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Review of the Electric Propulsion Space Experiment (ESEX) Program

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The U.S. Air Force Research Laboratory's Electric Propulsion Space Experiment was launched and successfully operated on the Advanced Research and Global Observation Satellite, demonstrating the compatibility and readiness of high-power electric propulsion. This flight was the culmination of an Air Force technology program to demonstrate the applicability of high-power electric propulsion for satellite applications. A brief history of the program is presented, followed by a description of the flight operations, which successfully demonstrated the critical system components, the arcjet, power processor, and propellant feed system, verifying the interoperability of high-power electric propulsion with satellite operations. The two anomalies experienced during on-orbit operations, and their proposed causes, are also described.

Introduction

THE Electric Propulsion Space Experiment (ESEX) was a space demonstration of a 26-kW ammonia arcjet sponsored by the U.S. Air Force Research Laboratory with TRW Space and Electronics Group as the prime contractor. The program objectives were to demonstrate the feasibility and compatibility of a high-power ammonia arcjet system for satellite operations and to measure and record flight data for comparison to ground results[1–3] in four different areas: electromagnetic interactions, contamination effects, optical properties of the plume, and thruster system performance. The onboard flight diagnostics included four thermoelectrically cooled quartz crystal microbalance (TQCM) sensors, four radiometers, a section of eight gallium-arsenide solar array cells, electromagnetic interference (EMI) antennas, a video camera, and an accelerometer. ESEX was one of nine experiments on the U.S. Air Force Advanced Research and Global Observation Satellite (ARGOS), launched on 23 February 1999 from Vandenberg Air Force Base, California, on a Delta II.[4,5] Once on-orbit, the satellite was operated from the Research and Development, Test and Evaluation Support Complex at the U.S. Air Force Space and Missile Test and Evaluation Directorate at Kirtland Air Force Base, New Mexico.

The ESEX flight system (Fig. 1) includes a propellant feed system (PFS)[6]; power subsystem,[7] including the power conditioning unit (PCU)[8] and a silver-zinc battery; the command and telemetry modules; the onboard diagnostics[1,3]; and the arcjet assembly.[9] ESEX was designed and built as a self-contained system to minimize the impact of any effects from the arcjet firings on ARGOS. This design allowed ESEX to function semi-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, Hawaii. The eight firings were executed mostly without incident, and the arcjet, PCU, and PFS performed well. There were, however, two anomalies experienced during the mission: ingestion of a small slug of liquid ammonia during PFS operations and a battery anomaly that precluded further firings.

Data from all of the onboard diagnostics were collected for each of the firings. Ground-based measurements were performed for several of the firings as well. In general, the thruster performance was nominal and, although there were measurable effects observed, none of the onboard or remote diagnostics indicated any issues with integrating high-power electric propulsion onto spacecraft. Furthermore, none of the firings showed any negative effect on the ARGOS spacecraft or its operations.

This paper provides a summary of the program history including a brief review of the program objectives, describes the flight operations, and concludes with a discussion of the two anomalies experienced during the mission. Companion papers discuss the design and development of the arcjet, PCU, and associated hardware,[9] the integration and test activities,[10] and the results obtained from the onboard and remote instrumentation suite.[11–17]

Historical Summary

ESEX was conceived in the late 1980s as a result of several studies showing the significant benefits of using high-power electric propulsion for orbit transfer missions.[18–21] These studies compared the use of 30–100 kW electric propulsion systems to traditional chemical upper stages such as the Atlas Centaur, identifying significant gains

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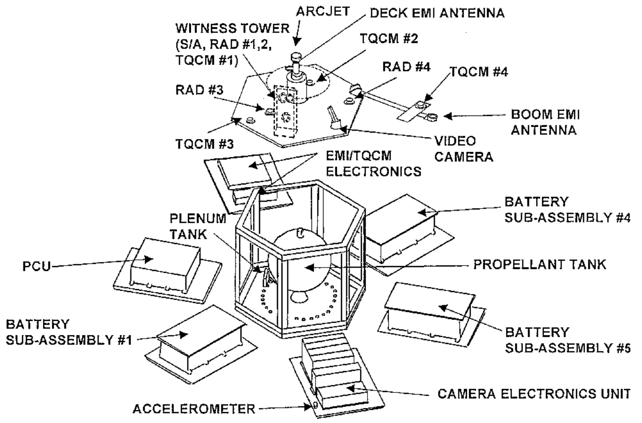

Fig. 1 Exploded view of ESEX flight unit: height 1.45 m (56.9 in.); maximum width 1.25 m (49.2 in.); empty weight 438 kg (966 lb); propellant weight 4.54 kg (10 lb); power source 126-cell, 100 A · h, 150–250 V dc silver–zinc battery, 28 V dc nominal bus; nominal arcjet performance thrust 2 N and I_{sp} 815 s.

in payload delivered to geostationary orbit, albeit at the expense of trip times as long as 60–90 days from a low Earth orbit. The effect of these long trip times can be significant including higher operational costs and increases in solar array degradation as a result of spending more time in the Van Allen belts. Because the potential payoffs were so large, however, government, university, and industry research into high-power electric propulsion dramatically increased in arcjets, ion engines, magnetoplasmadynamic thrusters, and other devices.

