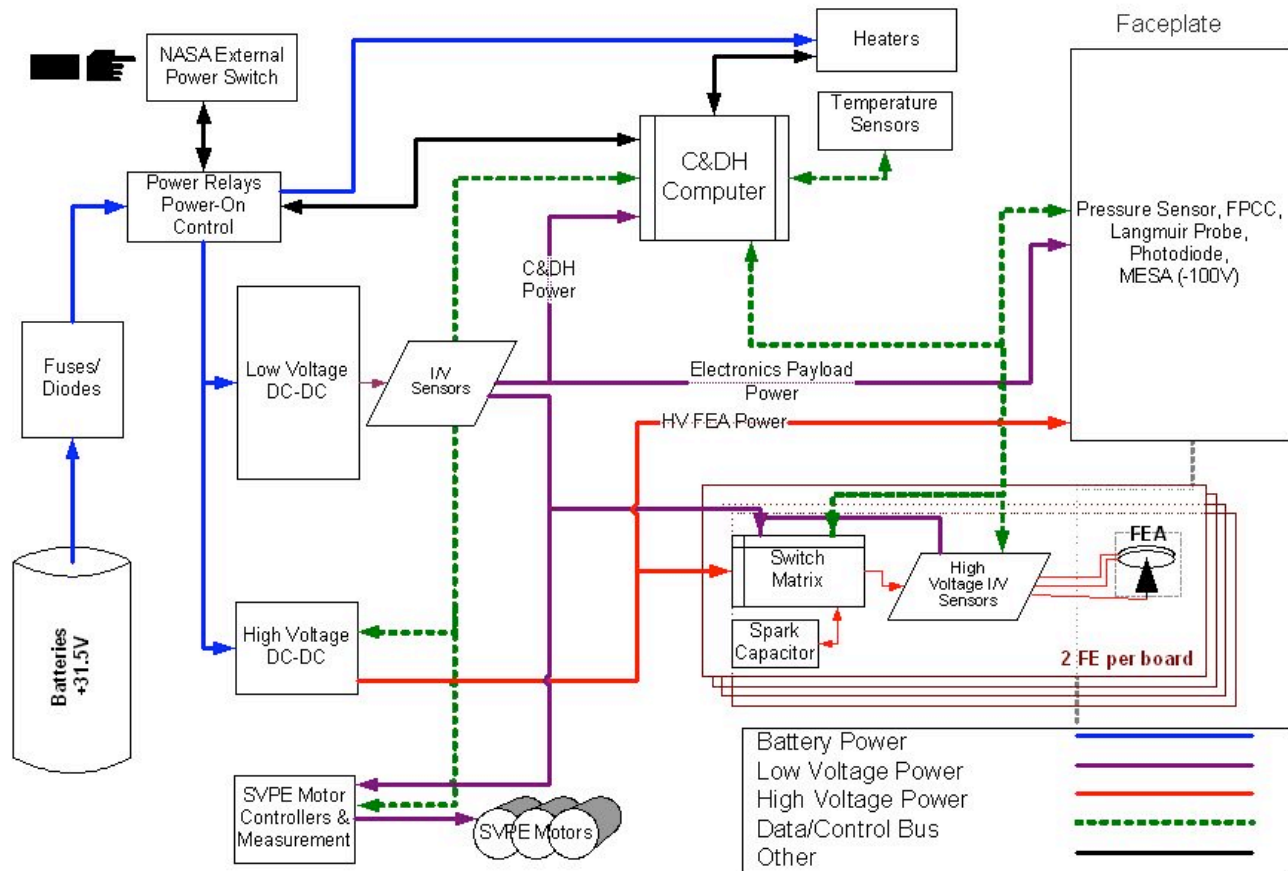 Mechanisms: SVPE motor, proximity sensors

Figure 4.5: Power and electrical subsystem block diagram

4.4.1 Batteries

Power to FEGI systems is supplied by 5 strings of 22 batteries each for a total of 110 batteries. The combined batteries supplies 31.5V. The batteries are Duracell alkaline D cell batteries.

