ELITE/STAR Arcjet System End-to-End Test

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June 23, 1994

Abstract

In cooperation with TRW, the end-to-end test of the ELITE/STAR electric propulsion system was performed at the Jet Propulsion Laboratory (JPL). The end-to-end test demonstrates operation of the major electrical components of the ammonia arcjet propulsion system, The test included the TRW Solar Array Simulator (SAS) and Power Distribution Unit (PDU), the NASA Lewis Research Center (LeRC) Power Conditioning Unit (PC U), and the J PL ammonia arcjet; and was performed in the JPL arcjet test facility. The main objective of the test was to demonstrate successful operation of the complete system early enough in the program that potential problems could be corrected, During testing, the ELITE/STAR design provided extremely stable control of the arcjet thruster. The system was operated up to a maximum 8 kW power level for 3 hours. Tile control system also successfully tracked representative on-orbit solar array output power curves. These curves represent the solar array beginning-of-life, end-of-life, and radiation degraded operating characteristics.

Introduction

Electric Orbit Transfer Vehicles (EOTV's) propelled by arcjets have the potential to provide greater launch vehicle flexibility, increase payload capability and prolong on-orbit time for commercial and military satellites. The Air Force in cooperation with TRW has defined the Electric Insertion Transfer Experiment, / Space Track and Autonomous Reposition (ELITE/STAR), a flight test designed to demonstrate critical technologies required for an operational EOTV, including the arcjet propulsion subsystem, large solar arrays and autonomous guidance, navigation and control in an integrated system, The 1800 kg spacecraft, would be boosted into an initial orbit at 370 km. An ammonia arcjet would then raise the spacecraft to a final altitude of 3900 km, where system degradation in the Van Allen radiation belts would be studied. The electric power for the propulsion subsystem would be provided by solar arrays with a beginning-of-life power of 10 k W; however, solar array degradation in the Van Allen environment could result in an end-of-life power of 3-4 kW. This mission would require a specific impulse greater than 500-600 s at an efficiency of more than 0.30 and a minimum engine lifetime of 1000 hours with the capability for 700 on/off cycles, (dictated by the occurrence of an eclipse once each orbit as the spacecraft enters the Earth's shadow). Each cycle would therefore initially consist of about 60 minutes of engine operation followed by 30 minutes with the engine off.

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The operation and control of the high power arcjet thrusters has been identified as a high technical risk for the ELITE/STAR spacecraft. The high risk assessment is based on the following concerns. First, the arcjet thruster's dynamic negative impedance load characteristic raised questions concerning the ability to stabilize the arcjet control loop. Secondly, because of the high cost associated with solar power, the operating point of the thruster must track at the peak power point of the solar array to take maximum advantage of the available array power.

As part of the ELITE/STAR risk reduction effort, tests of the power control system were conducted. The power control system comprises the TRW solar array simulator (SAS), the TRW Power Distribution Unit (PDU) which contains the peak power tracker (}'1''1'), the NASA LeRC arcjet power conditioning unit (PCU), and the JPI. 3 to 10 kW ammonia arcjet thruster. The tests were performed in the JPL arcjet test facility.

A candidate engine for this flight test is the 30 kW-class arcjet that has been tested extensively at the Jet Propulsion Laboratory (JPL) [1] and by the Olin Aerospace Corporation [2]. Throttling capability of the baseline engine design [3] to power levels below 10 kW was demonstrated in an earlier program [4], A modified design offering higher performance was developed at Olin [2]. Because the arcjet performance requirements for ELITE/STAR are relatively modest, the focus of the recent JPL program has been on establishing the required lifetime. A total of 1462 hours of operation with minimal electrode erosion was achieved in an endurance test of the modified design in continuous operation at 10 kW [5]. In a subsequent test, 707 cycles (total of 701.8 hours of operation) were completed before the test was terminated by a series of external arcs caused by a propellant leak at the rear of the thruster [6]. The operating conditions for both tests were the same. A power level of 10 kW was chosen for both tests because it represents the most demanding condition that is likely to be encountered in the ELITE/STAR mission. An ammonia mass flow rate of 0.170 g/s was used to yield a specific impulse exceeding 600 s. Additional throttling tests were performed with a smaller constrictor engine to improve both the performance and the operating range [7]. A specific impulse of 650 s was achieved over a range of 3 to 10 kW.