To encourage technology development and transition a viable, high-power electric propulsion capability to the commercial sector, the U.S. Air Force initiated several programs to demonstrate high-power electric propulsion on-orbit. At that time, hydrogen arcjets were the most advanced technology for the required thruster performance in the 30–100 kW power regime, and so they were selected for advanced engineering development. A series of technology development efforts were initiated to address the component needs for a flight system including PCU development,[22] thruster life and performance improvements,[23,24] and conceptual designs of operational systems.[25] These efforts culminated in an Advanced Technology Transition Demonstration mission which came to be known as ESEX.

The primary goal of the ESEX program was to perform an on-orbit demonstration of a 30-kW-class ammonia arcjet subsystem. Ammonia was selected as opposed to hydrogen in spite of hydrogen's better performance, to eliminate the development costs associated with an on-orbit cryogenic feed system. The ESEX program included the flight design, fabrication, integration, and test of all of the components, as well as a science effort to address the potential interactions with the host spacecraft. This did not, however, include all aspects of the ultimate system. Several key functions were left for a follow-on mission including the hydrogen storage and feed system, autonomous guidance and control, on-orbit life demonstration, and measurement of the solar array degradation during the low-thrust, spiral orbit transfer. This follow-on mission was initiated and became known as the Electric Insertion and Transfer Experiment (ELITE) which became the precursor to the NASA Solar Electric Propulsion Technology Application Readiness (NSTAR) ion engine system that was ultimately flown on the NASA Deep Space-1 mission.[26–28]

The contract for the ESEX program was awarded in February 1990 to a team consisting primarily of TRW, General Dynamics Ordnance and Tactical Systems Aerospace Operations (formerly Rocket Research Company, Olin Aerospace Company, and Primex Aerospace Company), and Orbital Sciences Corporation (formerly Defense Systems, Inc., and CTA Space Systems). The scope of the effort included the design, fabrication, and test of the subsystem on the ground, but did not initially include any flight-operation related tasks because ESEX had not been manifested on a launch vehicle. Early concepts for the flight experiment portion of the program included a ballistic mission with a limited flight duration, a stand-alone experiment on the then untested Pegasus launch vehicle, or a ground unit development only. Ultimately, ESEX was manifested as one of the experiments on ARGOS, a dedicated U.S. Air Force research and development mission.[4,5]

Once ESEX was manifested and became a viable on-orbit experiment, the effort was restructured to include a more realistic flight design including flight software, flight qualification and integration tests, on-orbit operations development, science data planning, and operations support tasks. These tasks were divided between the contractor and government teams to minimize program cost, maximize expertise development across government personnel, and optimize the science data return. The contractor team was responsible for the design, fabrication, and test of all components up to and including the subsystem-level testing after integration into the ESEX flight unit,[1,2,6–10] as well as providing support throughout spacecraft-level tests and flight operations. The government team provided unique laboratory expertise for application to high-risk areas, supported all spacecraft-level integration and test activities, and led the flight-operations and science data acquisition and analyses. This arrangement resulted in a highly integrated government–contractor team and was highly successful in solving key technical problems and minimizing spacecraft integration support and operations costs, this approach successfully addressed such issues as arcjet ignition and EMI assessments,[29–32] ground support equipment design and development,[33] and maximizing the on-orbit data return.[3,12–17]

This program structure was especially important to ESEX because the original 5-year program was stretched to almost 10 years due to budgetary constraints early in the program and various technical problems with the host spacecraft. This long delay did not result in any major impacts to the success of the program because all of the primary technical team members remained throughout the program. The one major exception was the continuity of the science data results vs the original design of the sensors because the onboard diagnostics were designed and built early in the program, whereas the science team members responsible for the flight data reduction joined just before the flight-operations campaign. As a result, the science team was often forced to resolve configuration and operations questions of the onboard diagnostics with limited insight. Future experiments should involve these critical team members early in the program to help define all aspects of the science data including the instrument requirements and design, data latency considerations, and planning the flight operations. In general, however, this government–contractor team bolstered the program significantly by eliminating the restrictions inherent in traditional roles and responsibilities and building a spirit of camaraderie that led to solutions based on technical merit rather than political or other ancillary influences.

None of the subsystems required for the program existed in a flightlike state before this effort was initiated. As described in Refs. 9 and 10, key issues were resolved on almost every major component over the course of the program. These issues included achieving reliable, vaporized ammonia flow in zero gravity, consistently processing 26 kW of power while controlling radiated and conducted EMI, achieving reliable and repeatable arcjet ignition, ceramic and refractory metal fabrication techniques, thermal management of 5–10 kW of dissipated heat, development and integration of an advanced sensor suite, and a host of other spacecraft interface requirements to ensure the ESEX firings would not affect nominal spacecraft operations.