4.4.2 Low Voltage Power Supply

The low voltage power supplies provides power to the following devices:

- C&DH board (3.3V and 5V)
- P&E board/ Housekeeping (±5v, ±12V)
- Langmuir Probe (24V)
- Pressure Sensor (24V)
- MESA (5V, ±12V)

The necessary bus voltages are +3.3V, -5V, +5V, +12V, and -12V. DC/DC converters take 31.5V supplied by batteries and convert voltage to the necessary bus voltages of +3.3V, -5V, +5V, +12V, and -12V. Voltage conversion is performed on the power supply board, wired to

22

connectors on the back plane, and then routed using a specific bus to each analog board. The LVPS are flight grade DC/DC converters by Interpoint that have had vibration and shock testing.

4.4.3 High Voltage Power Supplies

High voltage supplies are necessary for field emitter (FE) biasing, electron cleaning, and for payload subsystem devices. There are four Ultravolt, A Series high voltage supplies. Two high voltage supplies have the capability to range from –500V to 0VDC at 2V increments with health sensors and current limiting protection. One supply is positive +150V and is used for electron cleaning. The last is –125V and is used for the MESA device. Short circuit protection is provided between all power supplies via diodes. A 0-5V digital signal is given from the C&DH board as a reference for the output voltage. The supplies are controlled via the I2C bus interface digital-to-analog converter (DAC).

The switching network provides the flexibility to use any of the three high voltage bus lines to any FE device under test. All high voltage power supplies are specified to provide the necessary safety precautions to be able to withstand a short between the positive and negative terminals.

4.4.4 Voltage Sensors

For every FE device that is flown, there is the ability to measure up to two gate/tip/grid voltages and currents. The emitters themselves are housed in a TO-5 header package with no lid. The design measures up to four out of the eight pins on the TO-5 header. There are voltage and current sensing for a large range of currents and voltages.

The ability to monitor twelve total FE devices requires 12 high voltage (HV) voltage sensors, 12 HV current sensors for each tip, and 12HV current sensors for each gate. In addition, other payload devices require HV sensing of up to +/-150V. A dual output HV current sensor is used and the sensor covers a current range on the order of 5 magnitudes. The low end current sensing (for gate/tip) is in the 100nA to 10μA range with 250nA resolution. The higher current sensing (for gate/tip) is in the range of 10μA to 10mA with 1μA accuracy.

Low voltage sensors in the form of voltage and current measurements are placed at various components in the system and sampled at 1 Hz.

4.4.5 Temperature Sensors

Thermal sensing is done with two types of devices. The first is a YSI precision thermistor, 44903 style with an operation temp of -55 to 90 deg C. The thermistor is used with additional circuitry to measure the initial temperature of the circuit as the astronauts flip relay A to power on the FEGI payload. Additional thermistors will be placed on the faceplate for faceplate temperature measurement. The second device is an integrated circuit thermal sensor, an I2C component. There are a maximum of four digital thermal sensors per electronics board. There are four thermistors in the battery box, three at each SVPE doors, and one on each motor. These sensors are sampled at 2 Hz.

4.5 Structures and Thermal

FEGI's structural and thermal design is described below.

