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ELECTRON BOMBARDMENT CESIUM ION ENGINE SYSTEM

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G. Sohl, F. A. Barcatta, and S. Zafran

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NAS3-7112

EOS ELECTRO-OPTICAL SYSTEMS, INC., PASADENA, CALIFORNIA
A Subsidiary of Xerox Corporation

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QUARTERLY REPORT

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ABSTRACT

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Work performed in the first quarter of a research and development program on an electron bombardment cesium ion engine is reported. Development of engine systems, including zero-g feed systems and neutralizers for extended testing, is described. Preparations for continuous tests of high-performance systems for 2000 and 4000 hours are discussed.

Author

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ILLUSTRATIONS

SUMMARY

This quarterly report describes work performed during the period 3 May 1965 to 31 July 1965 under Contract NAS3-7112. The objective of this program is to test two engine systems for 2000 hours and 4000 hours respectively. These engine systems are to operate at a power-to-thrust ratio of 160 kW/lb maximum at specific impulse of 5000 seconds. The total power must include that required by the neutralizer and feed systems.

During the quarter, the engine which had been operated in three consecutive tests for a total of 2610 hours at a power-to-thrust ratio of 183 kW/lb at 7000 seconds was redesigned for operation at the lower specific impulse. Neutralizers were developed from a new neutralizer concept initially developed at Electro-Optical Systems, Inc., under Air Force Contract AF 33(615)-1530. This neutralizer promises the high emission efficiencies and long life required.

A 20-lb zero-g cesium feed system developed under Air Force contract was modified for use on the 2000-hour test and a new 40-pound feed system was designed for the 4000-hour test. Finally, a new permanent magnet engine for possible use on the 4000-hour test was designed and is being fabricated.

In order to reduce the possibility of interruptions in the long tests, modifications to vacuum facilities and to the electronic engine control systems were begun. An operational checkout of the engine system was conducted at the end of the quarter. This test was quite successful.

1. INTRODUCTION

This is the first quarterly report under Contract NAS3-7112, Electron Bombardment Cesium Ion Engine. The program is a follow-on to Contract NAS3-5250 and is based on the continued development and life testing of the DF engine system developed under that contract.

1.1 Program Objectives

The goals of the program are to test one engine system (engine, feed system, and neutralizer) for 2000 hours and a second system for 4000 hours. These tests are to be conducted at a specific impulse of 5000 seconds and a power-to-thrust ratio of 160 kW/lb, including feed system and neutralizer powers.

A continuing research and development program to improve engine performance and reliability is being pursued. A quality assurance and reliability program is being followed on the extended testing portions of the contract.

1.2 Key Personnel

The key personnel on the program are as follows:

R. C. Speiser	Program Manager
G. Sohl	Engine Development and Testing
F. A. Barcatta	Zero-G Feed Systems
S. Zafran	Quality Assurance

These personnel supervise their respective tasks and are the major contributors to the contract reports.

1.3 General Status

During the quarter, development of a new electrode system, an improved cathode, a long life neutralizer, and neutralizer control system were completed and the engine system for the 2000-hour test was fabricated and assembled. This system was undergoing checkout tests with the modified laboratory power supplies and control system at the end of the quarter.

Design of a large feed system for the 4000-hour test was completed and fabrication of the engine system for the second test was begun. Facility modifications for the long tests were under way and a new permanent magnet engine for possible use on the 4000-hour test was being fabricated at the end of the quarter.

2. ENGINE DEVELOPMENT AND TESTING

During this quarter the DG engine was developed from the DF engine and preparations were made for the long test. The DF engine and development of the DG engine, engine systems, and test facilities are discussed in this Section.

2.1 DF Engine

The starting point for this program was the DF engine, which had been tested in three consecutive runs for a total of 2610 hours without failure at a specific impulse of 7000 seconds. While the DF engine had been operated over a specific impulse range of 3000 to 8000 seconds, the thrust obtainable at 5000 seconds was about 6 mlb. That level of thrust required a high negative accelerator potential (nearly equal to the positive source potential) which was not desirable from the standpoint of long lifetime.

Efficiency of the DF engine was high. Power losses of the source had been reduced significantly under Contract NAS3-5250. No increase in engine efficiency was anticipated under the present program, but an increase in thrust was sought.

The DF engine with the 750-hour feed system (approximately 5 lb) is shown in Fig. 1. This engine incorporated distributed geometry, high-perveance electrodes which promised lifetimes on the order of 20,000 hours as extrapolated from the 2610-hour test results. No erosion of the cathode had occurred during those tests but the reliability of the internal heater had not been firmly established.

In order to increase thrust and eliminate the internal cathode heater, the DG engine was developed.

2.2 DG Engine Development

The first requirement of the DG engine design was for higher electrode perveance. Using the aperture diameter distribution function