Once all of the development issues were resolved the flight unit was shipped in March 1996 to the ARGOS integration contractor, The Boeing Company (formerly Rockwell International), for the spacecraft-level integration and test. Once at The Boeing Company, the ESEX flight unit was tested with the ARGOS spacecraft to verify the interface between the spacecraft bus and the ESEX flight unit. These tests included several functional evaluations, acoustic and shock tests, an EMI compatibility verification, and a series of thermal vacuum tests.[34] Once completed, the satellite was shipped to Vandenberg Air Force Base for launch in December 1998. Several functional verification tests and maintenance tasks were performed including ESEX and ARGOS battery maintenance and a communications compatibility verification with the Air Force Satellite Control Network (AFSCN) as the vehicle was prepared for launch. After 10 scrubbed launch attempts, primarily due to inclement weather, the vehicle was successfully launched at 10:29:55 Greenwich Mean Time on 23 February 1999. The Delta II placed ARGOS within 1% of its nominal orbit at an altitude of 846.2 km (456.9 n mile), and an inclination of 98.73 deg, corresponding to an orbital period of 101.6 min.

The flight-operations and data analyses were the final step to achieving the ESEX program goals. As already stated, the primary goals for the ESEX program were to demonstrate the compatibility of high-power electric propulsion with nominal satellite operations and to increase the technology readiness of high-power electric propulsion in the commercial sector. The data presented in Refs. 9–17 demonstrate these objectives were satisfied. Unfortunately the interest in ESEX faded as the program progressed as the viability of on-orbit nuclear power faded and as technologies with higher performance than arcjets emerged. However, there has been a renewed interest in high-power electric propulsion technologies as satellites continue to grow to meet user demands for higher power with advancements in solar array technology. Because the payoffs identified early in the ESEX program remain so attractive, the U.S. Air Force and NASA have both revised their high-power electric propulsion development efforts.[35,36] Although these programs are now looking toward Hall thruster and ion engine technologies rather than arcjets, the ESEX program was a critical step toward validating power processing and integration approaches of high-power electric propulsion systems.

Flight-Operations Summary

The ARGOS mission was divided into three phases to maximize the data return from all nine of the experiments.[5] The goal of the first phase was to initialize the spacecraft and all of the experiments and to ensure that all of the systems were fully operational before proceeding with nominal operations. The second phase was reserved for ESEX and the critical ionization velocity (CIV)[4] experiments because these both performed gas releases during operations. Phase III was reserved for the rest of the experiments, most of which used high-voltage components that required a high-vacuum environment, severely limiting ESEX and CIV operations.

Phase I Operations

After the successful launch and initial acquisition and stabilization, the operations focused on verifying that the spacecraft bus and all of the experiments, including ESEX, were fully operational. ARGOS completed its nominal initialization except for two issues, both of which had an effect on the ESEX mission. The first was a propensity of the ARGOS global positioning system (GPS) receiver to drop out of the 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 eliminated the planned use of the receiver by ESEX as a means to measure the time-resolved arcjet performance.[3,14] This problem was partially resolved after the ESEX operations were complete by updating the ARGOS onboard flight software.

The second issue was a recurrence of an ARGOS ground-test anomaly and manifested itself as an inability to perform ranging, commanding, and telemetry downlink simultaneously with the AFSCN standard uplink power and command modulation index settings. This issue was mostly eliminated early in phase I by modifying the standard uplink power and command modulation index at each AFSCN site, until a satisfactory communications link was established. However, the problem did appear periodically throughout the remainder of the ARGOS mission, which hampered some of the ESEX electromagnetic test objectives[13] and made two of the firings difficult to monitor in real time.

On day 2, approximately 26 h after launch, the vehicle received an incorrect GPS initialization vector and went into a sunsafe mode, a safe mode that inertially points the arrays at the sun and turns off all unnecessary power loads. Phase I continued approximately 48 h later, and it was during this time that the first of two ESEX anomalies were observed. As a part of the power-reduction procedure that is executed when ARGOS enters sunsafe mode, 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, requiring battery charging immediately following the completion of the sunsafe recovery. During the first of these charging cycles, high oscillations on the battery charger output were observed when the battery voltage reached −225 V dc. This behavior, and the impact to the ESEX mission, is discussed in a later section on flight anomalies.

After the verification that the anomalous charger circuit behavior was not detrimental to the flight unit, the ESEX battery charging was continued. The remainder of the ESEX initialization and checkout was completed, which 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.[34] The ESEX EMI boom was deployed on day 14, later than originally planned,[3,34] to allow additional outgassing data to be collected from the contamination sensors located on the EMI boom while it was pointed at the ESEX diagnostic deck. These results are discussed by Spanjers et al.[15] Once the initialization activities were successfully completed, phase II experiment operations were initiated.

Phase II Operations

The original operations plan for phase II called for integrating ESEX firings with CIV releases for the duration of the mission.[3,34,37] This plan did not prove logistically feasible on-orbit due to a shorter amount of time between ESEX firings than planned, coupled with weather and instrument problems at the ground observation sites. The shorter firing times were a result of two considerations. The first was a decision to increase incrementally the firing time up to the full 15-min length over first half of phase II. The second consideration was a concerted effort to perform the firings while in view of the ground observation sites, which resulted in firings before a full state of charge was obtained on the battery. The modified experimental plan did not significantly affect either the CIV or ESEX mission success. As already indicated, the science results are not discussed here because they are included in Refs. 11–17.