In association with the space demonstration, ground testing and analysis will validate the performance of future propulsion designs to allow rapid transition into manufacturing. This paper describes the results of an end-to-end high power testbed demonstration ground test. The testbed represents the solar array to arcjet subsystem being designed for the ELITE/STAR spacecraft. The objective of the test was to simulate the ELITE/STAR spacecraft high power distribution system with an actual arcjet load. By demonstrating the end-to-end high power distribution system, many of the associated risks will be eliminated. This demonstration used a solar array simulator programmed to simulate solar array current-voltage (1/V) curves which represented actual on-orbit conditions. The solar array current and voltage characteristics simulated during the ground tests represented beginning of life, radiation degraded, and end of life performance. ELITE's Power distribution Unit (PDU) provides arcjet start-up and the ability to control the arcjet in either constant power or peak power tracking mode.

Experimental Apparatus

The engine used in these tests is a modified version of the D-1 E 30 kW-class design [3], with a different constrictor and nozzle geometry. A schematic of the thruster is shown in Fig. (l). The constrictor of the engine is 3,81 mm (0.150 in) in diameter and had a length-to-diameter ratio of unity. The conical nozzle had a 19° half-angle and an expansion ratio of 40. The cathode axial position is set by first inserting the cathode into the thruster until the conical tip contacts the constrictor inlet, then retracting it by 2.03 mm (0.080 in). A 7° lapped joint seals between the pure tungsten nozzle piece and the molybdenum body piece. All other seals in the rear of the engine are accomplished by compressing grafoil gaskets, The nozzle and body are plasma spray-coated with ZrB_2, which is intended to increase the surface emittance to provide better radiative cooling.

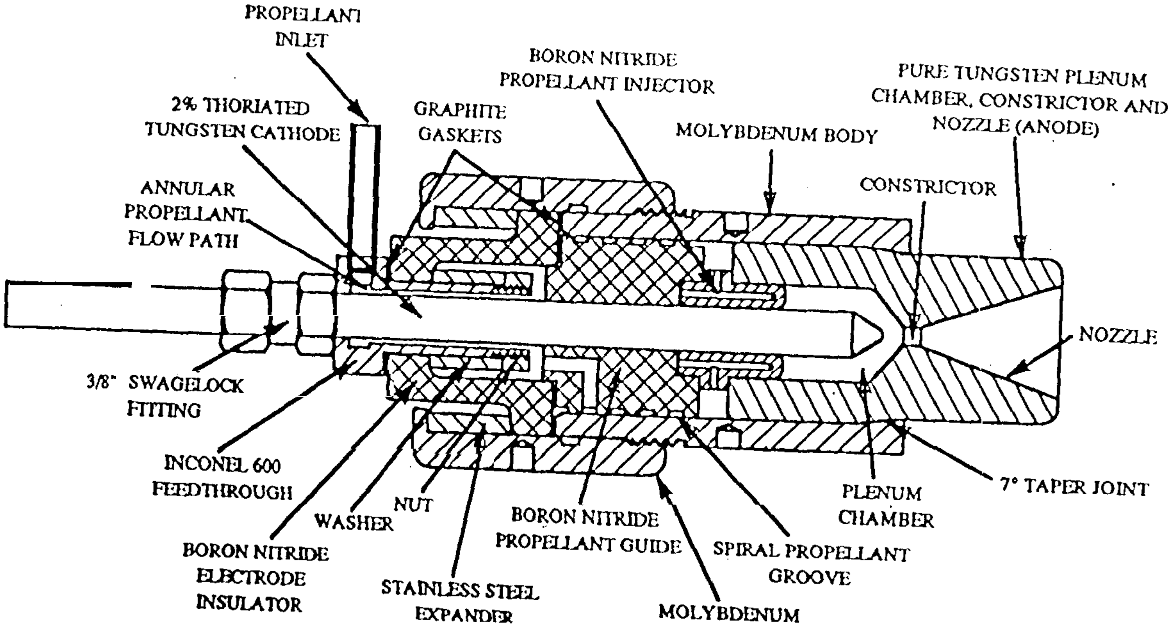


Figure 1: 30 kW-class ammonia arcjet.