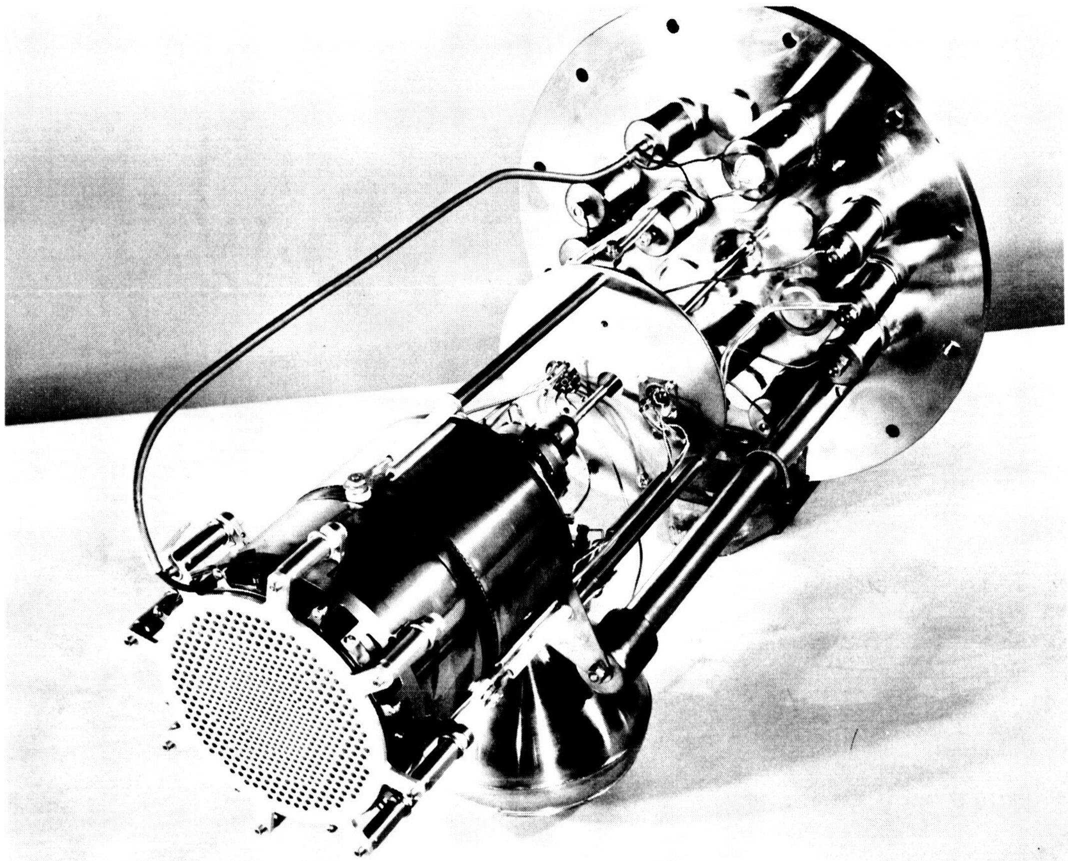


FIG. 1 DF ENGINE WITH 750-HOUR FEED SYSTEM

found to be so successful with the DF engine and scaling the aperture diameters by a factor of about 80 percent, a new electrode design was obtained. Four aperture patterns were used on the new electrodes. By reducing aperture diameters and decreasing aperture spacings, the number of apertures was increased by 67 percent. To maintain the shape of the extraction fields and the resultant focusing, the spacing between the electrodes was also reduced. The result of increasing the number of apertures and decreasing the gap was a significant increase in electrode perveance (the ratio of maximum beam current to the three-halves power of the potential difference between the electrodes). This increase in perveance allowed an increase in the beam current along with a reduction of the accelerator electrode potential to a satisfactory level for long lifetime.

Figure 2 shows the prototype screen electrode with the new aperture pattern. The transparency of this electrode was increased by about 10 percent. This created web areas between apertures which were too small for conventional machining techniques. In order to fabricate this new electrode it was necessary to machine oversize and chemically etch the part down to the desired dimensions. This process has proved very successful.

Figure 3 shows the perveance of the DG electrodes compared with that of the DF electrodes. The effect of this perveance is apparent in the operating data of Table I. The increased thrust and reduced accelerator potential should be noted.

The second major change in the engine consisted of redesigning the cathode. A solid tantalum structure was designed to replace the internally heated emitter of the DF cathode. The two cathodes are shown schematically in Figs. 4a and 4b. Response of the engine appears slower with the new cathode, but starting characteristics are not significantly changed. Source efficiency with the new cathode is as good as or better than the efficiency with the DF engine cathode.

In addition to the changes described above, there were some minor modifications in the engine configuration. Most significant among

