Nuclear Rocket Experimental Engine Test Results

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An extensive series of tests of a nuclear rocket experimental engine, XE-Prime, was completed in 1969. The main emphasis of the series was upon characteristics of starting from various conditions and upon operation of the test facility under nuclear firing conditions; however, engine performance at full power and throttled pressure were also investigated. This paper compares selected startup test results with predictions made by computer simulation of the test system, and it briefly describes full-power and high-specific-impulse operation. Representative startup data are presented for automatic temperature startups performed with initial levels of 0.1 wand 2.7 Mw, initial core temperatures of approximately 250° and 1250°R, and drum exponential set points of +11° and −8.5° from critical. The test results showed that startup can be controlled over a wide range of initial conditions.

Introduction

PREVIOUS testing in the NERVA Program‡ has been described earlier.[1,2] This paper will discuss in detail the XE-Prime test series which successfully concluded the technology phase of the NERVA Program. This test series used components in a flight-type configuration to further extend nuclear rocket technology in preparation for a flight system, evaluate several control concepts, and demonstrate the ability to start and restart the engine over a wide range of initial conditions. It consisted of 40 runs grouped into 10 experimental plans which began December 4, 1968, and ended September 11, 1969. The engine was successfully started 24 times, with 15 of these starts from initial conditions or using control logic never before attempted. The remaining 16 runs were deliberately conducted without the pump, to investigate low-temperature reactivity effects, run-tank flow operation, and prestart conditioning.

The XE-Prime engine system (Fig. 1) is a close-coupled hot-bleed-cycle nuclear rocket engine designed for ground-test development. Liquid hydrogen (LH_2) is the propellant. The engine was tested at the Nuclear Rocket Development Station's Engine Test Stand No. 1 (ETS-1), which permits nozzle-down firing with altitude simulation. The engine produces a nominal thrust of 55,400 lb with the reactor operating at a power level of ~ 1100 Mw, a chamber temperature (T_C) of 4090°R, a chamber pressure (P_C) of 560 psia, a nozzle flow rate of 70.0 lb/sec, and a total flow rate of 79.0 lb/sec (including 1 lb/sec diverted to the cool down system). The engine has an over-all specific impulse (I_{sp}) of 710 sec at rated conditions. It is 272-in. long, 102-in. in diameter at the upper module, and weighs approximately 40,000 lb.

There are two engine modules. The lower module contains the reactor and pressure-vessel assembly, nozzle, lower thrust structure, external engine shield, control-drum actuators, and lower-module instrumentation. The upper module consists of the upper thrust structure which houses the turbopump, lines, valves, and upper-module instrumentation. The upper module is designed to be replaced remotely should a major component fail within the module. All fluid lines and electrical wires which pass from the upper to the lower module have remote connectors. A test stand adapter houses the remote connectors which are used to attach the engine to the adapter, remote line disconnects, all lines and instrumentation cables leading from the facility to the engine, the propellant shutoff valve, and supporting instrumentation.

Control Description

The many control modes available have also been discussed earlier.[2] Therefore, only a brief description of the two modes discussed in the following sections of this paper are presented.

Temperature Autostart

The primary objective of the temperature-autostart system is to eliminate requirements for nuclear instrumentation in the engine control system, thereby simplifying the control system and improving reliability. It is designed to provide successful startup where there are large uncertainties in critical drum position and throughout a wide range of initial engine conditions. It also accomplishes the engine preconditioning

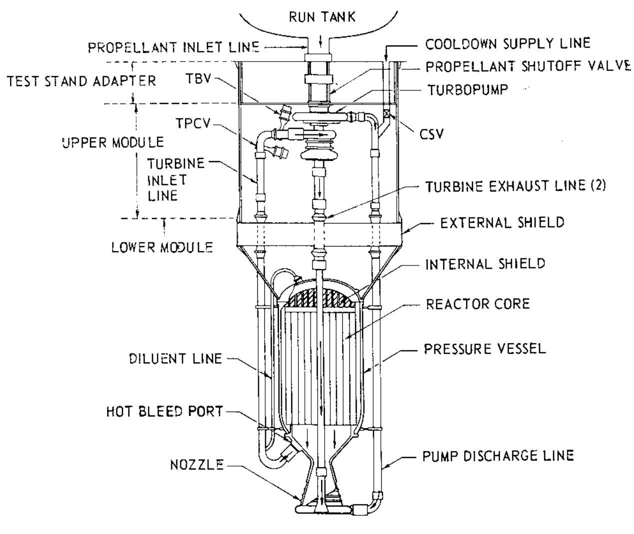

Fig. 1 XE-Prime engine schematic.