The arcjet is mounted on a thrust stand in a stainless steel vacuum facility with an internal diameter of 1.2 m and a centerline length of 2.1 m. The arcjet exhaust is collected by a water-cooled diffuser 16 cm in diameter and pumped by a 6320 liter/s Roots blower backed by a 610 liter/s Roots blower and a 140 liter/s Stokes mechanical pump. The system is capable of achieving a vacuum of approximately 0.27 Pa with no propellant flow, and a pressure of 4.7 to 5.1 Pa for the test flow rate of 170 mg/s. The exhaust is discharged to atmosphere through a dilution stack.

The ammonia propellant is stored in a tank located outside the building and delivered to the thruster through stainless steel lines, Two pressure regulators in series maintain a constant pressure upstream of a micrometer valve which is used to regulate the flow rate. The flow rate can be regulated within ±1 mg/s of the desired value by the system and is monitored with a Sierra Instruments Side-Trak Model 830 flow meter and a Micromotion Model D6 flow meter located upstream of the metering valve. The propellant gas passes through a plenum bottle on top of the tank before entering the chamber through a flange at the top. It then flows through the thrust balance and enters the engine through the cathode feedthrough at the rear.

The thruster voltage, current, thrust, propellant mass flow rate, tank pressure, plenum pressure, feed system pressures, arcjet temperature, and various facility temperatures are continuously monitored with a Macintosh computer system utilizing LabView software. The system allows unattended operation, shutting down the facility when specified engine or facility parameters exceed upper or lower bounds or when a computer failure occurs.

The arcjet voltage is measured differentially with leads mounted near the cathode and the anode feedthroughs in a flange on the side of the vacuum tank, When corrected for the resistance between the measurement, point and the engine, the measured values are accurate within ±0.2 percent. The current, is determined by measuring the voltage drop across a 505.6 $\mu\Omega$ coaxial shunt with an accuracy of ±0.10 percent. A variable-capacitance type transducer mounted in a flange on the top of the tank is used to determine the tank pressure, This gauge has a range of 0-1.333 kPa and is capable of measuring the pressure to within ±0.5 percent. The pressure measured at the tank inlet is referred to as the "plenum pressure" and is approximately equal to the pressure in the arcjet discharge chamber. The thrust is determined by measuring the deflection of an inverted pendulum on which the engine is mounted with a linear variable differential transducer (LVDT). The assembly housing the LVDT and the inverted pendulum are enclosed in a water-cooled jacket to minimize thermal shifts, and an active motion damping system is used to minimize transient thrust stand motion [8]. A set of known weights is used to calibrate the thrust stand in situ, and tests of the calibration indicate that the standard error of the measurement is approximately ± 1 g. This uncertainty arises primarily because of slight hysteresis in the thrust stand motion and slight drift with time. The mass flow meters were calibrated gravimetrically, applying corrections for any zero shifts [5].

A schematic of the test power configuration is shown in Fig. (2). The 10 kW solar array simulator (SAS) was programmed to simulate solar array current-voltage (1/V) curves representative of actual on-orbit conditions was used as the input to the spacecraft power distribution unit.