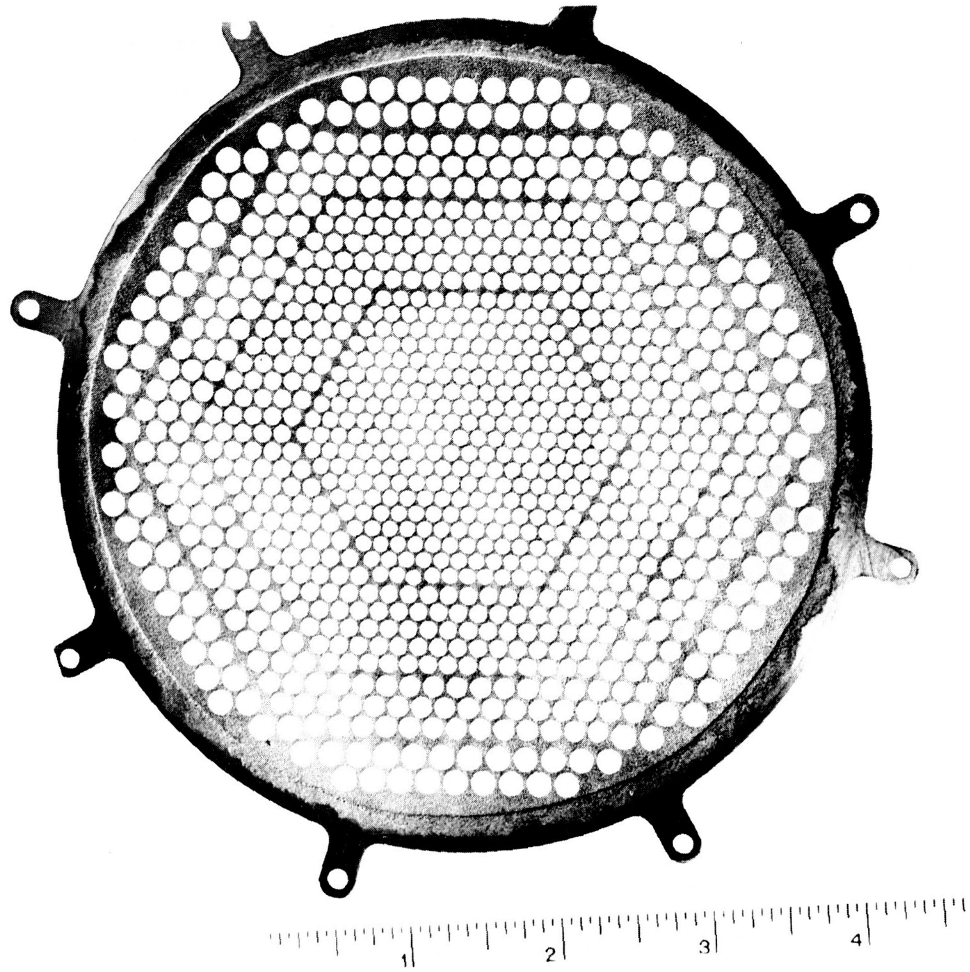


FIG. 2 PROTOTYPE DG SCREEN ELECTRODE

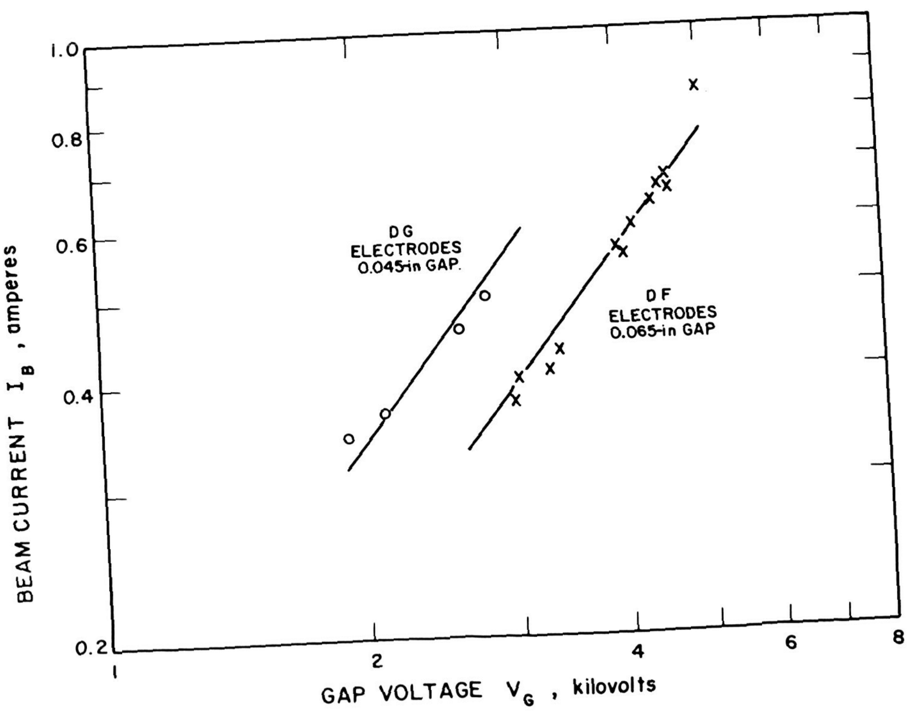
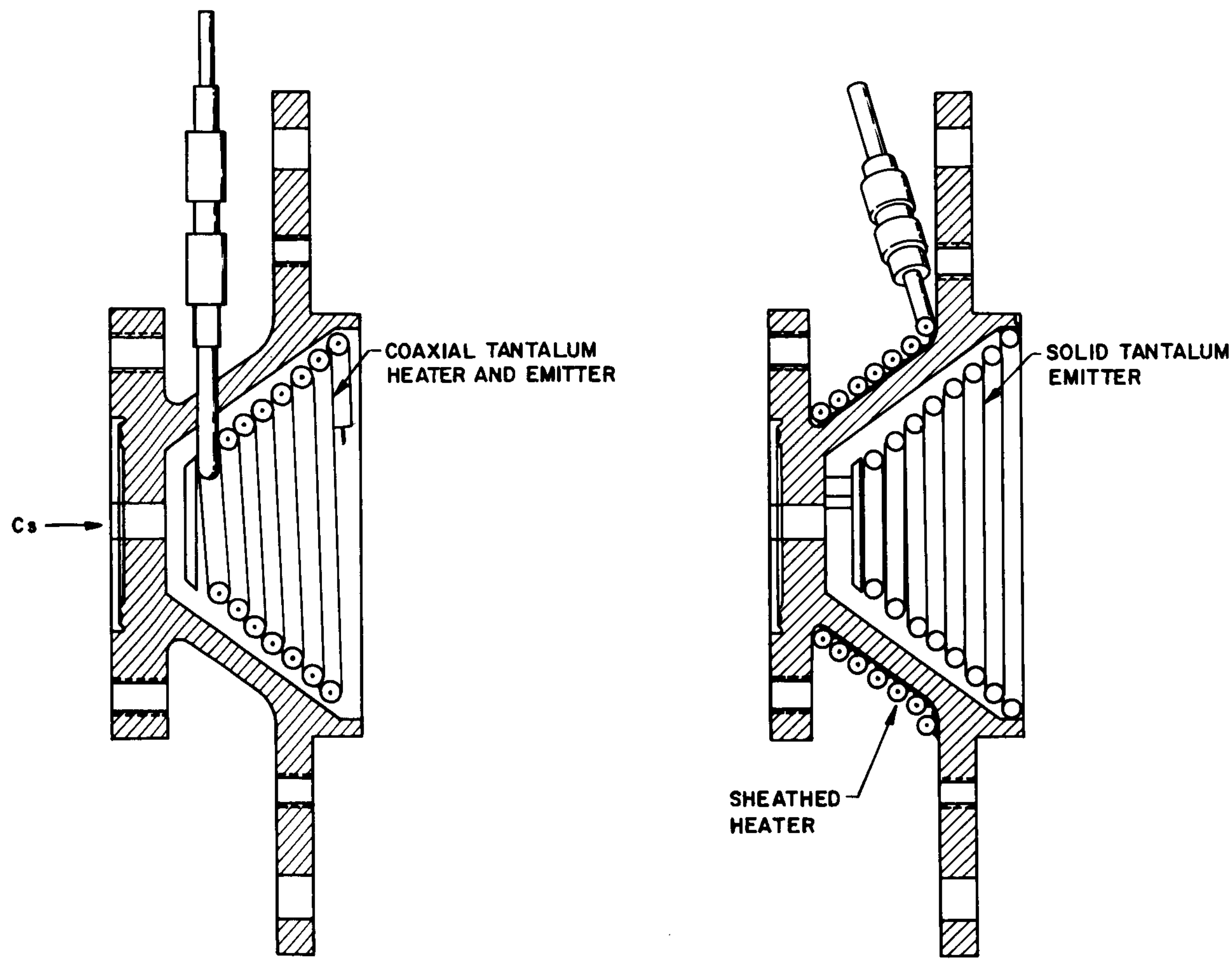


FIG. 3 PERVEANCE OF DF AND DG ELECTRODES

TABLE I

DF ENGINE PERFORMANCE WITH DF AND DG ELECTRODES

	DF	DG
Positive High Voltage, V_+ (kV)	2.05	2.0
Negative High Voltage, V_- (kV)	1.7	0.7
Negative HV Current, I_- (A)	0.0060	0.0063
Beam Current, I_B (A)	0.355	0.402
Arc Voltage, V_A (V)	6.5	7.7
Arc Current, I_A (A)	17.5	18.0
Magnet Current, I_M (A)	2.3	2.2
Beam Power, P_B (kW)	0.728	0.804
Drain Power, P_D (kW)	0.023	0.017
Magnet Power, P_M (kW)	0.013	0.012
Arc Power, P_A (kW)	0.114	0.139
Total Power, P_T (kW)	0.878	0.972
Thrust, T (mlb)	6.05	6.77
Power-to-Thrust Ratio, P/T (kW/lb)	145.1	144.0
Power Efficiency, η_p (%)	82.9	82.7
Mass Efficiency, η_M (%)	92.0	92.2
Overall Engine Efficiency, η_E (%)	76.3	76.2
Specific Impulse, I_{sp} (sec)	5099	5050
Ratio of Drain Current to Beam Current, I_-/I_B (%)	1.69	1.57
Source Energy per Ion, P_A/I_B (keV/ion)	0.321	0.346



a. Internal Heater Cathode   b. External Heater Cathode

FIG. 4 CATHODE SCHEMATICS

these was the elimination of four of the accelerator electrode support insulators. This was made possible by reducing the weight of the accelerator electrode by a factor of almost two; the material of the electrode was changed from 0.062-inch-thick copper to 0.125-inch-thick aluminum under Contract NAS3-5250.

Performance of the DG engine is equivalent to that of the DF engine. An increase in mass efficiency of 5000 seconds due either to increased electrode transparency or to the new cathode was offset by a slightly higher drain current. While the electrode spacing was reduced (lower voltages), the thickness of the accelerator was not changed. This requires more precise ion trajectories to prevent interception near the downstream end of the accelerator apertures. Therefore, higher accelerator drain current is expected initially, but this current should decrease as the apertures erode on the downstream side.