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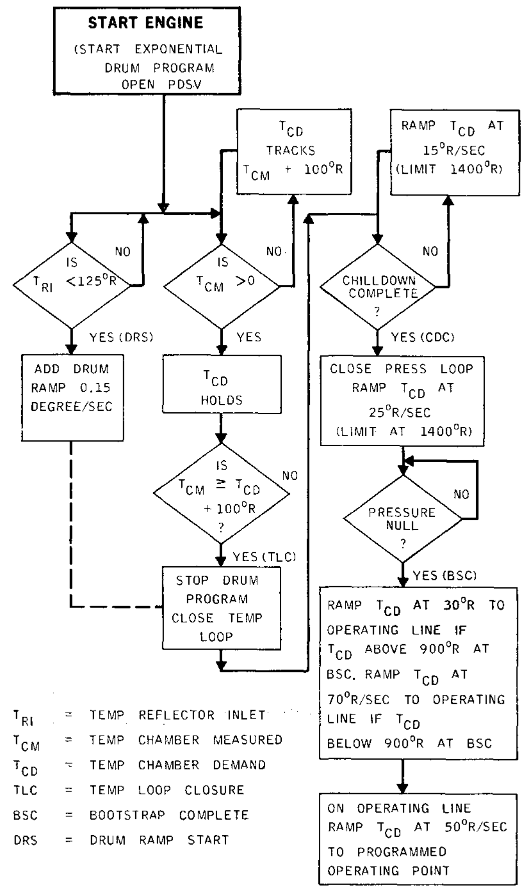

Fig. 2 Wet-temperature autostart logic diagram.

operations required to establish system impedance and energy level in a proper sequence prior to bootstrap initiation. The temperature autostarts in the XE-Prime engine are either "wet" or "dry." The primary differences between the two are the location of thermocouples used to detect nuclear heating and the time at which propellant flow is initiated. In wet-temperature autostart, propellant flow is initiated

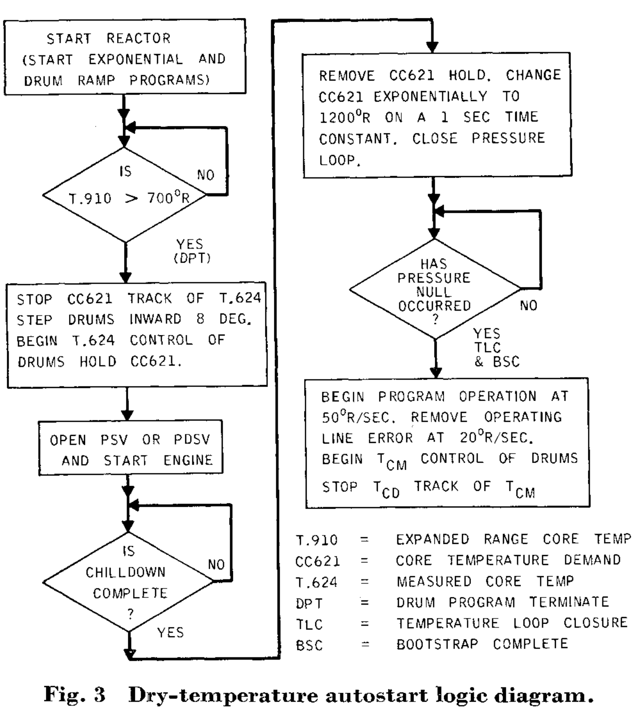

Fig. 3 Dry-temperature autostart logic diagram.

with the start of control-drum programing, and nuclear heating is detected by nozzle-chamber thermocouples. The dry-temperature autostart detects nuclear heating by means of core material thermocouples and does not initiate flow until a predetermined range of nuclear heating is detected. A modified temperature-autostart method also was evaluated later in the test series. It used the dry-temperature autostart equipment but initiated flow at the start of drum programing; it is referred to as "damp."

