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AN OVERVIEW OF THE ON-ORBIT RESULTS FROM THE ESEX FLIGHT EXPERIMENT

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Abstract

The United States Air Force Research Laboratory's Electric Propulsion Space Experiment (ESEX) was launched and operated in early 1999 in order to demonstrate the compatibility and readiness of a 30 kW class ammonia arcjet subsystem for satellite applications. ESEX was one of nine experiments on the USAF's Advanced Research and Global Observation Satellite (ARGOS). Preliminary results indicate the system operated nominally, and all data verify the interoperability of high power electric propulsion with nominal satellite operations.

Introduction

The Electric Propulsion Space Experiment (ESEX) is a 30 kW ammonia arcjet sponsored by the USAF Research Laboratory with TRW as the prime contractor. The experiment objectives (which were all met) were to demonstrate the feasibility and compatibility of a high power arcjet system, as well as measure and record flight data for subsequent comparison to ground results.[1-3] The flight diagnostics included four thermo-electrically-cooled quartz crystal microbalance (TQCM) sensors, four radiometers, a section of eight gallium-arsenide (Ga-As) solar array cells, electromagnetic interference (EMI) antennas, a video camera, and an accelerometer. ESEX is one of nine experiments on the USAF's Advanced Research and Global Observation Satellite (ARGOS). ARGOS was launched on 23 Feb 99 from Vandenberg AFB, CA on a Delta II into its nominal orbit of approximately 460 nmi (846 km) at 97° inclination.[4-5] Once on-orbit, the satellite was operated from the RDT&E Support

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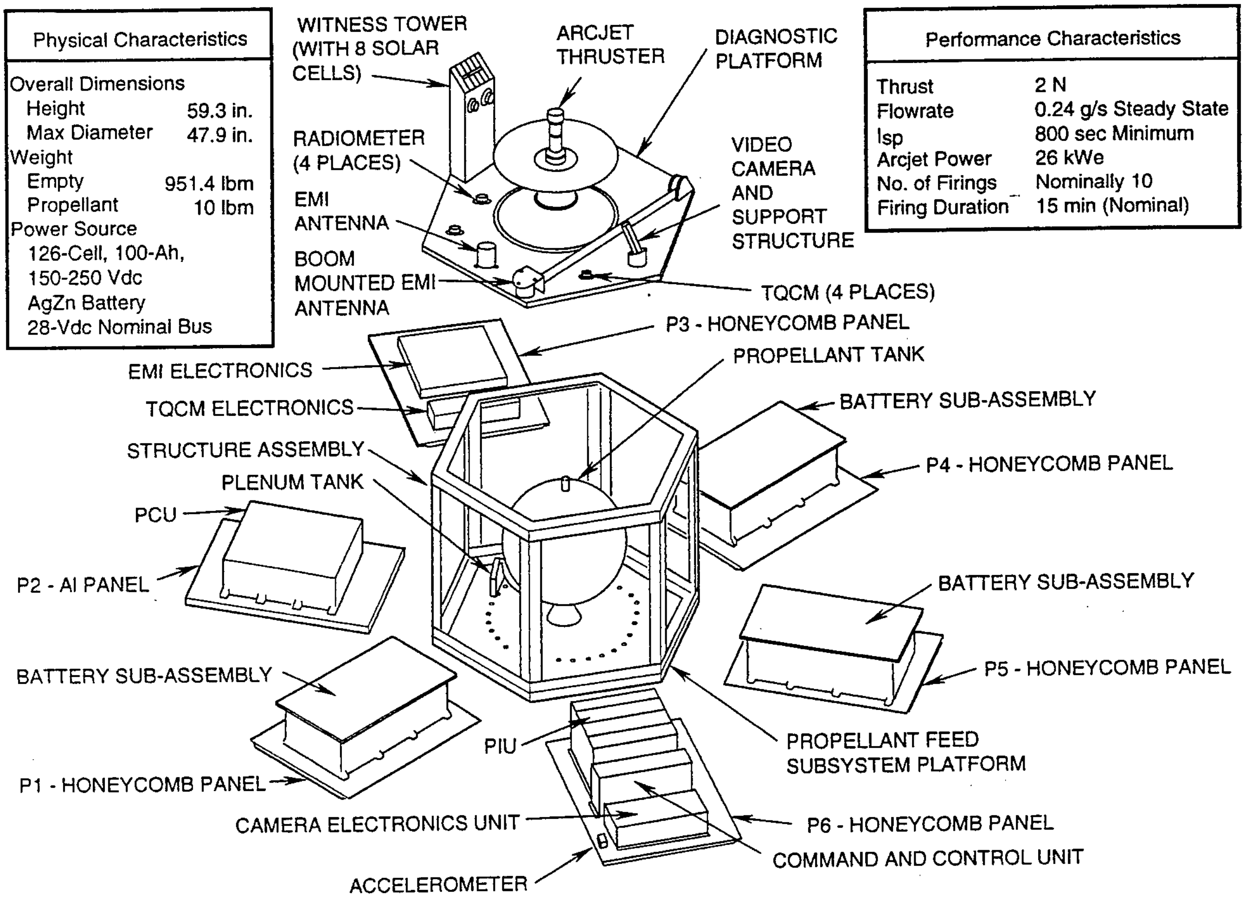

Physical Characteristics	
Overall Dimensions	
Height	59.3 in.
Max Diameter	47.9 in.
Weight	
Empty	951.4 lbm
Propellant	10 lbm
Power Source	
126-Cell, 100-Ah, 150-250 Vdc AgZn Battery	
28-Vdc Nominal Bus	

Performance Characteristics	
Thrust	2 N
Flowrate	0.24 g/s Steady State
Isp	800 sec Minimum
Arcjet Power	26 kWe
No. of Firings	Nominally 10
Firing Duration	15 min (Nominal)

Figure 1. Exploded view of the ESEX flight unit

Complex (RSC) at the USAF Space and Missile Test and Evaluation Directorate at Kirtland AFB, NM.