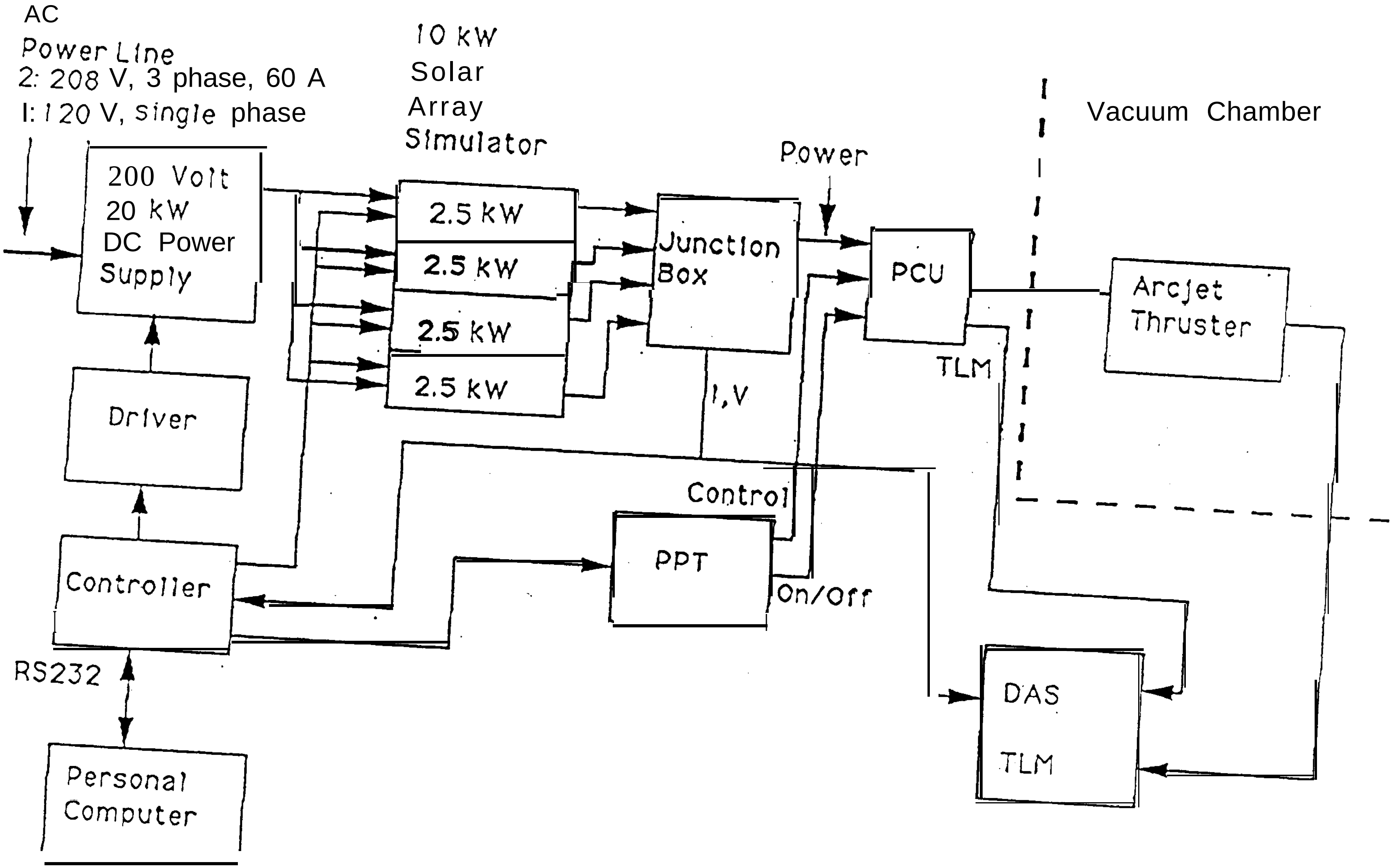
The PCU used in these tests was provided by NASA LeRC. The PCU employs a single phase, nonresonant, Ii-bridge topology with phase shifted PWM control. The output filter inductor contains an integral pulse generation winding which is used to produce a high voltage pulse at the PCU output for arcjet ignition. The PCU maintains a constant output, current to within 1 percent of an input reference over 1 to 10 kW output range, with a power efficiency of 0.92 to 0.95 depending on the input and output conditions. The PCU also contains a soft-start circuit which limits the initial in-rush current to the arcjet at ignition and operates the arcjet at a reduced power level for a period of onc second. More detailed descriptions of the PCU and the soft-start circuit can be found in Refs. [9] and [10].

End-to-End Test

The objective of the end-to-end test was to demonstrate operation of the power control system and to identify potential system interface problems. The results of the test will be used to validate the actual spacecraft design. The test also demonstrates, for the first time, the end-to-end firing and peak power tracking control of a high power ammonia arcjet thruster.