4.5.1 Structures Overview

The faceplate provides the mounting surface that exposes payload instrumentation and the SVPEs to the local space environment when the MDA opens. Constructed of 6061-T6 aluminum, the faceplate is bolted directly below the MDAEMP via vented #10-32 UNBRAKO stainless steel screws. As a radiative surface when the MDA is open, the faceplate is coated with a layer of silvered Teflon. This coating is electrically conductive such that the faceplate can serve as the electrical ground for payload instruments.
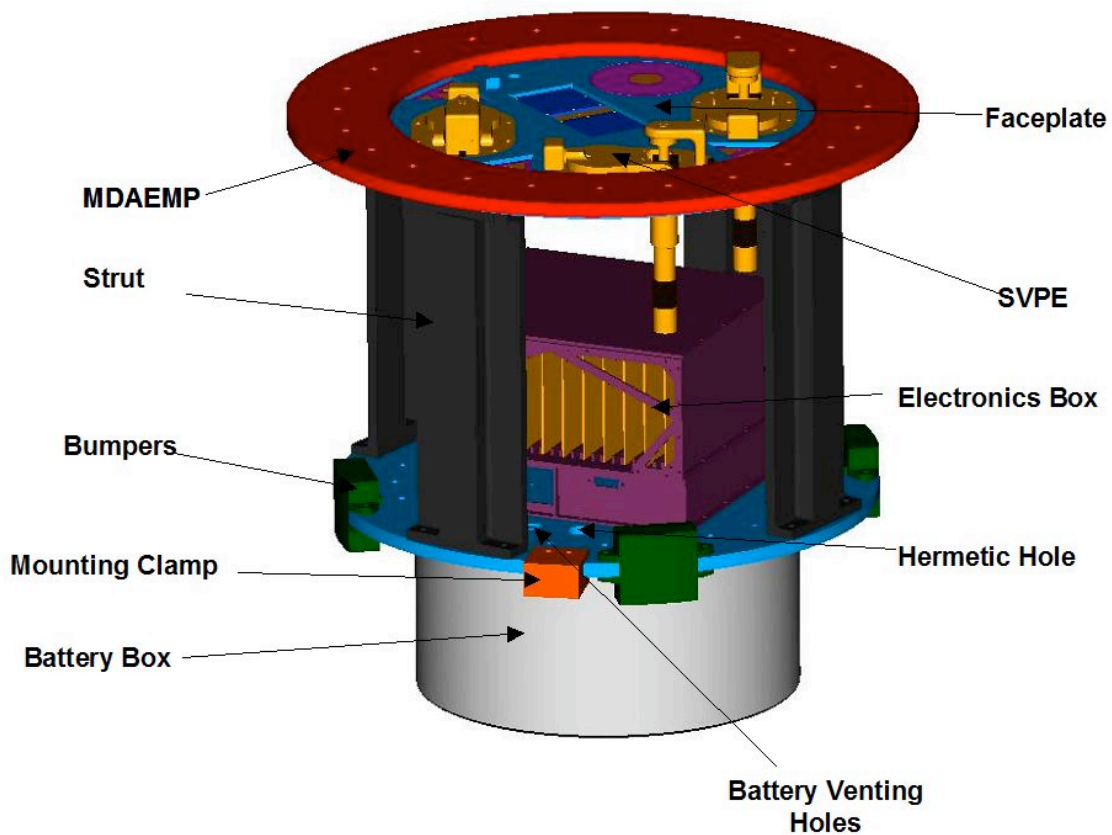

Figure 4.6: FEGI configuration

Four struts compose the primary load-bearing structure for FEGI and the mounting surfaces for the wiring harnesses. The 6061-T6 aluminum struts are placed 90 degrees apart and are parallel to FEGI's vertical axis. Each strut has two #10-32 UNBRAKO screws bolted through the

faceplate into the MDAEMP. A vented 0.25-inch UNBRAKO screw in the center of each strut's footprint bolts to the faceplate in a blind-hole manner.

The lower mounting plate (LMP) serves as the interface between the struts, the support bumpers, and the main electronics box. In doing so, the 6061-T6 aluminum LMP acts as the lid for the sealed battery box and as the base for the electronics housing. To maintain the LMP's integrity as a lid for the sealed battery box, no through-holes other than for power lines and battery vent tubing via hermetic connectors are present within the projected area of the battery box o-ring. Through-bolting of the battery box flange, rather than screwing into blind holes in the LMP, is used to more reliably seal the battery box. A mounting clamp from the ground mounting stand can be attached to the LMP to physically support the FEGI payload during preflight assembly, integration, and testing; the mounting clamp is removed prior to FEGI's integration with the GAS canister.

While not mandated by the Get Away Special (GAS) program, support bumpers are included on FEGI to provide additional lateral support.   The bumper design is based on the Swedish Space Corporation's WIS module, flown as G-730, and has noted heritage on at least five previous GAS missions. Four bumpers are mounted symmetrically about the LMP. The lateral support bumpers prevent the FEGI payload from directly contacting the GAS canister walls during loading conditions. In addition, the bumpers support radial loads at FEGI's non-cantilevered end. The bumper is made of 6061-T6 aluminum, with the bumper itself composed of Viton rubber. Inside the bumper body, a worm gear mechanism is employed to push out the bumper foot to come in contact with the GAS canister. The worm gear is activated by a screw that extends outside the bumper body below the LMP for easy adjustment, satisfying the need for the bumper's positive locking mechanism to be accessible from below the FEGI payload. Since the worm gear is adjusted and locked prior to flight, lubrication for the mechanism is not mandatory.