The ESEX flight operations were governed by a conservative approach to validating this technology while ensuring ARGOS and ESEX operations were not adversely affected. This approach resulted in the short firing times discussed earlier, but also resulted in several aborted operations whereas a series of overly conservative, self-imposed software limits were redefined to better match the on-orbit conditions. These limits defined the parameters within which ESEX must function and included temperature, flow rate, and pressure constraints that were established based on the designers' conservative estimate of the expected on-orbit conditions. The ESEX computer compared the measured value with the user-established limit 30 times/s. If the measured value exceeded the limit, the computer aborted all operations and placed ESEX in a safe configuration. These limits were easily changed, and these initial adjustments to the ESEX system were not unexpected, nor did they reflect system behavior that was anomalous or out of specification. In hindsight, the flight limits could have been made less conservative to avoid interruption during these initial operations, but the program philosophy used to define these limits was sound.

The first ESEX activity in phase II was to perform a series of outflows from the PFS, first of gaseous nitrogen and then of ammonia, while monitoring the ESEX and ARGOS telemetry to ensure no deleterious effects were observed. These activities are summarized in Table 1. The objective of these outflows was fourfold: 1) to bleed the nitrogen blanket from the plenum tank, 2) to verify the functionality and operation of the PFS, 3) to verify that the arcjet cold flow thrust would not have a detrimental effect on the ARGOS attitude control system, and 4) to determine if any off-axis thrust was present as a result of the arcjet alignment,[34,37] either from internal arcjet geometry changes from firings or from the launch

Table 1 Summary of ESEX arcjet firings and propellant releases

Firing (F) or release (R) no.	Date/Time (zulu)	Duration	Location	Comments
R-1 (N_2)[a]	11 March 1999/1928	8:29 (509 s)	Not observed	Initial N_2 bleed required majority of pass.
R-2 (N_2/NH_3)[b]	12 March 1999/0027	1:13 (73 s)	Not observed	N_2 bleed completed. NH_3 aborted due to overly conservative software constraints on PFS heaters.
R-3 (N_2/NH_3)	12 March 1999/1258	1:59/3:59 (119/239 s)	Not observed	All systems operated nominally. Liquid ingestion first observed.
F-1A	13 March 1999/1240	N/A	MSSS	First arcjet ignition (on 10th start pulse), firing aborted due to overly conservative software constraints on mass flow rate.
F-1B	15 March 1999/1210	N/A	MSSS	Firing attempt aborted due to overly conservative software constraints on PFS heaters.
F-1C	15 March 1999/2155	2:21 (141 s)	CPCA	Modified firing sequence to account for liquid ingestion and ensure vapor outflow to arcjet. CPCA performed passive data collection.
F-2	19 March 1999/2232	5:01 (301 s)	CPCA	Flow rate setpoint increased to 250 mg/s. All systems operated nominally. CPCA acquired first active data set.
F-3	21 March 1999/1224	5:33 (333 s)	MSSS	All systems operated nominally. No MSSS data acquired due to inclement weather.
F-4	23 March 1999/2127	8:02 (482 s)	CPCA	All systems operated nominally except for low battery output voltage, caused arcjet to shut off early. First indication of battery trouble.
F-5	26 March 1999/2145	6:04 (364 s)	MSSS	Low battery voltage forced early termination. Telemetry problem made operating arcjet difficult. MSSS acquired first on-orbit arcjet firing spectra.
R-4 (NH_3)	30 March 1999/0636	8:54 (534 s)	N/A	Attempted PFS heater modifications to eliminate liquid ingestion did not succeed.
F-6	31 March 1999/1305	4:30 (270 s)	MSSS	Low battery voltage forced early termination. Telemetry problem reduced by increasing ground transmitter power. No firing spectra acquired.
F-7A/B	2 April 1999/2209	53 s/38 s	CPCA	Attempted to discharge battery as much as possible before reconditioning. Arcjet stopped/restarted due to PCU command logic. CPCA acquired start and stop transient data.
R-5 (NH_3)	9 April 1999/1548	9:06 (546 s)	N/A	Further attempts to eliminate liquid ingestion with PFS heater modifications did not succeed.
F-8	21 April 1999/1222	42 s	MSSS	Battery reconditioning had no effect on arcjet firing time. No MSSS data acquired. No liquid ingestion observed.

[a]Nitrogen. [b]Ammonia.

environment. The nitrogen outflow was performed by opening the arcjet valve without activating the PFS algorithm, the software method by which flow to the arcjet is actively controlled.[6,9] The outflow was conducted over two passes, to allow enough time to evacuate the plenum tank pressure to <7000 Pa. The ammonia release was planned in the same pass as the second nitrogen release (R-2), but was aborted by a software limit on the PFS temperature. The second ammonia release attempt (R-3) was executed successfully with a more relaxed, but acceptable limit and exhibited nominal behavior except for a momentary ingestion of a slug of liquid ammonia at the initialization of the PFS algorithm. This is discussed in detail in a later section on flight anomalies.