Early testing identified a significant amount of noise coming from the PCU which was severely affecting the SAS and the arcjet data acquisition system. The noise was severe enough to make the SAS control system unstable. Therefore, the system noise had to be reduced before other system integration issues could be addressed, This noise is inherent in the switching characteristics of the PCU design. Additional filtering capacitors were added to both the input and output power leads to the I'CU. In addition, some of the the single conductor power feeds were replaced with braided strand cables. A filter system with a round off of about 40 Hz, provided by TRW, was also added to the power lines between the SAS and the PCU to reduce conducted noise to the PCU, and radiated noise from the cables themselves. Modifications were also made to the PCU control circuits to prevent synchronization problems between the power FETs. During these tests the power FETs in the PCU were damaged and required a lengthy repair time, Once these modifications were made, the system noise level was reduced sufficiently that real system control issues could be addressed. After the noise problems were corrected, the end-to-end tests were performed. The solar array simulator provided current/voltage waveforms corresponding to an actual solar array with power output ranging from 3 to 8 kW. Upon command, the power distribution control unit initiated the arcjet startup sequence and ignited the arcjet. After a commanded 15 second warm-up, the PDU switched to the peak power operating mode. The peak power tracker monitors the spacecraft bus current and voltage levels and commands the PCU to keep the arcjet operating at the peak power point.

One test measured the solar array simulator's loop gain performance using a network analyzer. Figure 3 shows the loop gain measurements. As can be seen in this figure, the circuit was stable with cross-over around 10 kHz and greater than 90° phase margin.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Junction
Box
Power
PCU
Vacuum Chamber
Arcjet
Thruster
TLM
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PPT
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RS232
Personal
Computer
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TLM

Fig 2

Figure 2: Schematic of end-to-end test electrical configuration.

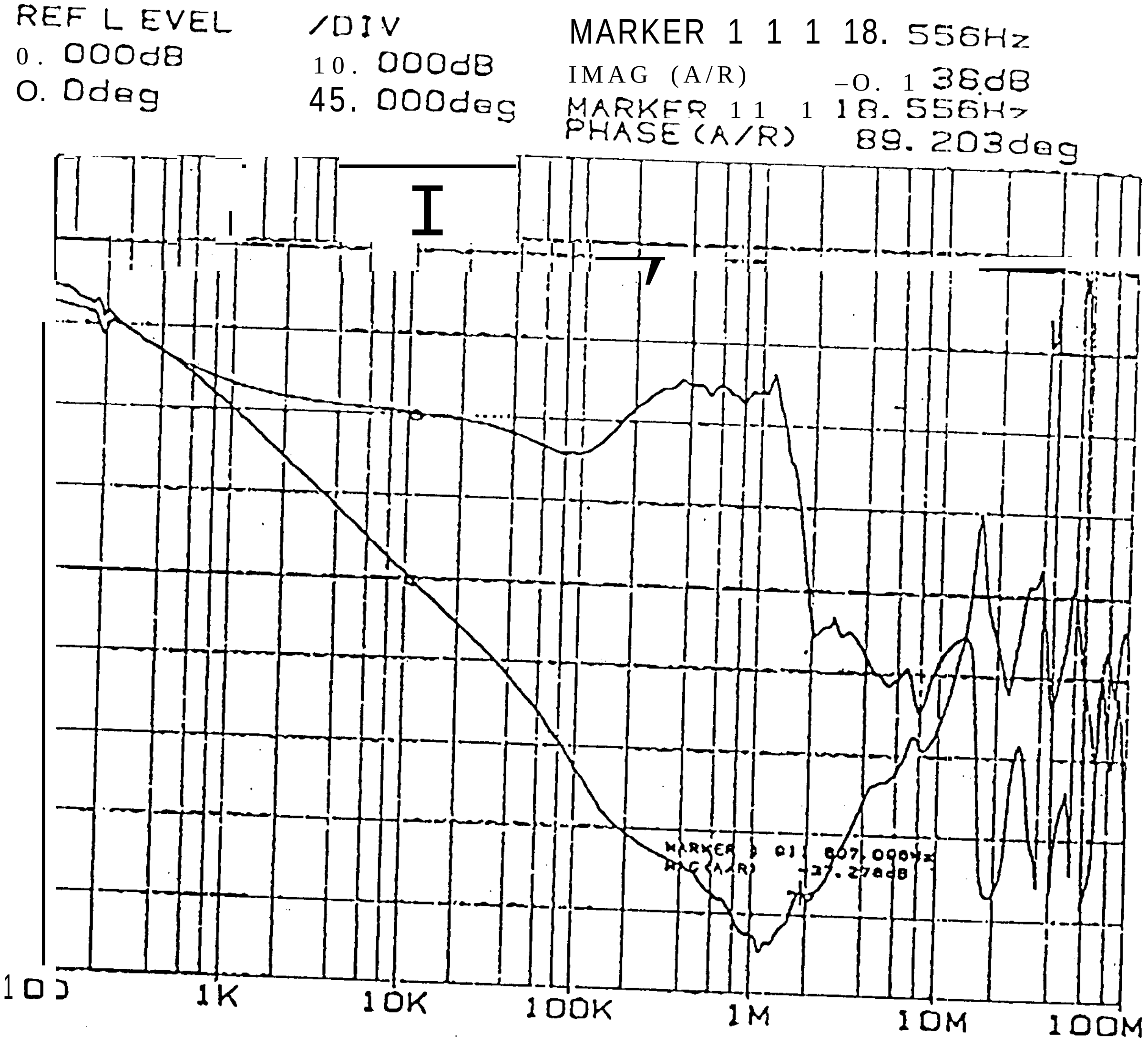
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Fig 4