The main electronics box houses FEGI's supporting electronics and flight computer. To limit the height of the electronics box due to frequency concerns, the electronics boards are slotted vertically rather than horizontally so as to prevent the need of vertically stacking layers of boards. To prevent against electromagnetic interference concerns, the electronics housing is divided into two levels. The more massive power supply section is isolated on the lower level so as to minimize mass-intensive supports within the housing itself; on the upper level, up to 15 analog and computer boards are vertically slotted into a single level of the rack. A backplane board contains I2C components for the command and data handling subsystem. To better secure the boards in this orientation as well as to provide a better thermal contact with the boards, a Card-Lok system manufactured by Calmark, Inc. is employed.   The electronics housing is oriented such the boards can be accessible from the outside between two struts.

4.5.2 Battery Box

The battery box was constructed and delivered by PSU for final integration into the EDU. The EDU battery box is of cylindrical shaped (spun aluminum) housing a square, HDPE (high density polyethylene) encasement that secures the 110 batteries in place.   The battery box secures to the lower mounting plate and is held at 1 atm, preventing risk of battery outgassing. Venting holes are in place on the LMP to stabilize battery box pressure.

<u>4.5.3 Heaters</u>

To ensure operating temperatures in the LEO environment, some critical components are fitted with heaters to raise temperatures to operating levels. The 15 W heaters made by Minco 15 watts are secured on the batteries, pressure sensor, and the faceplate. Due to cost, the heaters are not a part of the EDU but would have been a part of FEGI given the guarantee of flight.

5. ENGINEERING DESIGN UNIT OVERVIEW

The Engineering Design Unit's purpose was to fabricate, test, and validate the FEGI concept into a working and functional prototype. Additionally, the EDU served to encourage and facilitate exclusive construction by S3FL of a student-run satellite project from design to completion. The completion of the EDU showed S3FL's ability to reach the objectives from design to fabrication to completion.

Due to the cancellation of the GAS program, the EDU is the final product of the FEGI program. However, the knowledge gained through fabrication, assembly and test are relevant for future S3FL supported programs. Lessons learned in the EDU will be used in future projects to increase productivity, efficiency, and success. Furthermore, the FEGI EDU has developed hardware that will be used in FEGI-spawned programs, such as the mFEGI and FENIX projects.

5.1 FEGI EDU vs. FEGI Flight

The EDU has distinct differences versus the flight version of FEGI:
- Only one SVPE was fabricated and integrated.
- The EDU was tested using power supplies to mimic 31.5V from batteries to save on consumption of batteries during testing.
- The wiring scheme was less compact for flexibility during test.
- The connectors between e-box and electronics boards were standard D-sub connectors, not flight-grade selected connectors.
- E-box card configuration included only one FE card instead of 6.
- Backplane designed for D-sub connectors instead of flight grade connectors chosen for flight model.

Decisions on differences in EDU design were chosen to cut down on cost and time while still keeping the maximum and relevant result of testing for the EDU phase. The EDU was successful in mimicking flight version functionality.
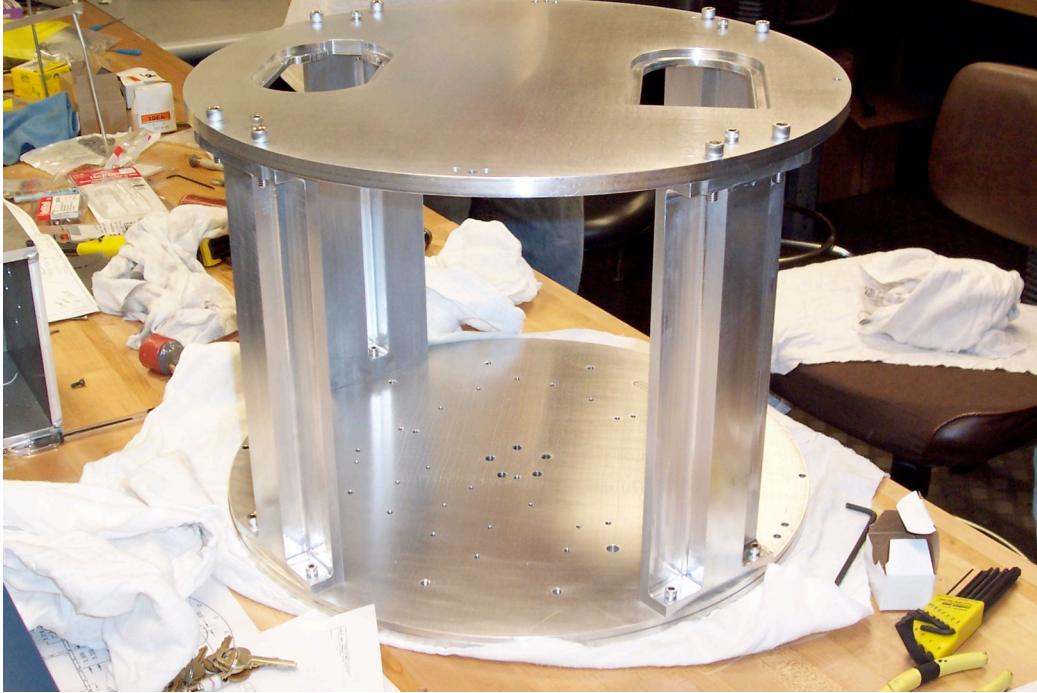
5.2 EDU Pictures