Like the conservative software limits, the cold-flow tests were performed to incrementally test the capabilities of the ARGOS and ESEX systems to ensure the firings would not affect the spacecraft operations. The reaction wheel speeds and spacecraft attitude control sensor outputs were monitored throughout these releases and during the initial arcjet firings to ensure the vehicle was not affected by these operations. No off-axis thrust was measured during any of the cold gas releases or with the arc present. In fact, releases performed after completing several firings (R-4 and R-5) in support of the liquid ingestion anomaly troubleshooting were monitored in the same way, and no change to the cold flow thrust vector was observed. These initial releases also demonstrated a large control margin for the duty cycle of the flow control valve, the dual pressure control (DPC) valve. During steady-state operations, the indicated flow rate was typically within ±0.3 mg/s of the setpoint and was always within the specified requirement of ±5 mg/s. Although the flow measurement accuracy was fairly coarse, approximately 4.5%, other telemetry, such as the arcjet voltage, confirmed the flow rate was correct. This requirement was critical because the operation and performance of the arcjet was so dependent on the flow rate, and a significant development effort was performed early in the program to ensure the PFS could maintain this flow accuracy.[6,9]

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 with battery charging conducted between the firings.[3,37] These two sites are the 1.6-m telescope at the Maui Space Surveillance Site (MSSS) for optical observations[3,12] and the Camp Parks Communications Annex (CPCA) in Dublin, California for the communication experiments.[3,13] This scheduling philosophy maximized the opportunities to collect data from the ground-based observations, but limited the duration of each firing by limiting the amount of charging between each event. 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 overly conservative software limits, similar to the experience on the first ammonia outflow. Subsequent data review showed the arcjet ignited on the first firing attempt (F-1A) on the 10th start pulse, but was aborted within 2–3 s due to a mass flow rate limit that was too tight for the ramp up to full flow and full power. The need for 10 start pulses to ignite the thruster on the first attempt is consistent with ground-test experience, where multiple start pulses were often used. Additionally, flight experience with other arcjets has typically shown the first on-orbit ignition to be slightly more difficult than all subsequent starts. Both the ground and flight observations of this phenomenon are likely due to oxidation of the tungsten electrodes or slight, unavoidable contamination of the cathode from ground handling processes. Interestingly, all subsequent firings ignited on the first pulse, validating the work done early in the program to ensure reliable arcjet starts.[29–31] The first successful arcjet firing (F-1C) was completed after a thorough review of all software limits. The planned duration for the first firing was 4 min,[34,37] but was terminated after 141 s because the start of the firing was delayed as a result of the delay from the liquid ingestion. This first firing was performed over CPCA, while they passively acquired data on the ARGOS transmission spectra, as reported by Dulligan et al.[13]

Subsequent firings proceeded much in the same manner as F-1C. The mass flow rate for the remaining firings was increased, however, because the arcjet power appeared higher than the nominal 26 kW. Later analysis indicated this was not the case, as discussed by Fife et al.[14] Figure 2 shows a typical operational data set for a firing, in this case from firing F-4 on 23 March 1999. As shown in Fig. 2, all of the demonstration components (the arcjet, PCU, and PFS) operated

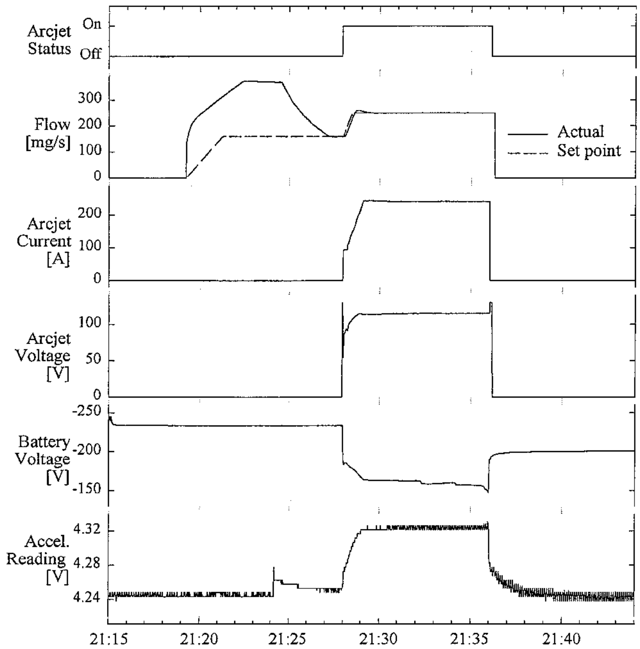

Fig. 2 Typical operational profile of an arcjet firing showing the ramp to full power and steady-state operation.

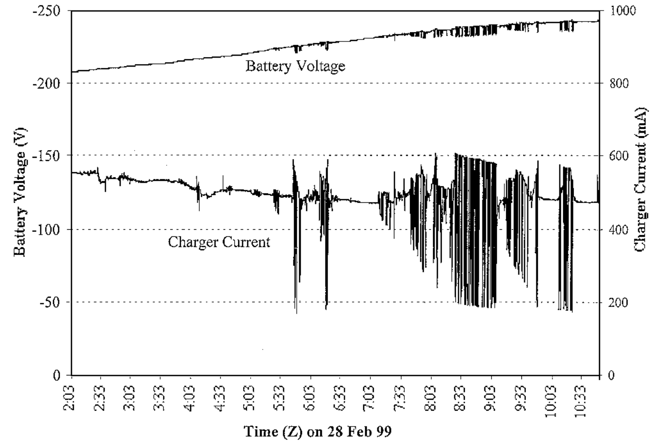

Fig. 3 Typical battery charging-circuit instability.

well, typically well within the specifications set forth at program initiation, although the liquid ingestion and a battery output voltage degradation is also evident. This battery voltage decay ultimately caused the arcjet to shut off because it was below the acceptable PCU input voltage.