2.3 PMG Engine

A permanent magnet version of the DG engine has been designed and is in fabrication for possible use on the 4000 hour test. A more stable permanent magnet material, Cunife (60Cu-20Ni-20Fe) than the Vicalloy formerly used on PM engines will be used. When hardened Cunife has a demagnetization curve similar to that of Alnico. As was done for the Vicalloy engine shells, Cunife strips will be electron-beam welded together to form a cylindrical permanent magnet. This is necessary because the material is not presently available in wide enough sheets to form the complete engine shell from one piece. As before, iron will be used for the screen electrode and cathode plate, to form the poles required to shape the magnetic field.

An electrode support system similar to that on the DG engine will be used and the cathode and electrode system will be nearly identical to that of the DG engine. This engine will undergo evaluation tests during the next quarter.

2.4 DG Engine Systems

Two systems have been designed for the long tests to be conducted under this program. Both systems use a neutralizer which will be described in Section 4. The principal difference between the two systems is in the feed system used with each. The system for the 2000-hour test uses a 20-pound feed system and the 4000-hour system uses a 40-pound feed system.

2.4.1 The 2000-Hour Engine System

The 2000-hour engine system is shown in Fig. 5. In order to fit the system in the facility available for this test, the feed system has been displaced upwards and to the side as illustrated. A U-shaped feed tube adapter has been added to allow this displacement and the manual valve has been inverted. (The power required for heating the U-tube and the manual valve will not be counted in the system power.) Two neutralizers will be mounted on the system since failure modes have not been determined for these new neutralizers. The feed system and neutralizers will be discussed further in Sections 3 and 4.

2.4.2 The 4000-Hour Engine System

The 4000-hour test facility (described in Subsection 2.5) will have a larger-diameter engine chamber. This allows elimination of the U-tube and normal orientation of the manual valve. The 40-pound feed system to be used on this test will be described in Section 3. Neutralizers for this test may be improved over those for the 2000-hour test since more development time is available.

2.5 Test Facilities

The vacuum facilities for both long tests will have extensive interlocks, backup pumping, and heavy-duty liner baffles and collectors. The vacuum functions will be interlocked with engine and power functions in a manner similar to that used on previous tests. Emergency power, water, and air will again be provided along with suitable alarm systems.

2.5.1 The 2000-Hour Test Facility

The facility used for the 2610 hours of testing under Contract NAS3-5250 will be used for the 2000-hour test. This facility is shown in Fig. 6. To accommodate a test of this length, a one and one-half inch thick copper collector has been fabricated in the basic