The ESEX flight system, Figure 1, includes a propellant feed system (PFS),[6] power subsystem[7] - including the power conditioning unit (PCU)[8] and the silver-zinc batteries, command~~ing~~ and telemetry modules, the on-board diagnostics discussed above,[1] and the arcjet assembly.[8] ESEX was designed and built as a self-contained experiment to minimize the impact of any effects from the arcjet firings on ARGOS. This design allowed ESEX to function somewhat autonomously, requiring ARGOS support only for attitude control, communications, radiation-hardened data storage, and housekeeping power for functions such as battery charging and thermal control.

The ESEX flight operations focused on scheduling firings concurrent with observable passes over ground-based sensors in northern California and Maui. The eight firings were executed mostly without incident, and the arcjet, PCU, and PFS performed very well. Ultimately, however, there was an anomaly with the battery that precluded any further firings.

Data from all of the on-board diagnostics were collected for each of the firings. Several ground-based measurements were also performed for specific firings as described below. In general, the performance of the thruster was nominal, and there were no deleterious effects observed on any of the on-board diagnostics or on the spacecraft operations. An optical survey of the startup and ramp to full power was acquired from the on-board camera, and ground-based spectra of the arcjet firing were acquired. These results are summarized below, and are described in detail elsewhere,[9-12] following a summary of the flight operations. This paper concludes with a discussion of the two flight anomalies experienced during the mission.

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[illegible]

Flight Operations Overview

Pre-Launch Activities - After a substantial test and evaluation program[13] of the ARGOS spacecraft, the satellite (with ESEX integrated) was shipped to Vandenberg AFB for launch. After a functional verification was performed, ARGOS was mated to the Delta II to complete the final launch readiness preparations. A series of tests were conducted while the vehicle was in this configuration including several functional tests, ESEX and ARGOS battery maintenance, and a communications compatibility verification with the Air Force Satellite Control Network (AFSCN).

Launch Attempts - There were 10 scrubbed launch attempts, the bulk of which resulted from inclement weather. The weather restrictions were mostly governed by winds aloft that either violated the maximum loading requirements on the Delta II fairing, or that would have created a potential hazard for falling debris on populated areas. The vehicle was finally launched successfully on 23 Feb 99, and the Delta II placed ARGOS into a nominal orbit of 456.9 nmi (846.2 km) at an inclination of 98.73°, with an orbital period of 101.6 minutes.

Phase I Operations – After the successful launch and first acquisition, the operations settled into the checkout routine for the spacecraft bus and for ESEX. ARGOS completed its nominal initialization except for two issues. The first was a propensity of the Global Positioning System (GPS) receiver to drop out of navigation mode - the method by which a position and velocity solution are determined. This behavior was eventually traced to a signal-to-noise problem, but effectively eliminated the ability of the receiver to support ESEX operations as originally planned.[3]

The second issue was an inability to perform ranging, commanding, and telemetry downlink simultaneously with the AFSCN standard uplink power and command modulation index. This problem first appeared during ground test, and was somewhat expected, but was mostly eliminated a few days into Phase I. The solution required modifying the standard uplink power and command modulation index at each AFSCN site, until a satisfactory communications link was established. This problem did appear periodically throughout the remainder of the ESEX mission, however, and made some of the electromagnetic test objectives difficult to accomplish.

The first ESEX activity following turn-on was to initialize the TQCMs and begin cooling these sensors in order to characterize the vehicle outgassing. This experiment has been done before on other vehicles,[14] and this baseline was acquired to compare these sensors with previous analyses.

On day two, approximately 26 hours after launch, the vehicle received an incorrect GPS initialization vector and went into its "sunsafe" mode – a safe-hold mode that inertially points the arrays at the sun and sheds all unnecessary power loads. This mode optimizes the chances of survival given an anomaly of unknown origin. This anomaly, however, was a known problem (a bad initialization vector) and so the recovery process was started immediately – and Phase I continued approximately 48 hours later.

When ARGOS enters sunsafe (as a part of the power load shed procedure), a series of lower heater setpoints are triggered for the ESEX electronic boxes. This includes the battery panels, which have thermostatically controlled bleed resistors designed to dissipate the battery charge following the end of Phase II. These resistors were engaged as a result of all sunsafe events during Phase II, and so battery charging was initiated immediately following the completion of the sunsafe recovery. It was during this charging cycle that the first of the two ESEX anomalies ~~were~~ was observed. High oscillations on the battery charger output were observed when the battery voltage was above approximately -220 Vdc (the arcjet and battery are connected so that the anode is at ground potential, thus a more negative voltage is "higher"). This was probably related to a problem with the battery cell interconnections (as discussed below) which ultimately led to the battery failure.

As the ESEX battery was charging, the remainder of the ESEX initialization and checkout was completed. This checkout included a verification of all of the electronic boxes, the thermal control system, and the command sequences used to control the majority of the ESEX operations.[15] The ESEX EMI boom was deployed later than originally planned to allow data to be gathered on the TQCM co-located on the boom while the sensor was pointed at the ESEX diagnostic deck. Once all of the initialization activities were completed successfully, ESEX and ARGOS were declared ready to support experiment operations, and Phase II began.

Phase II Operations - Phase II was dedicated to two primary experiments[4,5] - ESEX and the Critical Ionization Velocity (CIV)[4] experiment. The original operations plan[15] called for integrating ESEX firings with CIV releases for the duration of the mission. This concept, however, did not prove logistically feasible due to a shorter amount of time between ESEX firings coupled with mechanical and weather problems at the CIV ground observation sites. This ultimately led to fewer CIV releases than originally planned, but did not dramatically affect either the CIV or ESEX total mission success.