Phase II proceeded with seven more ESEX firings and several CIV releases. The ESEX flight unit performed flawlessly, except for the PFS liquid ingestion, battery voltage fluctuations, and some telemetry issues with the arcjet current and inlet pressure. Except for the battery problems, each of the issues was ameliorated with relatively simple operational work-around procedures and had no detrimental effects on the ESEX or ARGOS system performance. Ultimately, however, the battery failed completely, eliminating any chance for further ESEX firings. Because this failure occurred within days of the scheduled end of phase II and the majority of science data had been collected, the result had a relatively minor impact on the overall mission success. The missing data were primarily ground-based optical observations intended to investigate the arcjet plume in high resolution.[12] In terms of the demonstration aspects of the mission, the battery was not critical because an operational system would be powered directly from the spacecraft power system. Once the battery condition was stabilized, ESEX was placed into a long-term discharge configuration for the phase III portion of the ARGOS mission, while the phase III experiments initiated their flight operations and began collecting data to meet their mission objectives.[4,5] The battery discharge was completed in July 1999, but the flight unit power remained on until August 2000 while contamination[15–17] and electromagnetic[13] data continued to be collected.

Flight Anomalies

The two anomalies discussed in detail are the battery failure that ultimately led to the conclusion of the ESEX mission and an observation of liquid ingestion in the PFS. The observed data are discussed, followed by a 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 event. The charging circuit operated nominally (except for a lower output current than expected) until the battery voltage approached −225 V dc. At this point, as shown in Fig. 3, the output current from the charging circuit began cycling on and off, resulting in oscillations of the open-circuit battery voltage. These oscillations were believed to be a result of higher than expected internal battery impedance, perhaps exacerbated by a low charging-circuit output current. In an attempt to lower the charging-circuit impedance, high-capacitance filters in the PCU were switched into the battery circuit via high voltage relays connecting the battery with the PCU[7–9] earlier than planned.[34,37] Although this procedure decreased the frequency of the oscillations, it did not eliminate them entirely. Because this instability was determined to be nondetrimental to the ESEX battery or the spacecraft bus, the charging continued through these oscillations and the charging inefficiencies were accounted for by extending the total charging time. Subsequent charge cycles showed increasingly degraded stability that caused the charging circuit to shut off before attaining a full state of charge. Later analyses indicated these oscillations were likely symptomatic of the earliest stages of the ultimate failure mechanism.

Beginning on F-4, further anomalous behavior on the battery output appeared that resulted in limited firing duration. This was manifested as a low battery output voltage while firing the arcjet, resulting in unstable PCU and arcjet operation, and eventually extinguished the arc. Noted, however, that the voltage at which the arc extinguished was less than −150 V dc, well below the lower PCU specification limit of −160 V dc. As can be seen in Table 1, the duration of each firing after F-4 steadily decreased, as the battery performance deteriorated. On F-7, the arcjet cycled on and off twice due to the command logic in the PCU, with both firings having extremely short durations. After this event, an attempt to recondition the battery was performed by executing a deep discharge through the battery bleed resistors[7] and restarting the 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 19 days passed without an automatic shutoff, the charger was commanded off and a firing was attempted. Unfortunately, as can be seen by the short duration of F-8, the reconditioning did not have the desired effect. Because the charger did not automatically shut off, as it did earlier in the mission, it is likely that none of the battery cells were actually being charged and the charging-circuit output energy was simply dissipated by some other mechanism internal to the battery.[38]

Following the completion of F-8, the battery voltage fluctuated erratically between −175 and −200 V dc with periodic drops as low as −30 V dc, where it eventually stabilized. This behavior lasted approximately 24 h until, as subsequent analysis revealed, the battery subassembly on panel 1 (Fig. 1) had a catastrophic failure. This failure was most likely 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 through the short circuit, there was a corresponding increase in battery temperature and pressure as hydrogen gas was generated from decomposition of 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

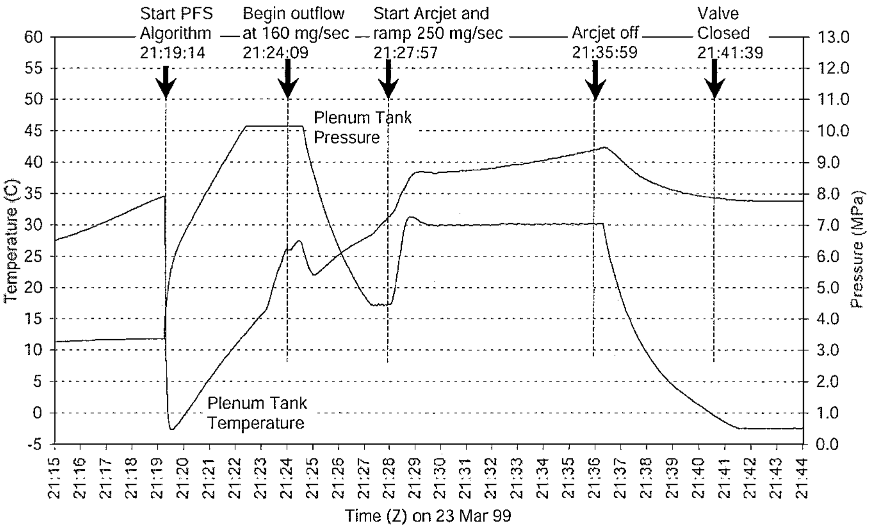

Fig. 4 Typical PFS performance showing liquid ingestion into the plenum tank.