Startup using wet-temperature-autostart logic begins with the simultaneous exponential programing of the control drums to a predetermined position (normally the critical position plus 3°) and the start of propellant flow (see Fig. 2). When the reflector-inlet temperature becomes less than 125°R, a drum-ramp program of 0.15°/sec is added to drum-position demand. The propellant flow initially reduces T_C until the increasing reactor power level is sufficient to begin propellant heating. When T_{CM} increases by 200°R from its minimum value, the temperature-control loop closes and automatically terminates drum programing. After temperature-loop closure, temperature demand T_{CD} is ramped at 25°R/sec, if the reflector-inlet temperature T_{RI} is below a preset value (60–80°R), or at 15°R/sec if it is not. Achieving this T_{RI} is called "chilldown complete." At chilldown complete, the turbine power control valve (TPCV) is opened by activating the pressure-control loop, which has an initial pressure demand of 40 psia. Bootstrap is complete when pressure-null ($P_M = P_D = 40$) occurs. Operation is then continued in the program mode after pressure-null, using nozzle-chamber temperature as the control parameter.

A dry-temperature-autostart begins with the control drums programed outward on an exponential profile to a predetermined position and then at a constant ramp rate (see Fig. 3). Drum programing is terminated when the average of three core-material-temperature thermocouples indicates a predetermined level (typically 700°R). Then the drums are stepped in ~8° and switched to in-core temperature control, which maintains a fixed demand until chilldown is complete. Propellant flow is normally initiated at the completion of drum programing. When T_{RI} reaches a preset level (chilldown complete) the pressure loop is activated, the TPCV opens, and core-temperature demand is exponentially increased to 1200°R on a 1-sec time constant. When the engine bootstraps and pressure-null occurs, control of the drums is switched from dry-autostart core-temperature control to the state-programed temperature controller for the program mode of operation.

Program Control

Program control provides common-time programing of temperature and pressure demand. The feedback signals are measured nozzle-chamber pressure P_{CM} and temperature T_{CM}.

Program control is selected by the operator, who also determines the terminal point of program operation. The rate of temperature programing is limited to 50°R/sec. Program operation is available for three operating lines (normal, high specific impulse, and high thrust) by substitution of one "plug-in" printed circuit board in the engine programer. The program mode of operation along an operating line is electronically prohibited until start-program logic is satisfied.

With temperature autostart, the start-program logic is satisfied with pressure-null and the temperature level existing at the time of pressure-null. In cases where the temperature level is either above or below the program operating line, the temperature error may be removed at rates of 0, 10, 20, or 50°R/sec. For the XE-Prime series, a rate of 20°R/sec was used; therefore, the initial rate of temperature increase is 70°R/sec if the temperature is below the operating line when pressure-null occurs, or 30°R/sec if temperature demand is above the operating line. As soon as the temperature operating-line error is removed, the temperature-demand rate returns to 50°R/sec along the programed operating line. The pressure-demand ramp rate for the normal operating line is 5 psi/sec until the program breakpoint at 310 psia, at which point the pressure-demand ramp changes to 25 psi/sec. The corresponding values for the high-I_{sp} operating line are 3.18 and 5 psi/sec after the 250-psia breakpoint.

Test Operations

Prior to the full-power test, two preliminary test phases were conducted. Phase I tests at very low-power levels conducted between December 4, 1968, and February 27, 1969, established initial criticality, irradiated dosimetry, determined critical drum-bank position, calibrated neutronic instrumentation, and verified proper operation of the nuclear-safety and startup-control systems. Phase II tests conducted March 20, and April 17, 1969, consisted of low- and intermediate-power runs to verify control system temperature-loop closure and program-mode operation, evaluate instrumentation performance, and confirm facility system performance at intermediate power.