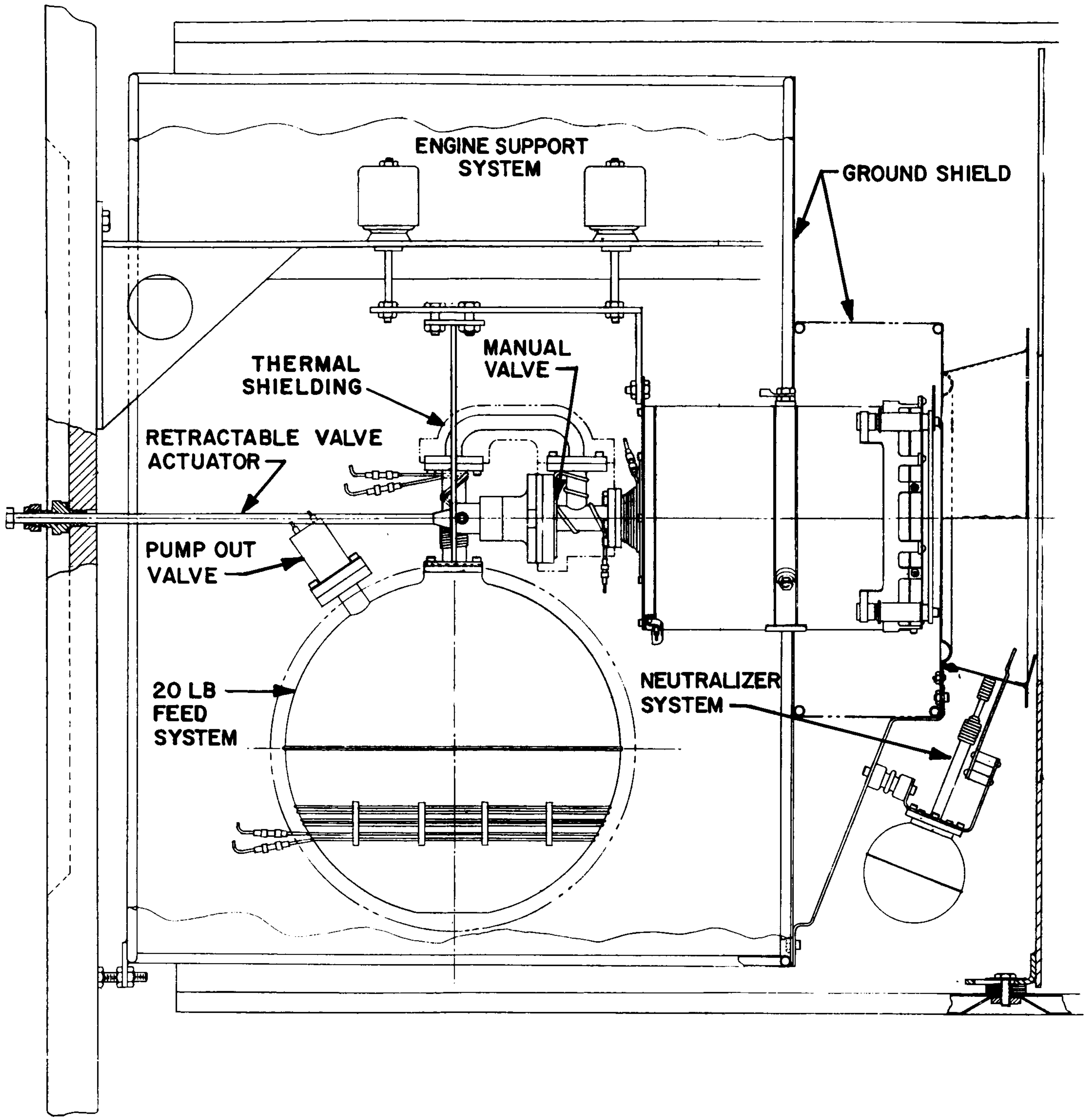


FIG. 5 THE 2000-HOUR ENGINE SYSTEM

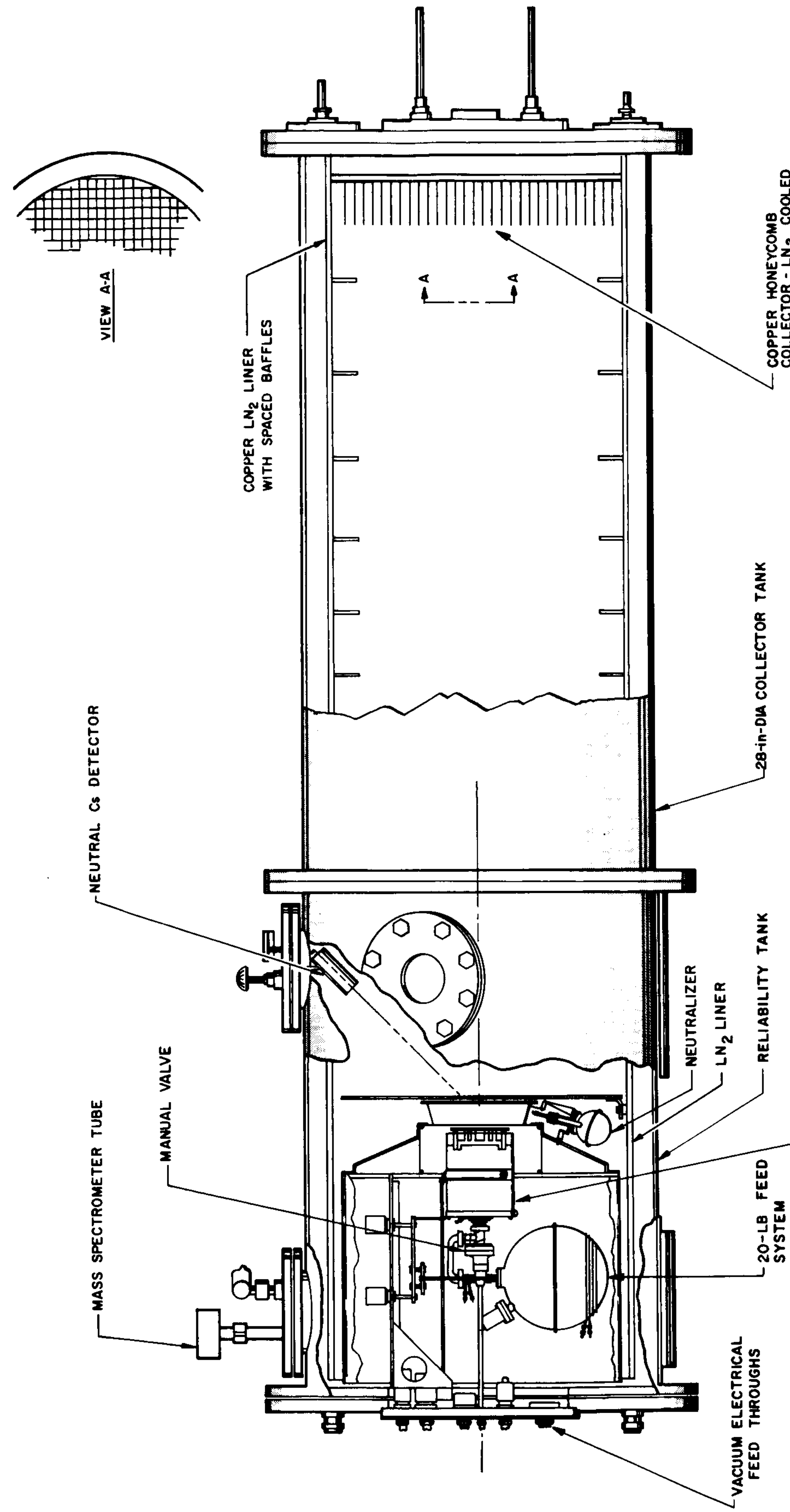


FIG. 6 THE 2000-HOUR ENGINE SYSTEM

design used before. Also, improved baffles have been made for the collector section liner. It is expected that a pressure of 1×10^{-7} mm Hg will be obtained as was the case during previous tests. A mass spectrometer has been added to the system to analyze the residual gas content.

2.5.2 The 4000-Hour Test Facility

Presently being fabricated is an engine antichamber which will extend one of the 2-ft x 6-ft vacuum systems at Electro-Optical Systems, Inc. This antichamber, shown in Fig. 7, will be 3 feet in diameter and 2-1/2 feet long. The liner will be replaced, and aluminum baffles and an aluminum collector are being fabricated. These modifications will take advantage of the low sputtering yield of aluminum to reduce the rate of contamination of engine surfaces by backsputtered material.

2.5.3 Control Systems

The engines for both tests will be operated by control systems developed under Contract NAS3-2516, and modified under Contract NAS3-5250 and this contract. Modifications for interlocking have been made; arc suppression and neutralizer control systems have been added. Also, changes to enhance long-term operation have been effected.

The arc suppression system takes advantage of the response of the discharge to prevent continuous arcing. When an overload is detected, the arc power supply output is immediately depressed. This reduces the plasma densities within the engine and allows the high-voltage power supplies to turn back on into a reduced load. Continuous arcing will be detected after about six cycles, as before, and a rest cycle will be initiated. Excessive rest cycles will generate an alarm to allow correction of system operation.

The neutralizer control system will be described in Section 4.

In order to improve the reliability of the electronic support system, the circuitry, primarily the high-voltage supplies, has been improved.