Figure 3: Solar array simulator loop gain response.

In another test, the PCU was connected to the SAS and peak power tracking was attempted. As the PPT algorithm tried to find the peak power, a point was reached when the load power demand exceeded the SAS constant power load and the SAS current source shut-down. A typical SAS current-voltage curve is shown in Fig. (4). The lines designated as 1, 2 and 3 represent different load values. For curve 1, only one solution exists while for curve 2 two values are possible, Of the solutions for curve 2, B is the desirable operating point because the side of the SAS curve on which C lies may be unstable. Point E represents a system operating at the peak power point. At this point the thruster remains off until the SAS voltage is increased to the minimum PCU input voltage of 80 V. Once this voltage is restored, the thruster fired until the load power was exceeded again resulting in a thruster turn off. This results in an intermittent thruster operation, To correct this problem, the PPT control circuitry was modified to avoid operating in this unstable region.

The PCU cross-over was around 5 Hz and was determined manually because it was below the capability of the network analyzer. Loop gain plots were retained and it was decided to control the loop with a power supply in place of the digital to analog converter. The SAS voltage was controllable and stable from 80 Vdc to 130 Vdc. However, the hardware of the PPT had a corner frequency of 200 Hz which was too fast for the PCU. Changes internal to the PPT hardware were made to stabilize the loop.

With the PPT circuit modification in place, the PPT was able to move the peak power point in less than 0.5 seconds. Power tracking to within ±100 W of peak power (within the resolution of the A to D converters) has also been demonstrated. The PPT was manually driven off peak power into both the voltage slope and the current slope, and returned to peak power tracking within less than 0.5 seconds. The "Run Mission Simulation" software was set up to transition between various solar array I/V curves. On each of these power level transitions, the PPT went to the peak power within 0,5 seconds.

Conclusions

Successful tests of the end-to-end system verify that the current technical approach of meeting the