Full Power Test

The full-power run conducted June 11, 1969 (Fig. 4) began by establishing a reactor power level of 33 kw. The turbopump chill was then completed and liquid hydrogen flow to the engine initiated. When the reflector-inlet temperature reached 60°R, indicating engine chilldown complete, the power was increased to 10 Mw on a 2-sec period. When power reached 10 Mw, "start engine" was commanded. This activated the pressure-control loop opening the turbine power control valve and initiated an increase in power demand on a 10-sec period. Turbopump rotation began almost immediately, and the system began bootstrapping. After pressure-null and temperature-loop closure, program operation began along the normal operating line to a hold at 2400°R. During this hold, expected engine and facility performance was verified. The program demand was then increased to 3100°R. During this hold, low-frequency turbopump vibration of excessive amplitude was reported by the Test Diagnostic Center, and a normal shutdown-retreat to the 2000°R operating point was made.

During the retreat, the amplitude of the vibration was determined to be erroneous. The program was then increased to 3650°R. During the ramp to this operating point, run-tank topping of 14 lb/sec was initiated. When stable conditions had been established, a step of +90°R was inserted in the T_C demand to verify controller stability before continuing to full power. Program demand was then increased to 3800°R and a hold established for both engine and facility performance evaluation. Program demand was then increased to 4090°R and 560 psia (nominal full power operating conditions). During the ramp, a TPCV override trip occurred, and the valve returned to the tracked position. The override was cleared and full power condition established using TPCV position and chamber-temperature control.

Once stable conditions were attained, reactor power was switched from temperature-feedback control to drum-position control, and a full power hold was initiated. Control of P_{CM} and T_{CM} was now in manual control using only TPCV- and drum-position feedback. During this hold, the topping flow rate was increased to 56 lb/sec, and transfer-function measurements were made. Control was then switched to program mode, and the system was trimmed to full power conditions. Shutdown was begun by decreasing program demand to 2000°R. A hold was made at this point to terminate run-tank topping and to permit the system to approach neutronic equilibrium.

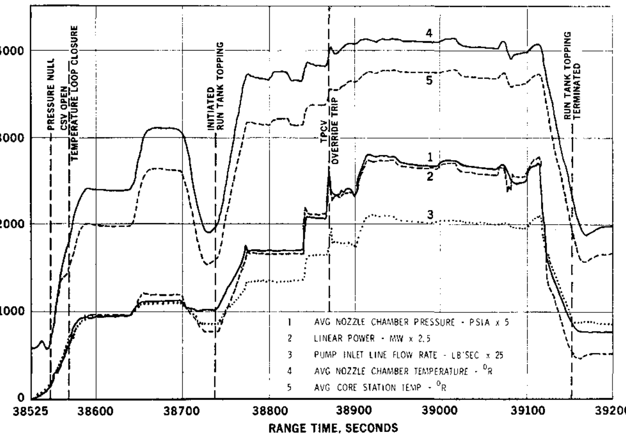

Fig. 4 Full power test operating parameters.

Normal shutdown was then commanded, continuing the retreat in program control. At 1600°R, the drums were rolled in and pump-tailoff control began. Flow of LH_2 was continued with a run-tank driving pressure of 35 psig until chamber temperature decreased to 800°R. This was followed by three LH_2 flow pulses, a gaseous hydrogen warmup, and LN_2 cooldown flow. The cooldown period lasted 31 hr and consisted of nine LN_2 pulses.

High-Specific-Impulse Start to Throttled Conditions

During Experimental Plan 9, August 1969, startup and restart in the wet-temperature-autostart mode, followed by programed operation along the high-I_{sp} operating line to throttled chamber conditions of 300 psia and 4090°R, demonstrated the ability of the system to repeat a programed operation as shown in Fig. 5.