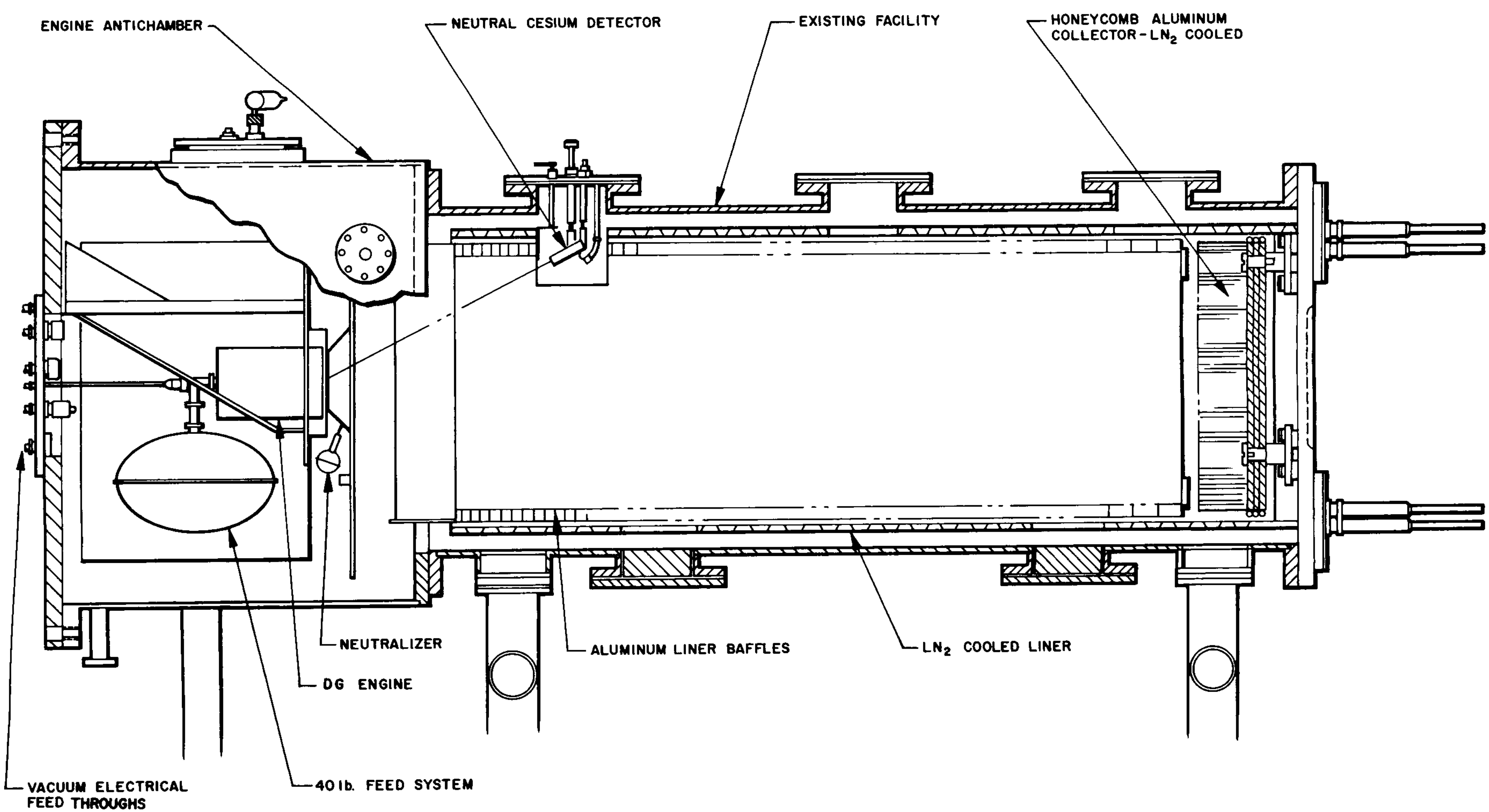


FIG. 7 THE 4000-HOUR TEST FACILITY

The superfluous meter ranges and adjustment provisions have been eliminated. The overload detection circuits were redesigned to use more reliable components and the overload cycling for the two high-voltage supplies was paralleled at the detection level, which reduced the number of components for these circuits by about 50 percent.

The programmer has been redesigned to eliminate self-latching relays and other components that were found to be affected by transients. In the process of this redesign, the automatic start and stop programs were eliminated, allowing further simplification and adding to the expected long-term reliability of the control system.

2.6 System Performance

Table II shows projected performance of the 2000-hour system. These figures were compiled from data obtained during checkout of the 2000-hour engine system at the end of the quarter, but not obtained simultaneously. The checkout test was intended to reveal any systematic errors involving the combination of engine, feed system, neutralizer, and the redesigned laboratory control system. Minor difficulties were found, all of which have been resolved.

As shown by the data of Table II, the power-to-thrust ratio of the over-all engine system is expected to be well below 160 kW/lb at a specific impulse of 5000 seconds. The choice of an operating level for this test will be based on performance mapping results obtained prior to the test.

TABLE II

PROJECTED SYSTEM PERFORMANCE

Engine Specific Impulse	5050 seconds
Engine Power-to-Thrust Ratio	144 kW/lb
Thrust	6.65 mlb
Engine Power	958 watts
Feed System Power	25 watts
Neutralizer Power	18 watts
Total System Power	1001 watts
System Power-to-Thrust Ratio	151 kW/lb
System Specific Impulse (corrected for neutralizer flow)	5000 seconds

3. FEED SYSTEMS

To fulfill the requirements of this contract, three different zero-g cesium feed systems are to be used. Two are new designs and the third is a modification of a feed system developed under Air Force Contract AF 33(657)-10980. All three feed systems depend solely upon surface tension forces to separate the liquid and vapor phases within the storage volume and to deliver cesium to the vaporizer; controllable feed is obtained from the vaporizer by heating and resultant evaporation. Each feed system consists of a storage volume broken into tapered cells which bring cesium to a porous nickel wick on the reservoir axis. One end of this wick forms the vaporizer surface from which cesium is evaporated.

3.1 The 20-Pound Feed System

This feed system, shown in Fig. 8, has a manually operated feed valve and an electrically operated port valve. These valves are used to protect the cesium from the atmosphere and contamination during handling. This system (less the manual valve) was developed under the above mentioned Air Force program.

The manual valve shown in Fig. 9 is opened at the start of engine testing and is closed before the system is removed from the vacuum chamber. The actuating shaft is retracted after the valve is opened in order to allow for high voltage isolation. This valve would not be used on flight systems.

Figure 10 shows the reservoir port valve used to evacuate the system during pumpdown of the test facility. An electromagnet actuation system was used here since this valve is allowed to close and remain closed during engine operation.

The reservoir heater shown in Fig. 8 is used only to heat the reservoir before operation of the engine in order that the cesium wet