The first ESEX activity in Phase II was to verify the operation of the PFS, and verify the arcjet cold flow thrust would not have a detrimental ~~a~~effect on the

Table 1 - Summary of ESEX arcjet firings and propellant releases

Firing (F) or Release (R) No.	Date/Time	Duration	Location	Comments
R-1 (GN_2)	11 Mar 99 1928 Z	8:29 (509 sec)	Not observed	Initial GN_2 bleed required majority of pass.
R-2 (GN_2/NH_3)	12 Mar 99 0027 Z	1:13 (73 sec)	Not observed	GN_2 bleed completed. NH_3 aborted due to overly restrictive software constraints on PFS heaters.
R-3 (GN_2/NH_3)	12 Mar 99 1258 Z	1:59/3:59 (119/239 sec)	Not observed	All systems operated nominally. Liquid ingestion first observed.
F-1A	13 Mar 99 1240 Z	N/A	MSSS	First arcjet ignition (on 10th start pulse), but firing aborted due to overly restrictive software constraints on mass flow rate.
F-1B	15 Mar 99 1210 Z	N/A	MSSS	Firing attempt aborted due to overly restrictive software constraints on PFS heaters.
F-1C	15 Mar 99 2155 Z	2:21 (141 sec)	CPCA	Modified firing sequence to account for liquid ingestion and ensure vapor outflow to arcjet. CPCA performed passive data collection.
F-2	19 Mar 99 2232 Z	5:01 (301 sec)	CPCA	All systems operated nominally. CPCA acquires first active data set.
F-3	21 Mar 99 1224 Z	5:33 (333 sec)	MSSS	All systems operated nominally. MSSS acquires first space-based arcjet spectra.
F-4	23 Mar 99 2127 Z	8:02 (482 sec)	CPCA	All systems operate nominally except for low battery voltage - causes arcjet to shut off early. First indication of battery trouble.
F-5	26 Mar 99 2145 Z	5:04 (364 sec)	MSSS	Low battery voltage forces early termination. Telemetry problem makes operating arcjet difficult. More firing spectra acquired.
R-4 (NH_3)	30 Mar 99 0636 Z	9:54 (504 sec)	N/A	Attempted PFS heater modifications to eliminate liquid ingestion do not succeed.
F-6	31 Mar 99 1305 Z	4:30 (270 sec)	MSSS	Low battery voltage forces early termination. Telemetry problem reduced by increasing ground transmitter power. More firing spectra acquired.
F-7A/B	2 Apr 99 2209 Z	53 sec/38 sec	CPCA	Attempt to discharge battery as much as possible prior to reconditioning. Arcjet stopped/re-started due to PCU command logic. CPCA acquires start and stop transient data.
R-5 (NH_3)	9 Apr 99 1548 Z	9:06 (456 sec)	N/A	Further attempts to eliminate liquid ingestion with PFS heater modifications do not succeed.
F-8	21 Apr 99 1222 Z	42 sec	MSSS	Battery reconditioning has no effect on arcjet firing time. No MSSS data acquired. No liquid ingestion observed.

ARGOS attitude control system. This validation was accomplished by performing a series of outflows, first of gaseous nitrogen (GN_2), and then of ammonia (NH_3) while monitoring the ESEX and ARGOS state of health telemetry. The GN_2 outflow was conducted over two passes to allow enough time to evacuate the plenum tank to < 1 psia. The NH_3 outflow also required two attempts before it was accomplished successfully with the initial problems attributable to a series of software constraints that proved too restrictive for the on-orbit conditions. Once these constraints were relaxed, the outflow was executed successfully. These, and all of the outflows performed over the course of the mission, are included in Table 1 as a part of the arcjet firing summary.

During this initial NH_3 outflow the data indicated that the plenum tank ingested a slug of liquid NH_3. This was not expected since it was not observed in any of the ground tests (later analyses show it may have actually been present). In order to remedy the problem, an operational solution was implemented to allow enough time for the plenum tank to vaporize the liquid, and the downstream flow rate to stabilize prior to arcjet ignition.

Once the PFS operation was verified, the arcjet firings were initiated. The firings were all conducted over two ground sites to facilitate ground-based observations.[15] These two sites are the 1.6m telescope at the Maui Space Surveillance Site (MSSS) for optical observations[9] and the Camp Parks Communications Annex (CPCA) in Dublin, CA for the communication experiments.[10] A brief summary of all of the arcjet firings is included in Table 1.

The first two firing attempts (F-1A and F-1B) were aborted due to software constraints similar to those experienced during the initial NH_3 outflow. The arcjet actually ignited on the first firing attempt (F-1A) on the tenth start pulse (probably due to contamination on the cathode), but was aborted within 2-3 seconds due to an overly restrictive constraint on the mass flow rate during the ramp to full power. The second firing attempt (F-1B) was aborted prior to the ignition command. The first successful arcjet firing (F-1C) was completed later that day, however, after a more thorough review of the software restrictions revealed no further constraints. This firing, and every subsequent firing, ignited on the first start pulse. The planned duration for the first firing was ~~four~~ 4 minutes,[15,16] but was terminated after 141 seconds because the pass was ending. The available time for firing during the pass was reduced since the operators had to verify vapor outflow to the arcjet following the typical ingestion of liquid NH_3. This firing was performed over CPCA while they were in a passive (i.e., "listen only") mode. Results acquired from CPCA are discussed briefly below, and detailed in another article.[10] Subsequent firings required similar waiting periods to verify vapor was present at the arcjet prior to ignition.

Battery charging was conducted between each firing, which were scheduled on high elevation passes at either MSSS or CPCA. This scheduling philosophy maximized the opportunities to collect data, but forced the duration of each firing to be limited by the amount of charging performed.

Phase II proceeded with the seven remaining firings, as well as a total of 16 CIV releases (using xenon and carbon dioxide). Besides the two anomalies already mentioned (the liquid ingestion and the battery), the entire ESEX flight unit performed flawlessly except for minor telemetry issues associated with the arcjet current and the flow rate pressure. Ultimately, the battery failed catastrophically, causing the vehicle to enter sunsafe, and eliminating any chance of further ESEX firings. This failure occurred within days of the scheduled end of Phase II, resulting in a fairly minor impact to the overall mission success. Once the battery was stabilized, ESEX was placed into a long-term discharge configuration for the Phase III portion of the ARGOS mission. ESEX is continuing to collect data from the on-board sensors until the flight unit power is disabled.