A severe chilling of the engine occurred prior to the first run when LH_2 was inadvertently admitted to the engine system. Subsequent attempts to perform an engine startup resulted in three aborts by period scram before a successful startup was achieved. Post-test data evaluation indicated that the reactor went critical following the scrams. This was attributed to hydrogen reactivity increase during the termination of LH_2 flow. This portion of the run provided significant data in a temperature-flow regime that had not been explored in prior technology tests, and it will aid in absolute-reactivity determinations and in development of criteria for engine startup with a cold reactor.

The successful start began with the initiation of LH_2 flow. When the initial temperature transient had passed, the pressure-control loop was enabled and the drum program started by commanding start engine. Since chilldown complete had occurred, the pressure loop was activated when the temperature loop closed. The TPCV then began opening in response to a 40-psia chamber-pressure demand and the engine began bootstrapping. Following pressure-null, programed operation continued along the high-I_{sp} operating line to steady-state

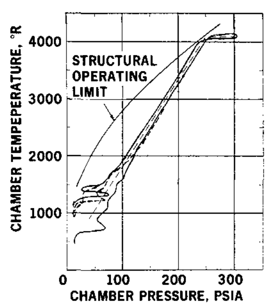

Fig. 5 High-I_{sp} start repeatability.

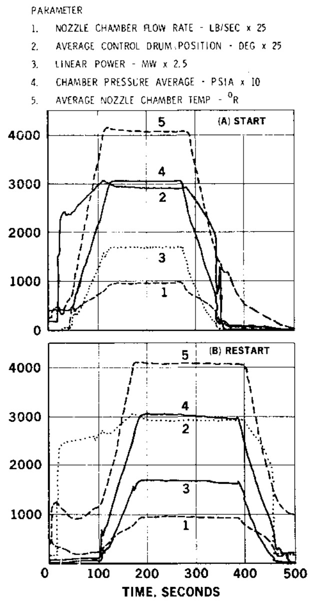

Fig. 6 Operating parameters: a) high-I_{sp} start and b) restart.

conditions at the 300 psia, 4090°R operating point. Run-tank topping at a flow rate of 38 pps was performed during the hold.

A shutdown was performed with a retreat in program control along the high-I_{sp} operating line to a chamber temperature of 1600°R. At this point, the drums were rolled in and TPCV control switched from P_{CM} to T_{CM}. Three LH_2 pulses were used following the shutdown to maintain a hot-core condition, within cooldown limits, for restart. Figure 6a shows important engine operating parameters during this run.

The restart was similar to the original start, but from higher initial temperature and power conditions. Liquid hydrogen flow was initiated and, following the initial temperature transient, start engine was commanded. Chilldown complete was also bypassed at this time; thus, the pressure loop became active after temperature-loop closure with a chamber pressure demand of 40 psia. The TPCV began opening and bootstrap began. Temperature demand began increasing at 25°R/sec from a level of 1030°R. At pressure-null it was ~1280°R, or 380°R above the operating line. The normal demand rate of 50°R/sec was thus reduced by an error-removal rate of 20°R/sec as program operation along the high-I_{sp} line was initiated. After ~20 sec, the error had been removed and temperature demand increased at 50°R/sec along the high-I_{sp} operating line to 300 psia and 4090°R.

Program control was maintained for about 60 sec, and control was then switched to TPCV and drum-position control for a nominal 2-min hold. At the end of the hold, program control was re-established and shutdown initiated. Programed retreat along the high-I_{sp} line was made to 1600°R where the drums were rolled in and cooldown initiated. Figure 6b shows important engine operating parameters during this run.