unit. This gas was eventually vented into space, causing a dramatic attitude disturbance on the vehicle, resulting in a sunsafe event. A discussion on the contamination effects from the battery venting is provided elsewhere.[15]

An analysis of the failure was conducted[38]; however, the exact cause of the battery problem could not be fully determined because the flight data do not present a complete picture of the anomaly. There was, almost certainly, a combination of effects that ultimately describe the observed data set. Recent data show, for instance, a significant increase in the impedance of silver–zinc batteries as they approach a full state of charge at a low charge rate, which would explain the charger instabilities but not the ultimate failure. Some phenomenon was responsible for rupturing at least one of the battery cells and causing electrolyte to leak out and short to the battery case. It is also likely that some of the electrolyte was vented from the battery cells during launch as the flight unit depressurized and also as the high current firings were conducted. This expelled electrolyte could have led to a variety of problems such as degraded mechanical connections or bridging the two-cell electrodes and causing a short. In any case, this battery was pushed beyond its normal operating characteristics and was still able to deliver eight successful firings.

Several lessons were learned from the anomaly regarding the use of these batteries for this type of application.[38] In the initial design, the charging circuit was constrained by the amount of power available from the spacecraft. The design solution was to charge the battery at 0.67 A, rather than more typical values of 1–10 A. In hindsight, a better solution would have been to charge at the higher current to ensure traceability to previous applications, but with a shorter duty cycle to satisfy orbit average power constraints. Another issue identified in the failure analyses was the encapsulation of the battery cell interconnections in potting compound. As these interconnections were subjected to the ESEX discharge currents (which were also higher than typical applications) and corresponding ohmic heating, the electrical characteristics between the cells and the interconnections could have been compromised. Again, in hindsight, a design that accommodated these high discharge rates might have avoided this failure. Finally, there was inadequate testing of the integrated battery and charging circuit before launch. Because of thermal constraints on the charging circuit in ambient conditions, all of the charging-circuit tests were limited in time to a few minutes rather than an entire charging cycle with the full battery assembly. A test of the system in the flight configuration, under orbital conditions, and conducted in the same operational way would have identified the problem on the ground, with enough time to implement a solution before the flight. All of these issues and the corresponding solutions have since been documented by the U.S. Air Force and The Aerospace Corporation, and subsequent uses of these batteries account for these shortfalls.[38]

Unfortunately, there were relatively few options available for the flight-operations team to try and mitigate the battery problem as it developed. The approaches used during the troubleshooting were not likely contributors to the ultimate failure, especially because all data indicate performance degradation as the mission progressed. Note that the ESEX flight was an experiment as opposed to an operational mission, and there were several single-string failure points in the design, most of which performed better than their specifications. Early in the design phase, these risks were determined to be acceptable in light of the cost constraints, and the separation between ESEX and ARGOS was maintained to avoid coupling these risks to the rest of the spacecraft. Future experiments have to make similar cost trades to determine the level of internal redundancy and the level of separation from the host spacecraft. The ESEX approach was successful in this case because a significant portion of the planned data were collected, all of the critical technology components were successfully demonstrated, and this anomaly did not hamper any further ARGOS operations.

PFS Liquid Ingestion

The liquid ingestion was initially observed on the first successful ammonia outflow (R-3, Table 1). Evidence of a single slug of liquid ammonia ingested into the plenum tank was observed on initiation of the PFS algorithm and the subsequent DPC valve cycle. Figure 4, and Fig. 2 to a lesser degree, illustrates the issue for a typical outflow. (Note that the plenum tank pressure output saturates at 6.89×10^5 Pa). As can be seen, the plenum tank temperature decreases by greater than 35°C within 35 s of initiating the PFS algorithm, indicating that liquid ammonia is expanding into the plenum tank. Approximately 5 min later, the plenum tank pressure and temperature indicate a super-heated condition and drying out of the liquid in the plenum tank as some of the ammonia vapor is vented through the open arcjet valve (indicated in Fig. 4 by the label "Begin outflow at 160 mg/sec"). A flow meter immersion thermistor located just upstream of the arcjet shows no corresponding drop in temperature, indicating that the liquid is confined to the plenum tank and never passed to the arcjet, even before arc initiation. To ensure that no two-phase flow reached the arcjet, however, the arcjet start was delayed until a dry plenum was achieved in all cases and positive flow control was obtained. After this initial ingestion, all PFS temperatures and pressures indicated no liquid was passed to the plenum tank or arcjet for any of the outflows or firings.