Preliminary Science Results

Although the mission was shortened somewhat by the battery failure, there was still an enormous amount of data collected during this unique opportunity. The science data was divided into sections corresponding to the scientific objectives and the specific sensors.[3,15] These areas are optical observations, electromagnetic interactions, performance, and contamination measurements.

As the on-board diagnostic data continue to be transmitted and processed, analyses will also continue. The following data are the initial results from the experiment, and only constitute the preliminary analyses performed to date. As further data are reduced and analyzed, these results will be updated.

Optical Observations - The optical observations were made from one ground-based sensor, the 1.6 m telescope at MSSS, and one on-board sensor, the still frame video camera.[9] These sensors were used to determine the optical properties of the plume in an attempt to understand the arcjet loss mechanisms (i.e. anode heating, frozen flow losses, etc.) as well as evaluate the effects of performing similar measurements in ground-based facilities.

The on-board camera acquired images during each of the eight firings with several different shutter speed settings. Unfortunately, there were not enough firings to test the full dynamic range of the camera, and there were several images that were mostly washed out by

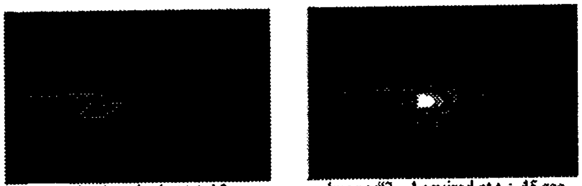

Image #1 - Acquired at t + 15 sec

Image #3 - Acquired at t + 45 sec

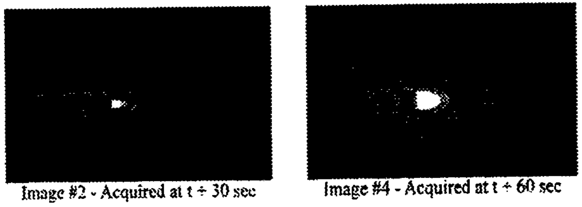

Image #2 - Acquired at t + 30 sec

Image #4 - Acquired at t + 60 sec

Figure 2 - Series of images acquired from the on-board video camera showing the ramp up to full power

the thruster at full power. There was, however, a significant survey of images of the arcjet during the first 90 seconds of operation which illustrate the rapid heating of the anode and the extent of the plume. A series of images is shown in Figure 2, which illustrate this startup period and the majority of the 70-second ramp to full power.

The MSSS data were acquired on the 1.6-m telescope over a series of wavelengths ranging from ultraviolet to visible. Calibration data were also acquired over a range of weather conditions and viewing angles in order to determine the effect of quenching through the atmosphere, as well as gauge the sensitivity of the instrumentation. A preliminary analysis was performed on the data acquired for firing #3 which generally indicate features observed in ground-based testing are repeated on-orbit.

Electromagnetic Interactions - The impacts of a 30 kW class arcjet on spacecraft communications and operations have always been a major integration concern. In order to address as many of these potential issues as possible, a series of tests were performed during the ESEX mission. These tests included measurements from the EMI antennas, communication bit error rate (BER) tests to quantify the effect of the arcjet on the ranging signal, and uplink/downlink tests to qualitatively verify the communication link integrity.[10] The results from the uplink/downlink test, and other qualitative results from the performance of the ARGOS subsystems, are still being evaluated, and will be presented in a future article.

The on-board EMI antennas measured the radiated emission from the arcjet in the lower gigahertz communication frequencies (e.g., S-band, X-band, etc.) The antennas sample 2, 4, 8, and 12 GHz signals with a ±5% bandpass filter on each channel. Data were gathered on the antennas for each of the eight firings, during quiescent spacecraft periods, and during routine spacecraft operations. The firing and non-firing data sets were compared in order to identify any effects from the arcjet operation. At no time did the antenna measurements during arcjet firing periods differ from non-firing data. This result compares well with ground test data.[17]

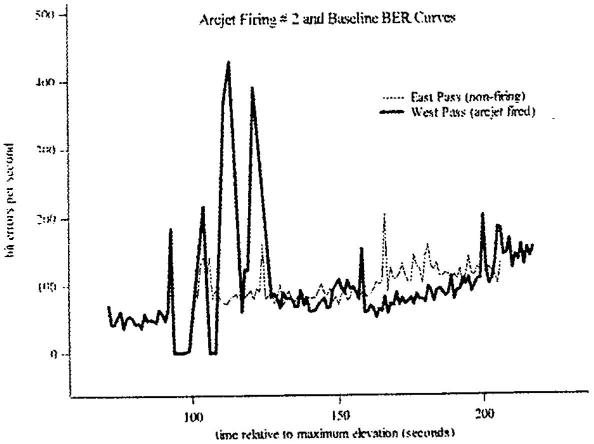

Figure 3 - Representative bit error rate data for firing #2 displayed with baseline pass taken under similar conditions.

The bit error rate test enabled a quantified assessment of the effect of the arcjet on the satellite ranging channel. This test is performed by replacing the nominal PRN ranging code on the satellite with a test pattern from CPCA and determining the number of bit errors on the return signal using a BER counter.[3,10,15] A series of baseline measurements were made while the arcjet was off, and with the vehicle in several transmit configurations for comparison with firing data. Figure 3 shows an example of the BER data with the arcjet firing vs. a baseline measurement in which there is no definitive effect from the arcjet. The BER data is displayed as the number of bit errors per second vs. time and trends proportionally with changes in slant range - the shortest distance from the ground station antenna to the satellite.

CONCLUSION?