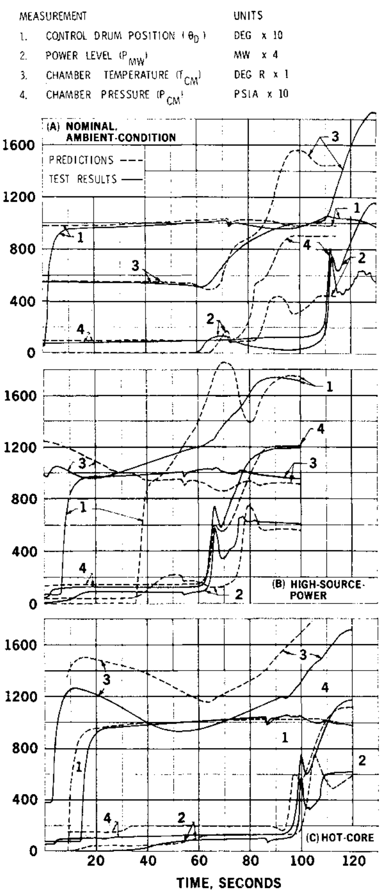

Fig. 7 Wet-temperature autostarts: a) nominal, b) high source power, and c) hot core.

Representative Temperature Autostarts

Twenty-temperature autostarts were made, successfully demonstrating the dry, damp, and wet methods. The following six runs have been selected to demonstrate tolerance to variations in startup conditions: 1) a nominal ambient condition, wet-temperature autostart; 2) a high source power, wet-temperature autostart; 3) a hot-core, wet-temperature autostart; 4) a cold-core, damp-temperature autostart; 5) a damp autostart where control drums are deliberately programed for a high-side miss of the critical angle; and 6) a damp autostart where control drums are deliberately programed for a low-side miss of the critical angle.

Wet-Temperature Autostarts

The nominal, ambient wet-temperature autostart is shown in Fig. 7a. The test results are shown in solid lines for comparison with the prerun predictions that are shown by dashed lines. The two traces have been time-correlated for the drum step which occurs at "drum program terminate." This is necessary because the model used for predictions does not provide a satisfactory representation of the reactivity-feedback coefficients prior to this time. Each of the six-temperature-autostart figures presented shows control-drum position, power level, P_{CM} and T_{CM}.

Figure 7a shows the exponential programing of the control drums to the cold critical angle plus ~3°. Hydrogen flow was also initiated at the time the drum program was started. A drum ramp of ~0.15°/sec occurred when reflector-inlet temperature was reduced by the hydrogen flow to 125°R. When power increased sufficiently to cause T_{CM} to rise 200°R above its minimum, the drums were transferred into T_{CM} control with an attendant drum step-in of ~4° and a programing of T_{CM} at 15°R/sec. Chilldown-complete temperature was preset for 60°R. Since the reflector temperature was above this value, the engine did not proceed to bootstrap. The operator allowed ~28 sec after the temperature loop was closed before he manually bypassed the chilldown constraint. The engine then proceeded to bootstrap through the closure of the pressure loop on the TPCV. At the same time, the temperature-demand rate was changed to 25°R/sec. When P_{CM} reached the preset value of 40 psia, the program demand of T_{CM} and P_{CM} then progressed toward the operating line and up to the hold point. The basic characteristics of the predictions were quite similar to the actual run after allowances were made for the longer predicted time to drum-program terminate (caused by the inadequacy of reactivity-feedback representation) and the delay in bootstrap after the temperature loop closed.

This test is of specific interest; i.e., though T_{RI} (not shown in Fig. 7a) was sufficiently low for a successful bootstrap at the time of temperature-loop closure, it was not sufficiently low to provide automatic initiation of chilldown complete. The 28-sec delay in operator action before bypassing chilldown was equivalent either to a deliberate hold or a timing miss of bootstrap equivalent to that delay. This demonstrates two important aspects of the autostart system: 1) the system tolerance to time variations in the bootstrap, resulting from different initial conditions; and 2) bootstrap may be delayed, after the constraints are satisfied, until thrust buildup is desired.

Fig 7b shows a restart from a high-temperature, high source power condition using the wet-temperature autostart system. Again, the drums were programed out and the flow initiated approximately at the time the drum program started. The temperature was ~1000°R at the time the drum program was initiated. The initial power level was ~3 Mw. The power rose rapidly with the drum exponential as a result of subcritical multiplication and subsequent exceeding of critical position. This rapid rise in power resulted in the fast turnaround in temperature, which then proceeded to increase to the preset increment of 200°R above its minimum, at which point the T_{CM} loop is closed in control of the drums. Because chilldown was accomplished prior to reaching the required temperature increment, bootstrap was initiated immediately upon closure of the temperature loop. Chamber pressure began to increase ~10 sec after closure of the temperature loop. When the pressure level reached the preset level of 40 psia, program operation began with attendant pressure and temperature rise characteristics similar to those of the ambient startup.