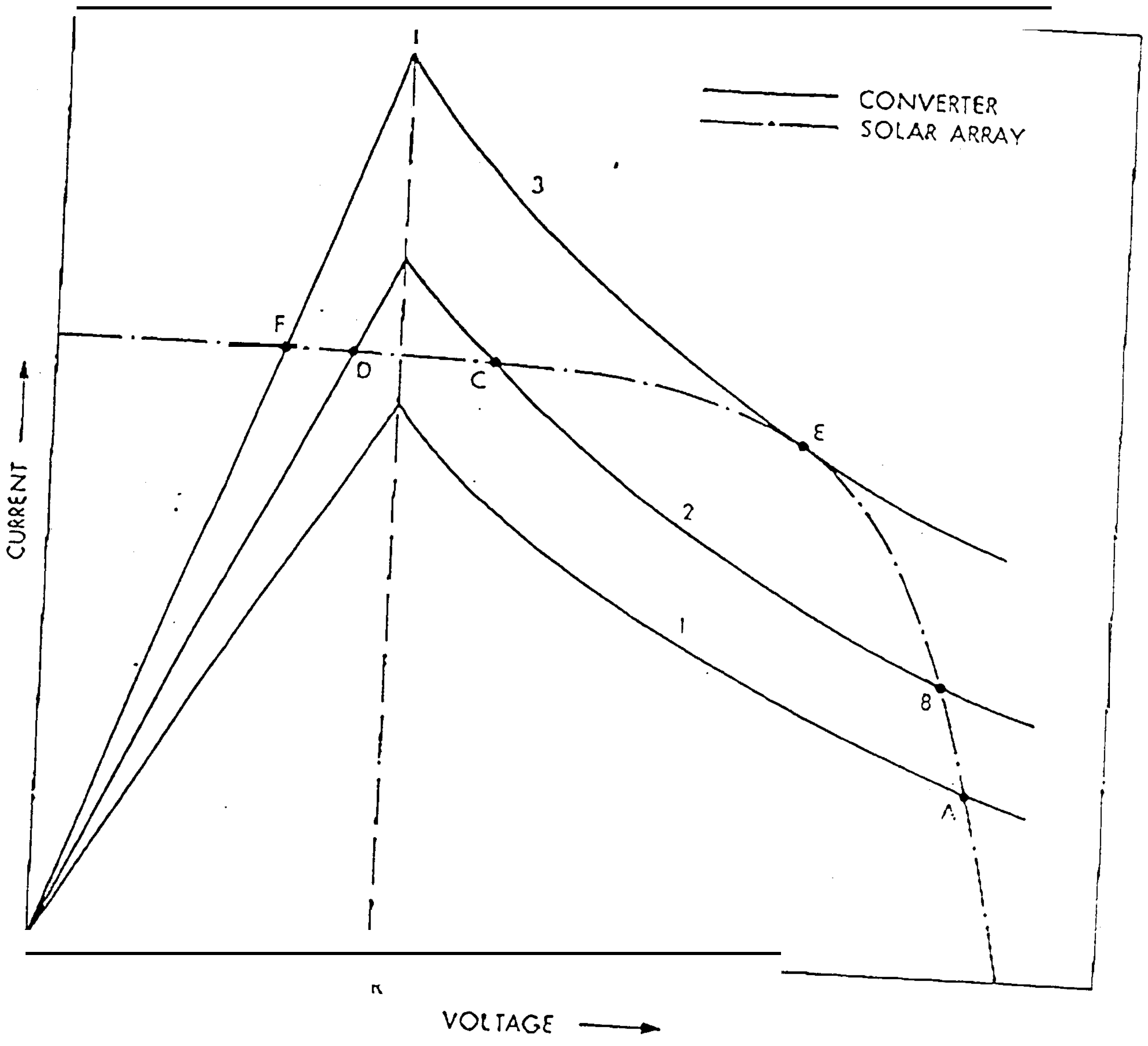

Figure 3. Solar Array-Converter Operating Points

Figure 4: Solar array simulator current-voltage curve with PCU load.

ELITE/STAR operational requirements is correct,. Because of the dynamic negative impedance load characteristic of the arcjet, questions were raised early **in the program** concerning the ability to stabilize the arcjet control loop. End-to-end testing, however, demonstrated that the project design approach provides extremely stable control of the arcjet thruster. The system was operated up to a maximum 8 kW for 3 hours. The control system also successfully tracked the representative on-orbit solar array output power curves representing the solar array beginning-of-life, end-of-life, and radiation degraded operating characteristics. Tests demonstrating stable system operation with peak power tracking were performed at power levels from 3 to 8 kW and over a range of flow rates.

Acknowledgements

The research described in this paper was conducted at the Jet Propulsion laboratory, California Institute of Technology, and was partially sponsored by the Air Force Phillips Laboratory through an agreement with the National Aeronautics and Space Administration. Dr. Robert Vondra was the the contract monitor, and his assistance in enabling these tests is greatly appreciated.

TRW's contributions to this test were lead by Mike CookThe author also thanks Jay Polk, Lew Pless, Bill Thogmartin, Robert Toomath and Al Owens from J PL for their technical assistance. Also, Don Baxter, Jim Donald, Jeff Campbell and Art Brown from TRW, who were responsible for the operation and modifications of the TRW system. Their cooperation during the end-to-end test is greatly appreciated. Finally, the author thanks John Hamley of NASA LeRC for the loan of the PCU for the end-to-end test and for his technical assistance.

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