Performance - The performance was measured by three different techniques: an on-board accelerometer, ranging data from the AFSCN sites, and the ARGOS GPS receiver.[11] The performance data from each of these three different techniques agree to within 1%.

The on-board accelerometer data were collected for all eight firings and all of the outflows since this instrument was always on. There are a number of uncertainties in the thrust derived from the acceleration measurement including thermal drift, spacecraft mass, and systematic uncertainties associated with the accelerometer, PFS, and PCU. Figure 4 shows a summary of the performance for all of the firings plotted against the ground test data on the engineering model hardware. This figure shows the data corrected for a suspected telemetry problem with the current sense transformer in the PCU.[11] Preliminary analyses indicate that the arcjet current telemetry repeatedly read approximately 6% high. Although this cannot be verified, much of the data examined to date appears to agree with the corrected numbers presented here.

The AFSCN ranging data is typically used for spacecraft orbit determination in support of nominal satellite operations. For the ESEX mission, this data ~~were~~ was also used to determine the performance of the thruster by comparing the orbit solutions before and after a firing. This technique provided an independent verification of the thruster performance by measuring the total Δv imparted to the spacecraft. Although the analyses have not been fully completed, Table 2 summarizes the results of the eight firings. Since ESEX fired into the velocity vector, all of the numbers are negative (i.e., energy is being removed from the orbit).

Table 2 - Summary of performance results from the AFSCN ranging

Firing No. - Duration (sec)	Δv (m/sec)	Change in semi-major axis (m)
1 - 141	-0.11	-216
2 - 301	-0.26	-505
3 - 333	-0.27	-530
4 - 482	-0.40	-783
5 - 364	-0.32	-638
6 - 269	-0.23	-440
7 A/B - 53/38	-0.07	-128
8 - 42	-0.05	-57.5
Total = 2,023 sec	-1.71 m/sec	3,298 m

Since the GPS receiver experienced some difficulty on-orbit, only a limited data set was acquired. Analyses on this data continue, but preliminary results agree well with the AFSCN ranging data and the accelerometer data presented here.

Contamination Measurements - The contamination sensors - the TQCMs, the radiometers, and the solar array segment - all acquired data throughout the duration of the mission, and will continue to collect data until ESEX is powered off. The radiometers and the solar array are passive instruments (since they cannot be commanded), while the TQCMs can be driven to hot or cold extremes to affect their deposition sensitivity.[3,12]

The radiometers were used to measure the radiated heat load resultant from firing the arcjet. Based on the preliminary analysis, it appears that the time response of the sensors was too large to attain a steady-state condition as a result of the shorter-than-expected firings. A transient analysis of the heat loading on these sensors indicates the thermal input from the arcjet increase is approximately 0-0.5 Watts.[12]

The solar array segment was designed to measure the open circuit voltage and short circuit current of two sets of four Ga-As cells. The data analyzed to date do show the effect of the bright anode on the open circuit voltage and the short circuit current. There does, however, appear to be an effect on the voltage as a result of the arcjet plume that suggests there is a current path