Again the prediction for this run was time correlated with the temperature-loop closure point because of the inaccuracy of modeling the reactivity feedback. In this run T_{CM} increased more rapidly than that predicted, a result in part of the reactivity-feedback effects of the model. This run also showed that a successful startup resulted even though T_{CM} had started to increase before the drums reached the exponential set point.

In the hot core wet-temperature autostart (Fig. 7c), the drum program to ambient critical plus 3° was initiated while the core was at 1250°R. One structural support temperature was close to its limit. The characteristics of this start were similar to previous starts. Temperature-loop closure occurred 72 sec after drum-program initiation, as compared with a prediction of 77 sec. This run is significant, because it indicated the limitation on restarting at elevated temperatures was established by structural support limits rather than by the ability of the engine to bootstrap or by startup-system capability.

Damp-Temperature Autostarts

The autostart of Fig. 8a was made to demonstrate the ability to start the engine successfully with a cold core (250°R), with hydrogen flow being initiated at the same time the start signal is given. The most significant effect observed on this start was the occurrence of a shorter period than predicted. The minimum period was ~0.13 sec, less than that predicted by prerun analysis. This difference again is attributable to the limitation in modeling the reactivity feedback effects. The combination of cold core and dense hydrogen had a more significant effect than expected. A successful startup was obtained under the extreme cold temperature of this test.

Figure 8b shows a damp temperature-autostart where the drums were deliberately programed for a high-side miss of critical position of approximately 11°, or \$0.78 above existing

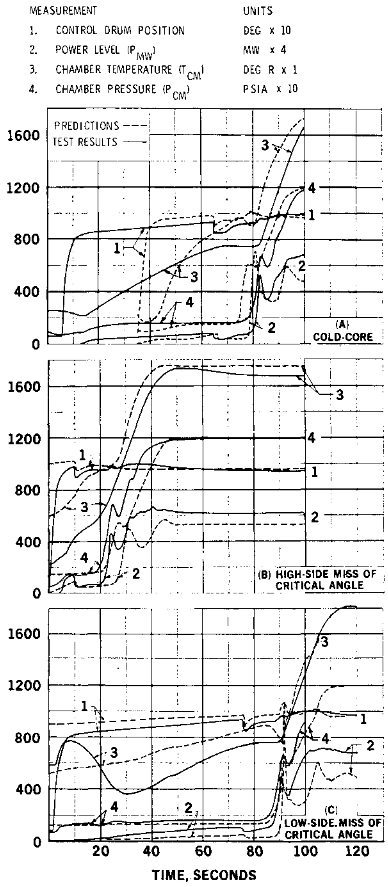

Fig. 8 Damp-temperature autostarts; a) cold core, b) high-side miss of critical angle, and c) low-side miss of critical angle.

critical. This is a miss of +8° in terms of normal programing. The temperature-power buildup is very similar to the nominal startup previously shown. The timing, however, is shortened considerably because of the higher drum profile. After time-correlating the drum program step, the prerun predictions and test results are very similar. The run was quite smooth with chilldown conditions existing at the time the temperature loop closed and the drums were stepped in. The pressure loop was then immediately closed, initiating bootstrap and providing an exponential demand to the in-core temperature controller. When P_{CM} reached the preset value, both the temperature and pressure demands were automatically operated to approach the operating line. The startup was successful.