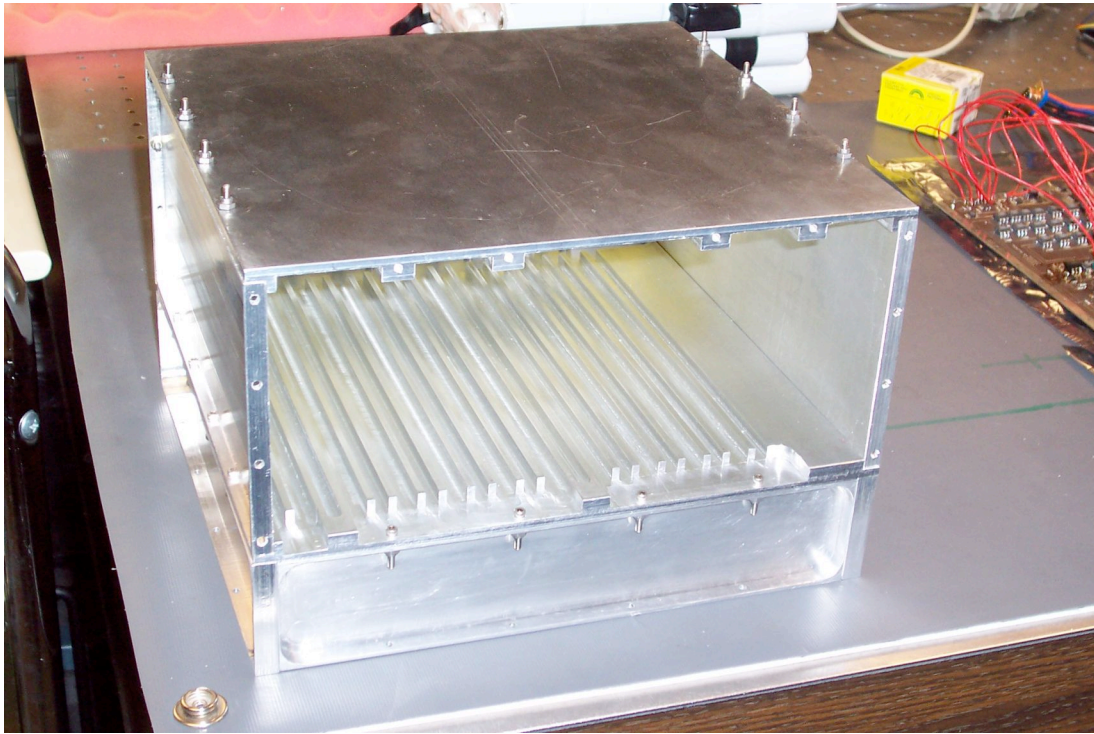Figure 5.1: EDU faceplate, struts, and lower mounting plate
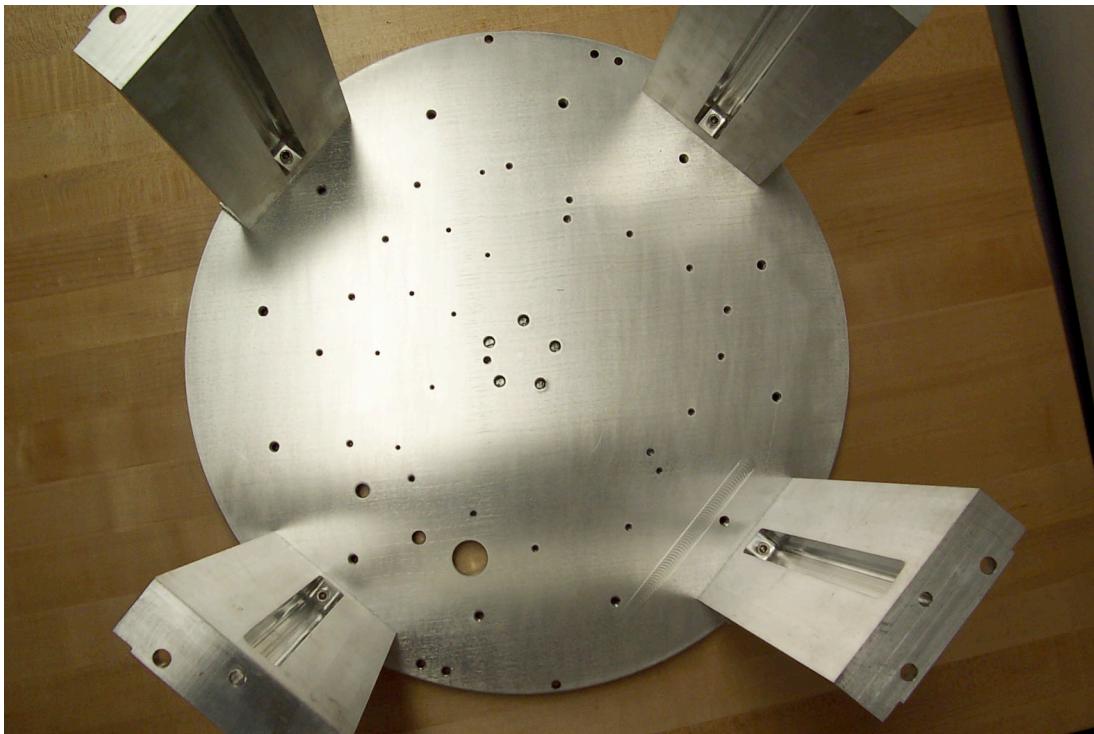
Figure 5.2: EDU electronics box