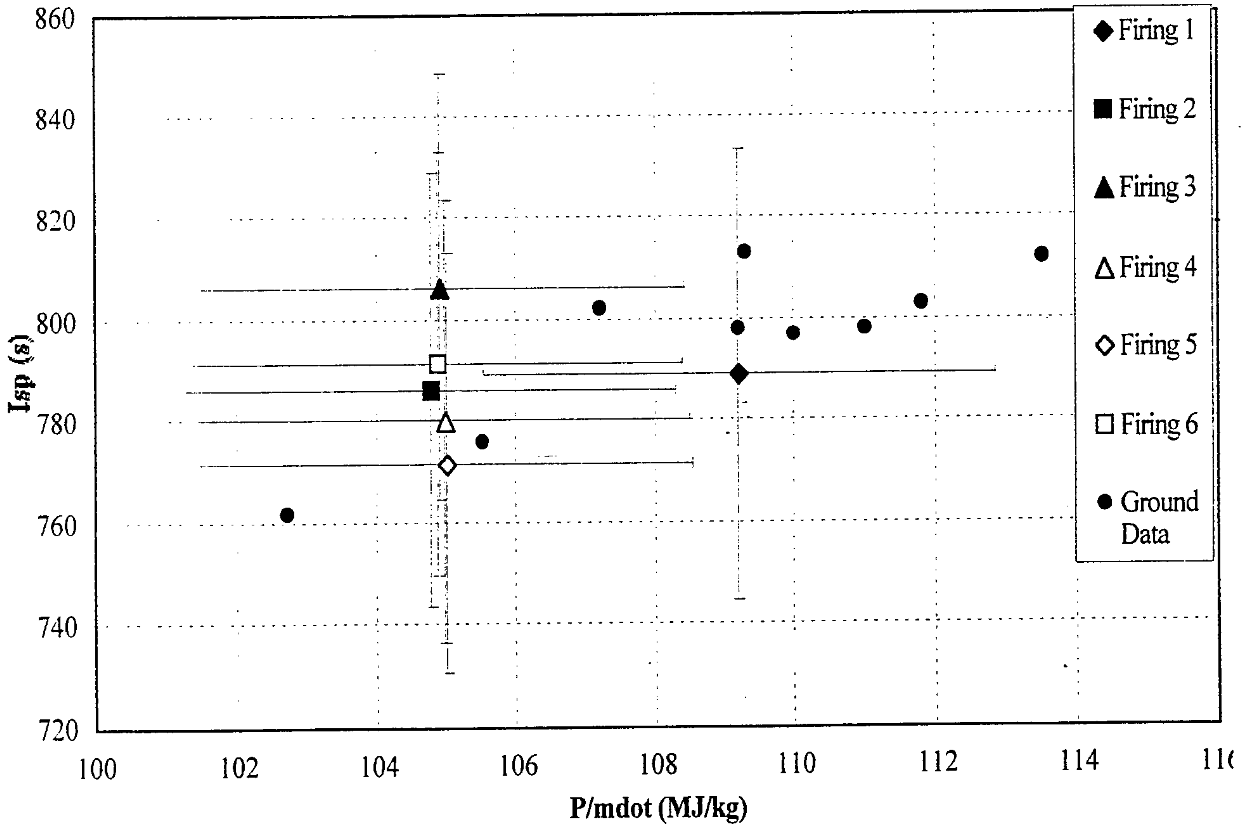

Figure 4 - Summary of the arcjet on-orbit performance

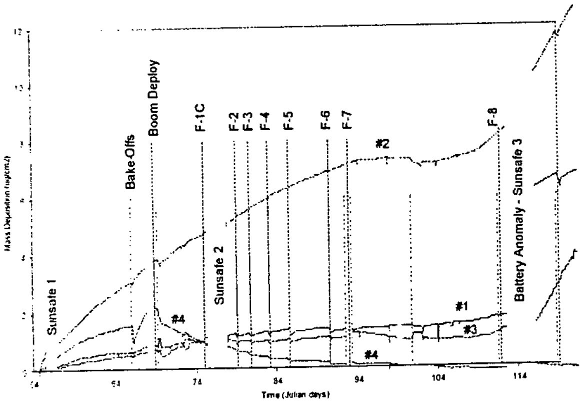

Figure 5 - Summary of TQCM effects from the arcjet firings

between the sensor circuit and the plume.[12] The resultant effect is a period of reduced solar cell voltage while the arcjet is operating. There also appears to be some longer term effect on the short circuit current.

The TQCMs were powered on approximately 6.5 hours after launch in order to measure the spacecraft outgassing. This data will be compared with data acquired on previous experiments with these sensors,[14] and also presents an opportunity to acquire a baseline of the ambient environment. The data from the TQCMs show an effect from each of the firings, as shown in Figure 5, as a decrease in frequency (indicating a decrease in accumulated mass) proportional to the length of the firing and the relative location of the sensor. As can be seen, however, the frequency recovers to approximately the same value and deposition rate. This is probably a result of ultraviolet radiation from the arcjet plume reacting with the deposited mass on each of the sensors.[12]

Flight Anomalies

The two anomalies discussed in detail below are the liquid ingestion observed in the PFS and the battery anomaly which ultimately led to the conclusion of the ESEX mission. The observed data are discussed, followed by some preliminary discussion of the proposed causes and resultant fixes, if applicable.

Battery Anomaly - The first signs of anomalous behavior in the battery were observed during the first charging cycle, shortly following the first ARGOS sunsafe. The charging circuit operated nominally (except for a low output current) until the battery voltage approached -225 Vdc. At this point, as shown in Figure 6, the output current from the charging circuit began cycling on and off, resulting in oscillations of the open circuit battery voltage. Initially, this was thought to be a result of a higher-than-expected internal battery resistance. In an attempt to lower the circuit impedance, high inductance filters were switched into the circuit via the high voltage relays connecting the battery with the PCU.[7,8] This did improve the stability somewhat, but did not eliminate the fluctuations. Since this instability was not detrimental to the ESEX battery or the spacecraft bus, it was decided to charge through this region and realize the charging inefficiencies by extending the charging time. Subsequent charge cycles showed a degrading instability that caused the charging circuit to shut off prior to attaining a full state of charge in the battery. Further analyses seem to indicate these charging instabilities were indicative of the ultimate problem, which appears to be related to the mechanical properties of the interconnections between the battery cells.

Beginning on firing #4, further anomalous behavior on the battery output started appearing which resulted in a limited total firing duration. The manifestation of this anomaly was low battery output voltage, resulting in an unstable PCU and arcjet operation - eventually extinguishing the arc. As can be seen in Table 1, the duration of each firing after #4 steadily decreased, as the battery performance deteriorated. Ultimately, on firing #7, the arcjet cycled on and off twice (due to the command logic in the PCU) – both firings being extremely short. After this event, the battery was reconditioned by performing a deep discharge through the bleed resistors, and restarting the battery charge. The initial plan was to wait until the battery was at a full state of charge (indicated by the charger circuit shutting off at the upper charge limit) before attempting the next firing. After approximately 19 days, however, the battery charger was commanded off and a firing was attempted. Unfortunately, as can be seen by the short duration of firing #8, the reconditioning was unsuccessful in resolving the problem.