Figure 8c indicates the results of a damp autostart where the drums were deliberately programed to miss the existing critical angle by −8.5° (low side). This run was very similar to the previous high-side run, with the exception that some temperatures were slightly lower, and that the timing was much longer because the drums reached the critical position at a later time. The buildup of the temperature to the point where the drums step in also was somewhat slower, but power buildup remained smooth. When the drums were stepped in, the requirements for chilldown complete were met. The exponential of the in-core temperature demand was initiated, as was bootstrap through activation of the TPCV pressure loop. Subsequent to the initiation of bootstrap, power, temperature, and pressure buildup were quite similar to the case where the drums were programed to well above their nominal value. This startup was smooth and showed a controlled startup to the desired operating level on the operating line. After time correlation of the drum step-in, the test results and prerun predictions were in good agreement. The startup was successful.

Conclusions

The analytical techniques used during the test program permitted accurate pretest predictions. These techniques are being applied in the NERVA flight-engine program and will greatly reduce the number of tests required at the subsystem and engine level. This proven analytical approach grants a higher confidence of success with a limited number of tests.

References

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Analysis of Solid Teflon Pulsed Plasma Thruster

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Studies of the pulsed plasma thruster used for stationkeeping in the LES-6 satellite are described. Current waveforms were measured, from which circuit parameters were deduced, an energy balance made, and thrust was computed. Each current pulse ablates $\sim 10^{-8}$ kg of Teflon (6×10^{16} molecules of C_2F_4), exhausts it at 3000 m/sec (specific impulse 300 sec) with an impulse bit of 31.2 μ N-sec (7 μlb-sec). Langmuir probe measurements of electron density and temperature, a K-band microwave interferometer measure of density and collision frequency, spectroscopic analysis of ion species, and a Faraday cup measurement of ion velocity were all made. Ion velocities of approximately 40,000 m/sec indicate that the gas is only partially ionized. A thrust stand was constructed to measure impulse bit and specific impulse. The impulse bit is linear with capacitor energy (1.85 joules, normally). Modifications in the current return path to the capacitor which changes the magnetic field behind the exhaust were made. Specific impulse could be tripled, but impulse bit dropped by a like factor, with no improvement in efficiency.

Introduction

A PULSED plasma thruster (PPT) using an arc discharge across a Teflon surface (Fig. 1) has been successfully providing east-west stationkeeping on the Lincoln Laboratory Satellite, LES-6, for over a year now. The thruster has been described in detail in Ref. 1. With the success of this thruster, further development work was begun to improve the design. At the same time, a research and testing program was initiated to understand the physics of the thruster, to determine plasma and circuit parameters, to analyze the performance under configurational changes, and to do reliability and life tests. This paper reports the results of the program to date. Although the work is continuing and further understanding is required, a physical picture of the thruster operation is emerging, and a useful model which predicts the correct thrust and efficiency has been developed.

Understanding of the device was improved by determination of electron densities, temperature and collision frequency in parts of the exhaust with Langmuir probes and a K-band microwave interferometer, measurement of ion velocities with a downstream Faraday cup, estimation of conductivity from magnetic probes, and determination of ion species spectroscopically. Circuit parameters were measured or deduced from voltage and current waveforms, giving the magnetic pressure on the exhaust gas, and a thrust stand was built to measure impulse bit and specific impulse vs energy into the discharge.

From the aforementioned information, it was found that a fraction of the ablated Teflon is ionized and accelerated magnetically to approximately 40,000 m/sec, and the remaining neutral gas appears to be gas dynamically pushed off the Teflon face at a velocity approximately 3000 m/sec, the average exhaust velocity. The circuit model predicts an impulse bit of 32 μN-sec, agreeing with the thrust stand measurements. The model shows only 2.96% of the energy converted to thrust, with approximately 32% dissipated in the capacitor. The remaining energy is required to ionize and heat the plasma and to heat the electrodes of the discharge.

The Circuit Model

As shown in Fig. 1, a spring feeds the Teflon into the region where the charged capacitor plates are discharged across the Teflon face upon ignition of the spark plug. The discharge current is repelled by the return current to the capacitor through a back plate (the Teflon is fed through a hole in this back plate). This current repulsion, or magnetic pressure, accounts for the largest fraction of the thrust given to the exhaust gas. Figure 2a illustrates a simplified model in rectangular geometry, showing the current and magnetic field

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