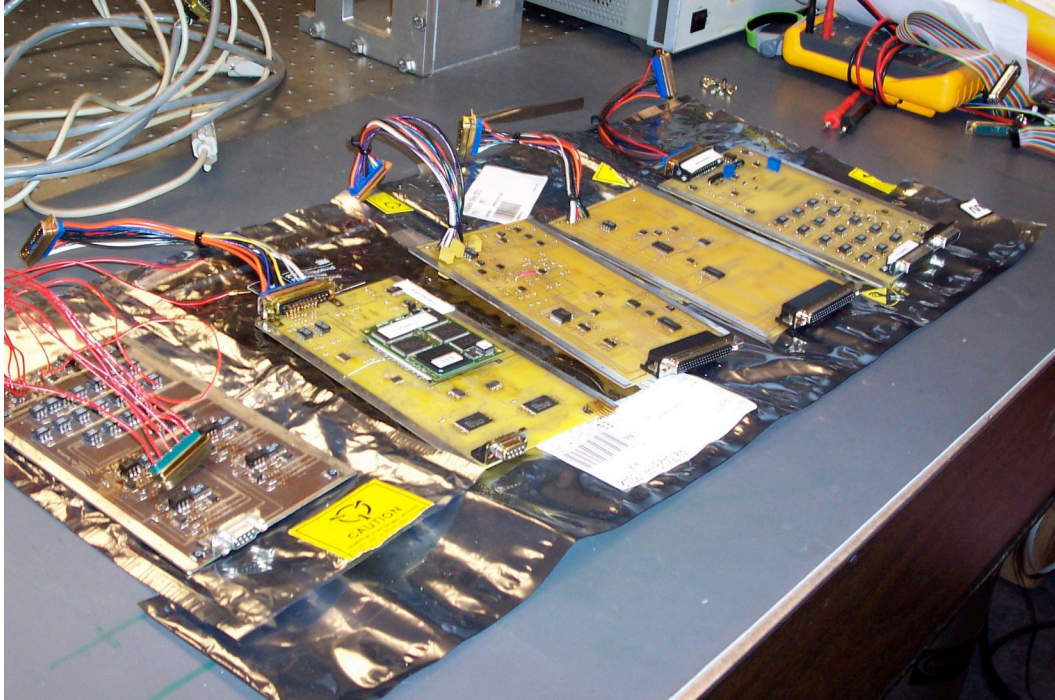Figure 5.3: EDU lower mounting plate and struts