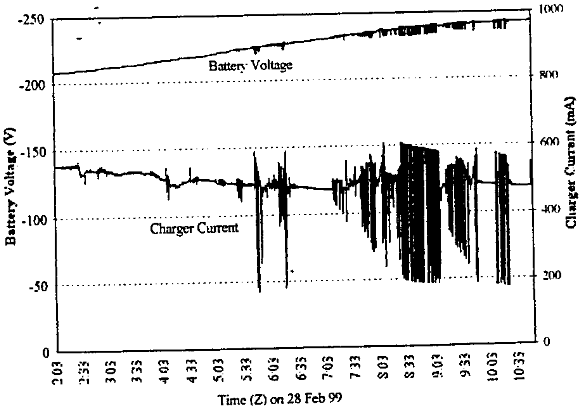

Figure 6 - Typical battery charging circuit instability

Following the completion of firing #8, the battery

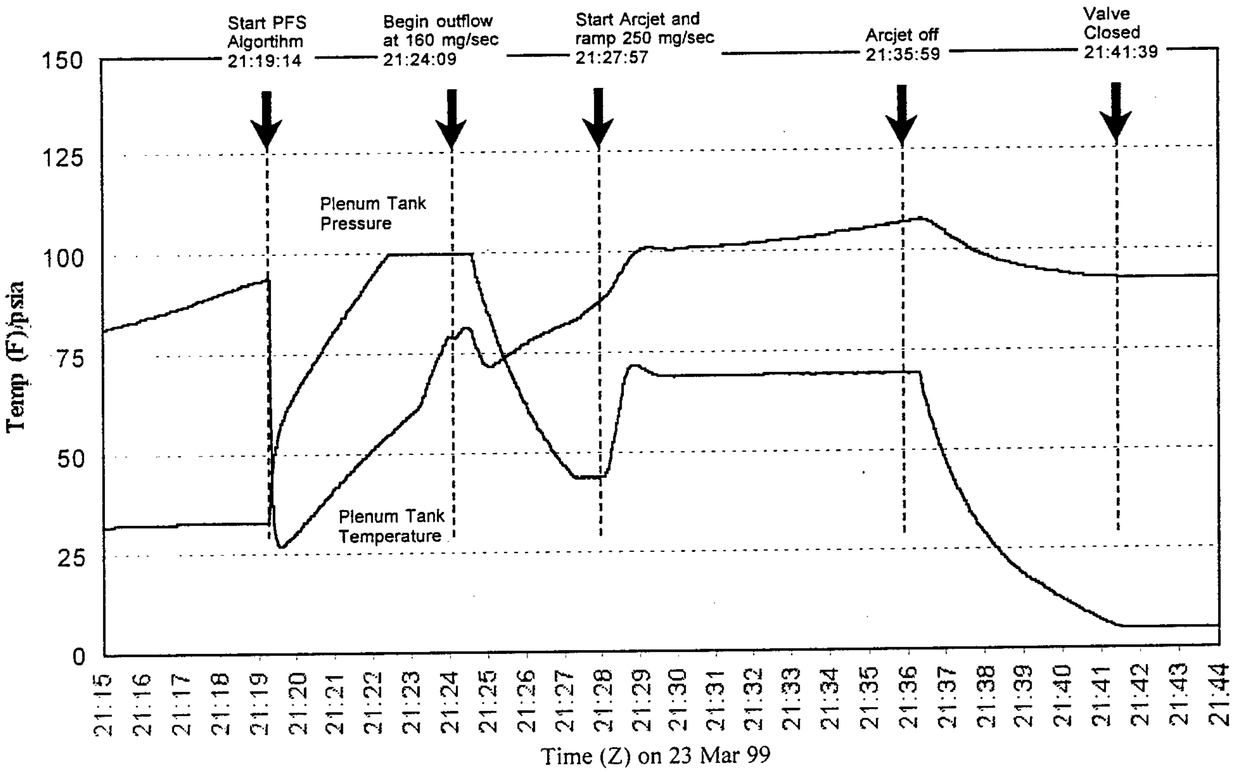

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Figure 7 - Typical PFS performance showing liquid ingestion into the plenum tank

voltage fluctuated erratically between -175 and -200 Vdc with periodic drops as low as -30 Vdc - where it eventually stabilized. This behavior lasted approximately 24 hours until, as subsequent analysis revealed, the battery sub-assembly on panel #1 (see Figure 1) had a catastrophic failure. This failure was probably a result of electrolyte leakage from one of the cells, causing a short circuit to the battery case. As the energy in the cell was discharging internally through the short circuit, there was a dramatic increase in the battery temperature and pressure as hydrogen gas was being generated from the electrolyte. This process continued until there was a breach of the battery case and a release of this super-heated gas internal to the ESEX flight unit. This gas was eventually vented into space, which caused a dramatic attitude disturbance on the vehicle, resulting in a sunsafe event. Further discussion on the contamination e~~a~~ffects from the battery venting is described elsewhere.[12]

The cause of the battery problem appears to be related to the mechanical interconnections between the cells. Although the analyses are not complete, preliminary results indicate the construction of the interconnections allowed the contact resistance to the cell to fluctuate and deteriorate over time (mostly as a function of temperature). This deteriorating contact resistance led to localized heating at the cell during any charge or discharge cycle, but would be greatly enhanced during the high current discharge associated with the arcjet firings. Eventually the heating would be enough to rupture the cell, causing electrolyte leakage, and the short circuit to the battery case. This scenario has not been proven explicitly, but it does account for all of the data observed including the charging circuit instabilities, the decreasing capability to support arcjet firings, and the ultimate failure of the battery.

As mentioned above, this failure actually occurred within a few days of the planned completion of Phase II. The primary result was a reduced number of firings observed from MSSS, which reduced the amount of arcjet firing spectra. This loss accounted for approximately 10% of the total ESEX mission success. The battery was not a part of the demonstration aspect of this mission since an operational system would be powered directly from the spacecraft power system. The critical demonstration components were the arcjet, PCU, and PFS - all of which operated very well.

PFS Liquid Ingestion - The liquid ingestion was initially observed on the first successful NH_3 outflow (see Table 1). Figure 7 illustrates a typical outflow, where the temperature in the plenum tank drops dramatically (between 30-100°F) as soon as the PFS flow control algorithm is initiated.