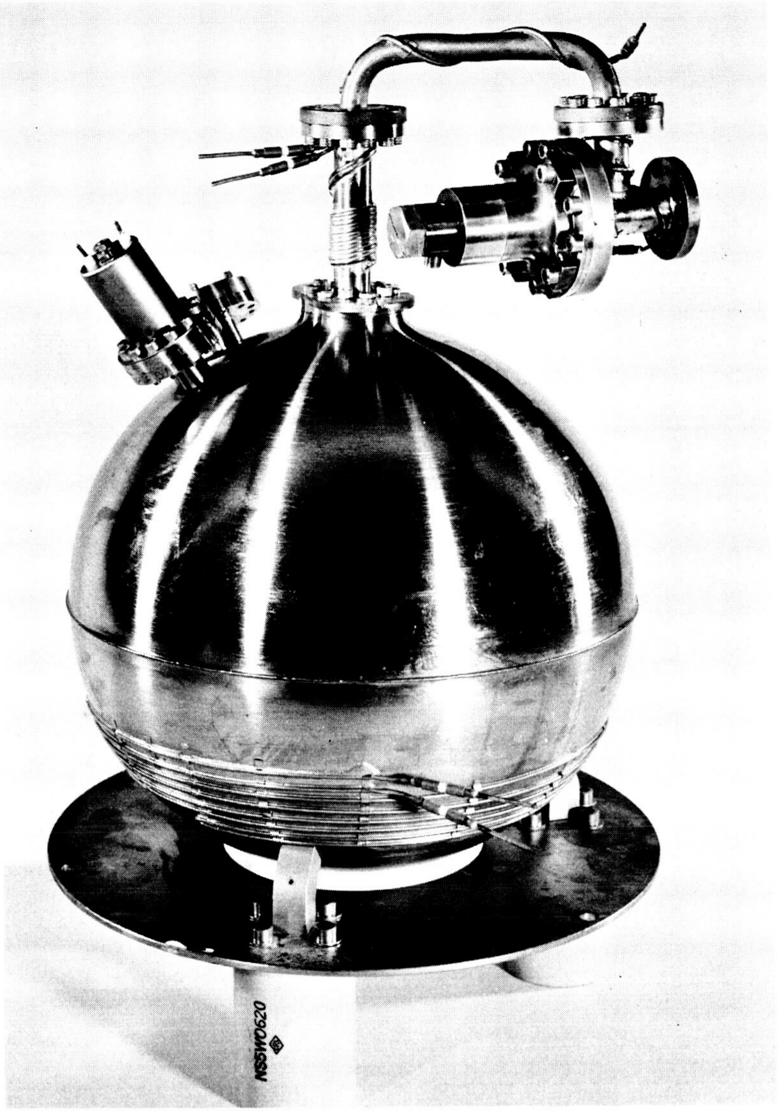


FIG. 8 THE 20-POUND FEED SYSTEM

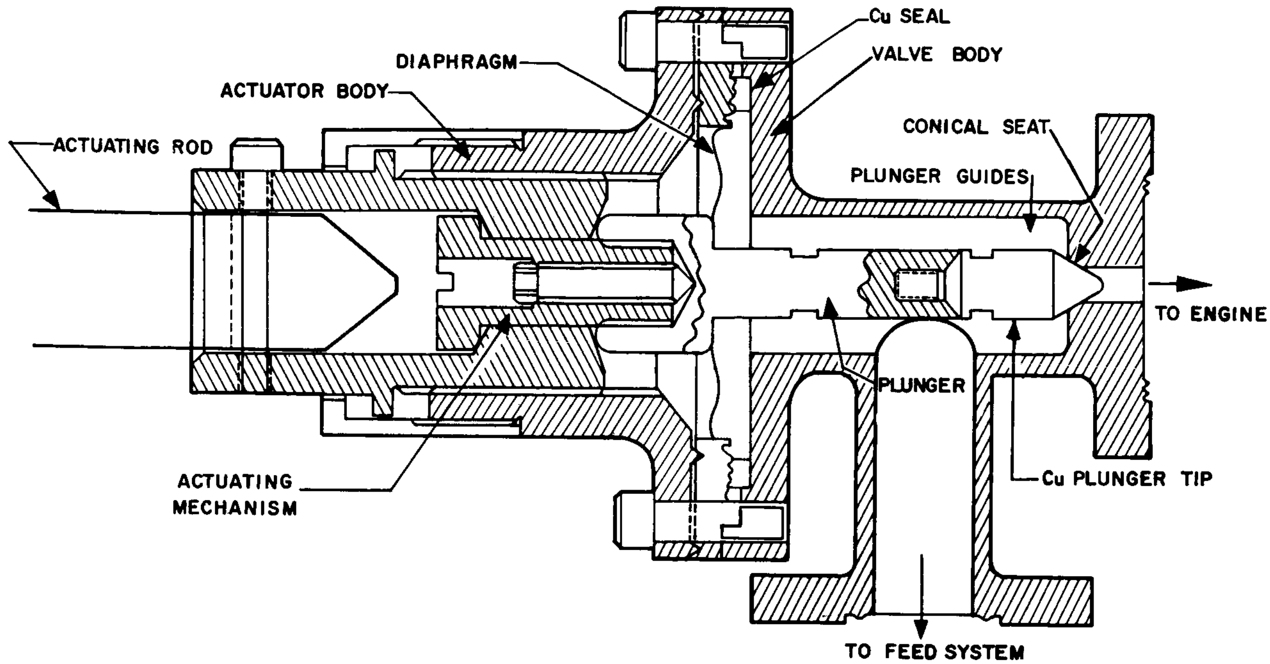


FIG. 9 MANUAL VALVE

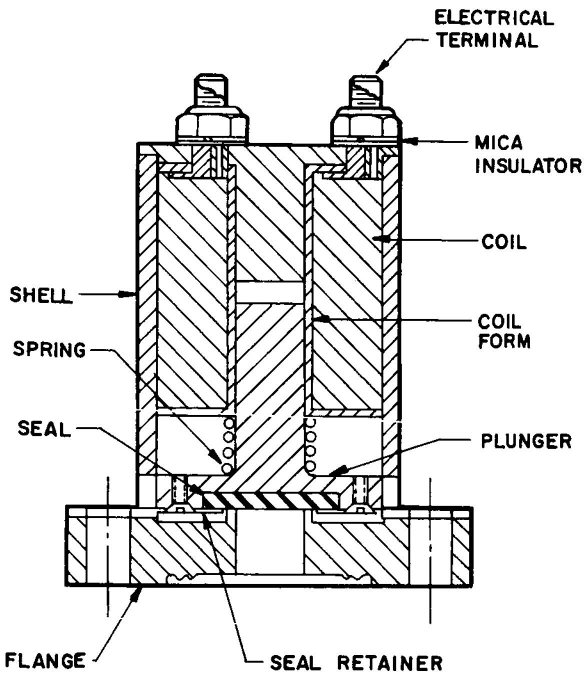


FIG. 10

PORT VALVE

the reservoir fins and the porous nickel wick. This function is also unnecessary for flight systems, as will be apparent from the discussion of Subsection 3.3.

The actual capacity of the 20-pound feed system is slightly over 18 pounds of cesium. Some of this capacity will be expended by startups and performance mapping, but a comfortable margin exists to cover false starts.

3.2 The 40-Pound Feed System

For the 4000-hour test a feed system with about twice the capacity of the 20-pound feed system was designed. This system has a capacity of 40 pounds of cesium and is illustrated in Fig. 11.

In order to reduce the height of the porous rod (significant only for testing in a 1-g environment), it was decided to use an oblate spheroid for the reservoir. The resultant height of the porous rod is 8 inches, approximately the same as that of the 20-pound system.

To reduce the feed system weight, only 90 fins were placed in the reservoir storage volume. This then required expansion of the vaporizer section to a diameter of 1 inch in order that the location of the liquid be stabilized in a theoretical zero-g environment. This system is presently being fabricated.

3.3 Neutralizer Feed System

The third feed system is the 1/2-pound or neutralizer feed system, designed to operate the neutralizer for 10,000 hours. Figures 12 and 13 show an exploded view and an assembled view of this feed system. The reservoir is 2-1/2 inches in diameter and has fin structure consisting of 72 fins. A porous nickel rod along the central axis delivers liquid cesium to the vaporizer.