Figure 5.4: E-box prototype electronics cards:
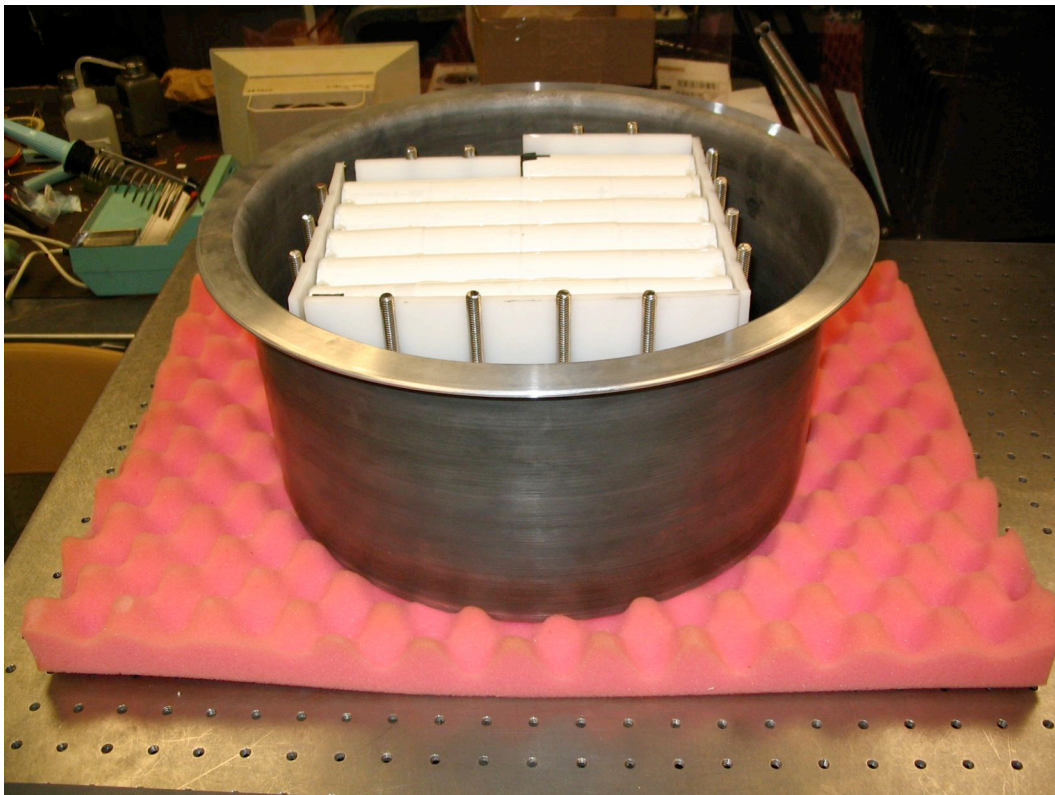Left to right - FE board, C&DH board, Payload board #2, Payload board #1, SVPE board

Figure 5.5: Battery box housing battery pack

6. FINAL SYSTEMS TEST

The final systems test of the EDU was the culmination of the FEGI programs. Individual subsystem components, while separately tested, will be jointly tested for the first time. The goal was to complete the following outline for this test.

- Ensure proper functioning of power supply.
- Check response of all I2C components.
- Store data to flash.
- Open/Close SVPE. Ensure accurate reading of three proximity sensors and motor sensors.
- Test FE switching.
- Ensure safe and accurate control of power supply using DAC and HVPS
- Run Busek-Type Emitter current sweep experiments
- Simulate Payload inputs.
- Test the shutdown sequence.
- Run FEGI lifetime mission.