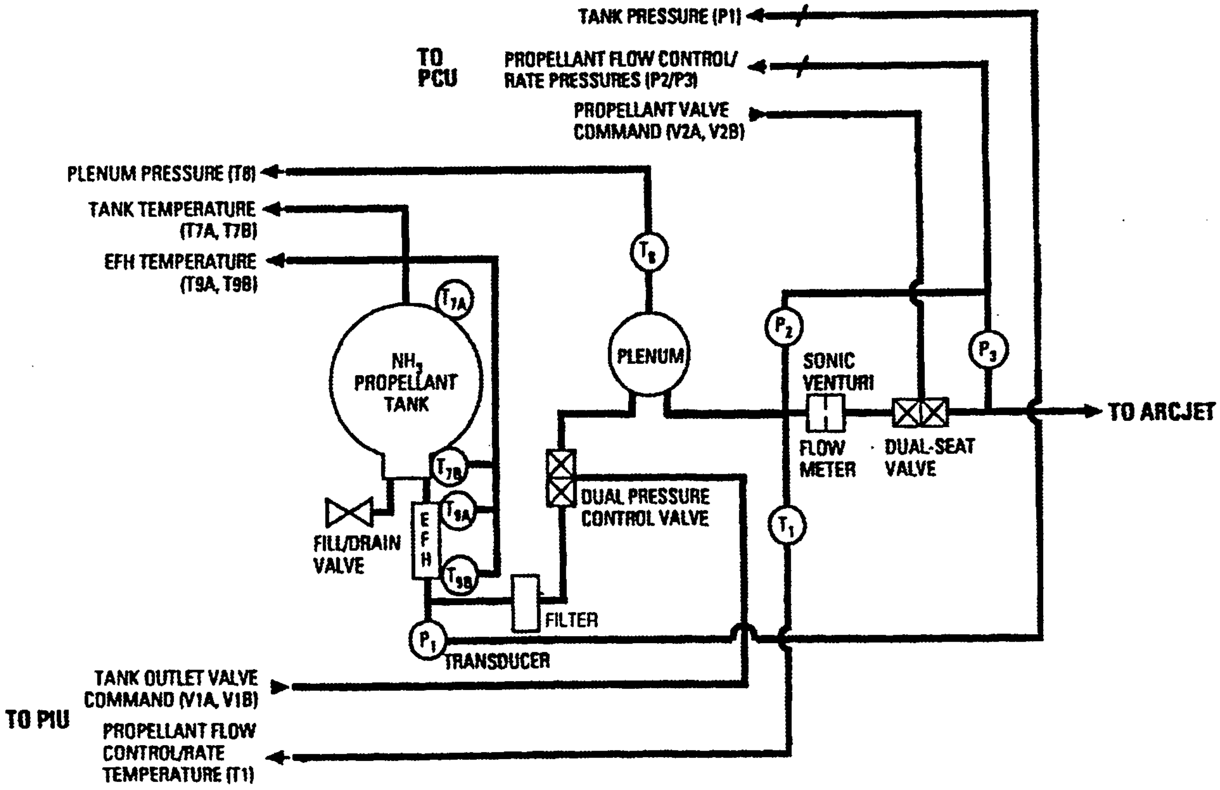

Figure 8 - Schematic representation of the propellant feed system

A schematic representation of the PFS is shown in Figure 8. The operational profile is presented in detail elsewhere[6,15,16] but basically consists of two heating periods prior to the outflow - one at t-17 hours, and one much closer to the event. This first pre-heat period is to ensure sufficient pressure in the propellant tank to support flow, and the second is to heat the system to ensure the impending outflow to the arcjet is vaporized. The PFS algorithm is started just before the firing and controls the NH_3 flow rate by cycling the dual pressure control (DPC) valve to maintain pressure in the plenum tank corresponding to the specified flow rate.

The problem appears to be a cold spot in the propellant line somewhere between the enhanced feedline heater (EFH) and the DPC valve. This cold spot allows NH_3 to condense and collect just upstream of the DPC valve. The liquid ingestion seems to occur only at the initiation of the PFS algorithm, which causes a single cycle of the DPC valve regardless of the plenum tank pressure. This valve cycle releases this slug of liquefied NH_3 into the plenum tank - which is at a relatively low pressure – resulting in a dramatic expansion and evaporation of the liquid. As can be seen in Figure 7, this expansion cools the plenum tank dramatically resulting in a saturated liquid in the tank. As the plenum tank heater vaporizes the ingested liquid, the pressure rises sharply until the transducer output is saturated. Once all of the liquid is vaporized (which must be verified by the operators), the arcjet valve is opened to initiate the flow. However, the plenum tank pressure is higher than required for the initial flow rate of 160 mg/sec, so the excess must be bled off through the arcjet. Eventually (usually 2-3 minutes), the flow would stabilize at 160 mg/sec, and the arcjet was started.

This phenomenon was not readily observed in any of the ground tests. Initially, there were some differences between the flight operations profile and the ground test, primarily the heater setpoints and timing, but ultimately the flight profile was changed to mirror the test flow. This did not, however, alleviate the problem. Further modifications were made to the flight profile (mostly adjusting heater setpoints) but none of these proved successful either.

The root cause of the problem - the cold spot in the system - was possibly a result of a cooler mounting platform than experienced during test. This platform temperature is not actively controlled, and can drift significantly - perhaps leading to a low enough temperature to condense NH_3 at the pressure in the propellant line.

To further support this possibility, there were some variations from the normal procedure on the last firing (F-8) and no liquid ingestion was observed. For that case, the PFS heaters were turned on many hours before the actual firing attempt as a result of waiting for the battery reconditioning to complete. This may suggest the cold spot in the propellant line had enough time to heat up and vaporize the condensed NH_3.

In summary, the liquid ingestion proved to be an annoyance, but did not seriously detract from the arcjet operation. Other than this issue, the PFS performed exceptionally well. The flow rate control generally operated to within ±0.3 mg/sec at steady-state conditions - much better than the design requirement of ±5 mg/sec. If this system evolves into an operational flight design, some heater power applied to the section of the propellant line in question could almost assuredly resolve the issue entirely - especially in light of the results from the last firing.

Conclusions

The ESEX flight demonstrated high power electric propulsion is compatible with nominal satellite operations. Although further analyses are in-work, all of the data analyzed to date indicate the thruster and the high power components have no significant, deleterious effect on any satellite activities.

Summary

ESEX is the culmination of over ~~ten~~ 10 years of effort to validate high power electric propulsion on-orbit and verify its compatibility with standard USAF satellites. There were a total of eight firings conducted over the course of the 60-day mission, all of them over 26 kW, for a total duration of 2024 seconds. There were two anomalies associated with the flight operations - a liquid ingestion problem that had only a minor effect on the mission, and a battery failure that precluded any further firings. Approximately 76% of the ESEX mission success was attained, with the biggest deficiencies resulting from the lack of GPS data, and the optical signature characterization. All of the data analyzed to date indicate the thruster operated nominally, and operated completely independently of the normal operations of the host spacecraft (ARGOS).

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