A schematic representation of the PFS is shown in Fig. 5. During operation,[6,34,37] the ammonia was stored in the propellant tank with the DPC valve closed until an arcjet firing. The system was heated 17 h before a firing to ensure sufficient pressure to support flow, the last 2 h of which included disabling the inlet heater on the

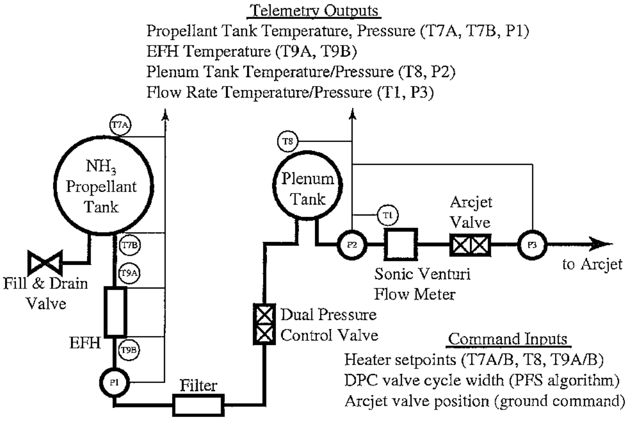

Fig. 5 Schematic of the propellant feed system.

propellant tank and enabling the heater on the plenum tank. This heater configuration vaporized some of the ammonia and drove that vapor to the propellant tank outlet to help ensure vapor-only flow to the arcjet. The enhanced feedline heater (EFH) was enabled to ready the system for the impending flow 7 min before a firing. The flow was initiated by enabling the PFS algorithm, which controlled the ammonia flow by cycling the DPC valve to maintain pressure in the plenum tank corresponding to the commanded flow rate. As a result of the software encoding, however, the DPC valve cycled once at the start of the PFS algorithm regardless of the plenum tank pressure. Finally, the arcjet valve was opened, and the flow to the arcjet was monitored through the sonic venturi flow meter. PFS heater performance before the outflow indicated that the bulk of the ammonia liquid remained away from the outlet of the propellant tank as the design intended. During the outflow, and throughout the mission, temperatures of the EFH indicated relatively little liquid entering the EFH and 100% vapor outflow at the exit.

The liquid ingestion phenomenon was not readily observed in any of the ground tests. Initially, there were some minor differences between heater setpoints and timing of the flight-operations profile and the ground tests as a result of the final thermal analyses conducted before the PFS integration. During the course of the on-orbit troubleshooting, the flight profile was changed back to mirror the test flow in an attempt to link the operational use with the test experiences, but the revised profile did not alleviate the problem.

Further troubleshooting identified a potential thermal gradient in the section of tubing between the EFH and the DPC valve, which could allow the ammonia to pool just upstream of the valve and result in the ingestion of a slug of liquid. Thermal modeling of this region was performed to identify an operational profile that would eliminate the temperature gradient and more heater setpoint modifications were made to the flight profile. Largely due to the lack of direct thermal control of this section of tubing, however, none of these changes proved successful.

The liquid ingestion appeared to be the result of a cold section of the propellant line, likely a result of a cooler mounting platform than experienced during test, coupled with the thermal gradient between the EFH and the DPC valve. The platform temperature is not actively controlled, and the thermal analyses conducted during the troubleshooting showed it could drift significantly low enough to condense ammonia at the pressure in the propellant line just upstream of the DPC valve. This hypothesis is supported by the fact that liquid ingestion was never observed during any steady-state operations of the PFS and by the lack of ingestion observed on the last firing (F-8), which deviated from the normal procedure. For the last firing, the PFS heaters were turned on several days before the firing attempt while waiting for the battery reconditioning to complete, which increased the overall flight unit temperature 6–12°C and eliminated the cold spot in the propellant line.

In summary, the liquid ingestion proved to be an annoyance, but did not seriously detract from the arcjet operation. If the ESEX mission had continued, a heater configuration that alleviated the problem would likely have been identified. Other than this issue, the PFS performed within specification and, in general, operated exceptionally well. The flow rate control generally operated to within ± 0.3 mg/s at steady-state conditions, which was more than an order of magnitude better than the requirement of ± 5 mg/s. If the flow system evolved into an operational flight design, some heater power applied to the section of the propellant line in question, or more direct thermal control of that section could almost certainly resolve the liquid ingestion issue entirely. This conclusion is based on the results from the last firing, where the overall flight unit temperature was higher as a result of the prolonged battery charging attempts, and no liquid ingestion was observed.

Conclusions

The ESEX flight was initiated to push the technology readiness of high-power electric propulsion, enabling satellite manufacturers to use this technology for future military and commercial satellites. ESEX successfully completed its mission goals by demonstrating high-power electric propulsion is compatible with nominal satellite operations and include significant advances in on-orbit high-power processing, ammonia flow system development, thermal control of a high power system, and developing an integrated set of flight and ground-based diagnostics. There were a total of eight firings conducted over the course of the 60-day mission, for a total duration of 2023 s. There were two anomalies associated with the flight operations: a liquid ammonia ingestion problem that had only a minor affect on the mission and a battery failure that precluded any further firings. All of the demonstration aspects of the program were successfully completed, and all of the demonstration hardware, the arcjet, PCU, and PFS, operated well within their specifications. All data show the thruster and the high-power components have no significant, deleterious effect on any satellite activities.

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