Due to time constraints, the close of the college semester, and termination of FEGI project, the final systems test did not meet all of the objectives. The FEGI team did however manage to complete the EDU unit. While both hardware and software were separately prepared, they could not be adequately integrated in time.

7. INTEGRATED SYSTEMS TEST

Integrated Systems Test were milestones of FEGI's development. Each IST test met with success.

7.1 IST Test 1

The first major IST test occurred in June 2004. The primary objective of the IST Test One was to control the SVPE motor by the stand-alone FEGI computer processing unit. The processor was required to run the Alpha Build of the FEGI software code that included threads, buffers, and alarms. Three secondary objectives were to output the data to the flash memory, to execute a simulation experiment, and to gather data using the housekeeping and MESA data threads. The high voltage control test was set as a tertiary objective.

7.2 IST Test 2

The second IST test occurred between July 24 and July 28, 2004, in the Plasmadynamics and Electric Propulsion Laboratory (PEPL) lab. The primary objective of the IST Test Two was to control the field emitter located in the SVPE assembly in vacuum by the stand-alone FEGI computer processing unit. The processor was required to run the FEGI software code that included threads, buffers, and alarms. The code was required to open the SVPE door, run a variety of function objectives (FO's) for the field emitter, and close the SVPE door at the end of

the experiment. Data collection was handled by Hyperterminal and Labview, so the Flash memory setup was not used for this test.

8. SUMMARY

The University of Michigan's Field Emission Get-Away Special Program was terminated May 2005. It saw the completion of the Engineering Design Unit, the success of which will be passed on to future S3FL projects. The lessons learned in the four-year lifetime of FEGI have been extremely beneficial not only to those who have worked on the project but also to future student engineers inheriting the legacy and knowledge of S3FL. Whether it was for credit, volunteer, or work-study, every student who worked on FEGI became a more practical, wiser, and capable engineer. They will make valuable contributions to their future fields that will be strengthened by their personal and professional involvement in FEGI and S3FL. Despite cancellation, the students endured to continue to create a successful product worthy of flight.

9. ACRONYMS

CDR	Critical Design Review
CTC	Contamination Test Coupon
C&DH	Command and Data Handling
EDU	Engineering Design Unit
FE	Field Emitter
FEGI	Field Emission Get-Away-Special Investigation
FENIX	Field Emission Nanosatellite Experiment
GAS	Get Away Special
HDPE	High Density Polyethylene
HOPG	Highly Oriented Pyrolytic Graphite
I2C	Inter-Integrated Circuit: Communications Protocol
ISS	International Space Station
LEO	Low Earth Orbit
LMP	Lower Mounting Plate
LP	Langmuir Probe
MDA	Motorized Door Assembly
MDAEMP	Motorized Door Assembly Experiment Mounting Plate
MESA	Miniature Electrostatic Analyzer
MFEGI	Modular FEGI
ProSEDS	Propulsive Small Expendable Deployer System
PSU	Pennsylvania State University
P&E	Power and Electrical
S3FL	Student Space Systems Fabrication Laboratory
SVPE	Small Vacuum Protective Enclosure
TSATT	Tether Systems Assessment Through Teaming
UM	University of Michigan

10. RELATED/ REFERENCED DOCUMENTS

Program Objectives
- Systems Overview
- FEGI White Paper
- Systems Baseline Document
- Integrated Master Schedule

Project Requirements
- GAS Payload Accommodations Requirements (PAR) Document
- FEGI Requirements Document (FEGIRD)
- Requirements Compliance Matrices

NASA GAS Submissions
- Safety Data Package (SDP)
- Structural Verification Document (SVD)

Configuration Control
- Subsystem Baseline Documents
- Master Catalog of Parts
- Electronics Master Document
- Subsystem Interface Control Documents (ICD)

Systems
- Budgets: mass, power, data, & cost
- Quality Assurance Plan (QAP)
- Risk Assessment Document
- Acceptance Plan
- Integration & Assembly Plan
- Operations Plan
- Ground Safety Document

Subsystems
- Test Plans
- Technical Drawings
- Procurement/ Manufacturing Plans
- Assembly Plans
- Fault Trees

Miscellaneous
- Materials List
- Contamination Control Plan
- Wiring Plan
- EMI/ EMC Control Plan