Unlike the other feed systems, which use a port valve to evacuate the system after loading and during pumpdown of the vacuum chamber, this system will enter the vacuum chamber completely evacuated with the porous rod wetted with cesium. The neutralizer with its orifice sealed with cadmium will be attached to the reservoir. The system will

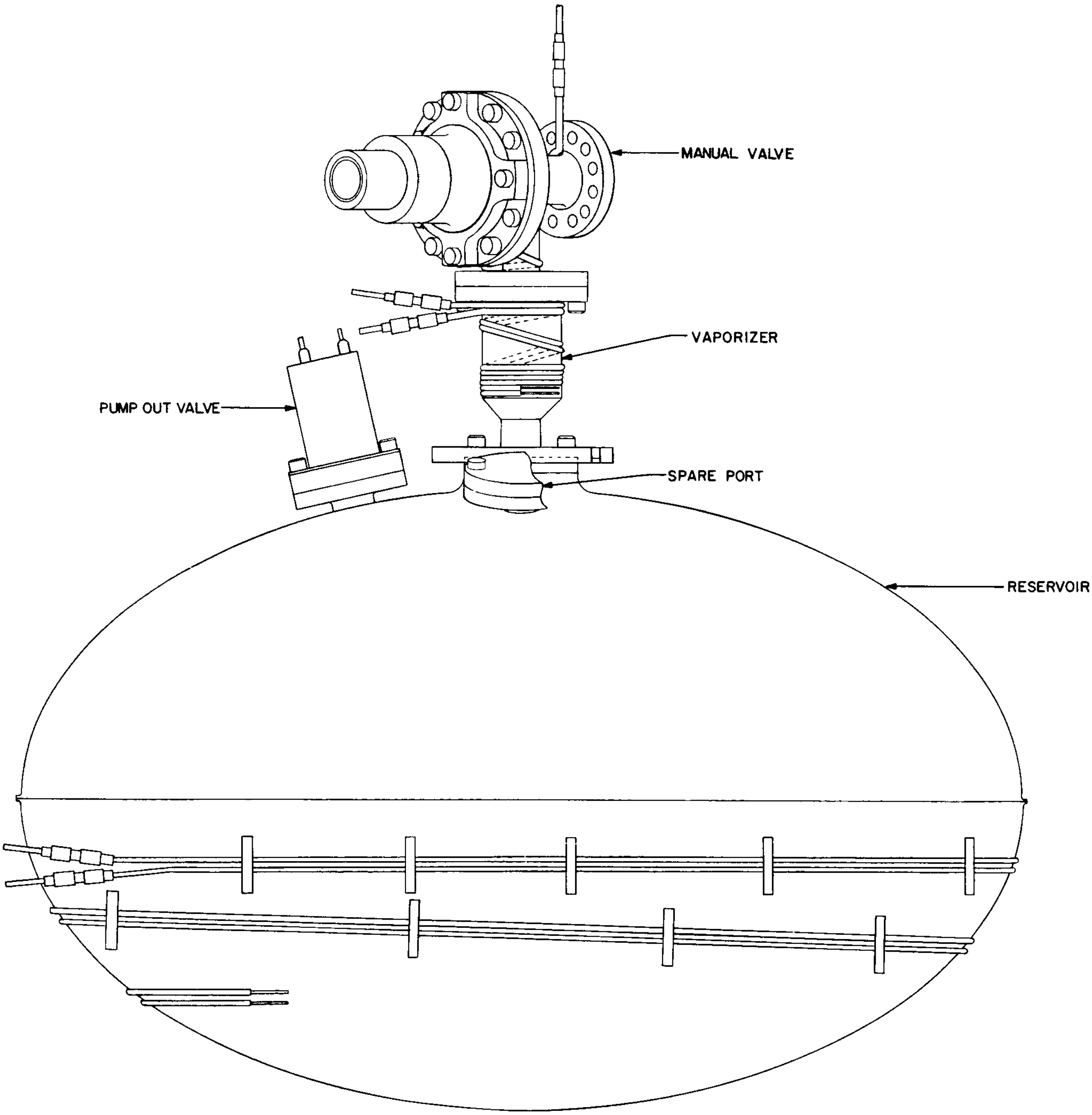


FIG. 11 THE 40-POUND FEED SYSTEM

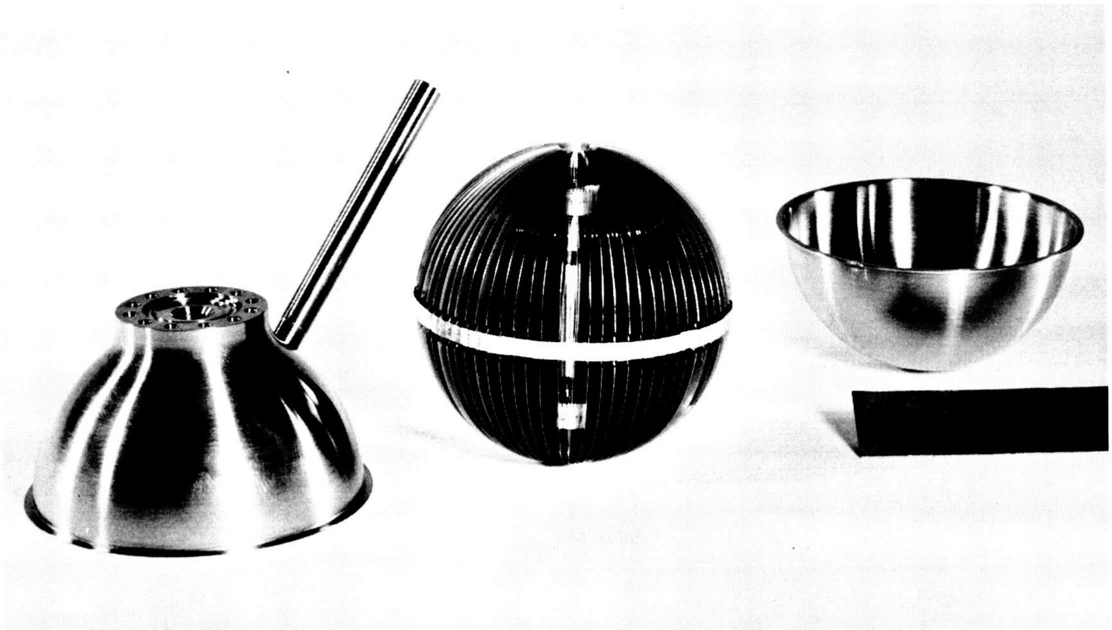


FIG. 12 THE 1/2-POUND FEED SYSTEM - DISASSEMBLED

FIG. 13 THE 1/2-POUND FEED SYSTEM - ASSEMBLED

then be leak-checked, loaded with cesium, evacuated, and sealed by melting shut the end of the fill tube in the electron-beam welding machine. The sealed system will then be heated in an oven to 200°C to wet the porous rod. Then the first time the neutralizer cathode is heated after evacuation of the chamber, the cadmium orifice seal will evaporate.

4. NEUTRALIZERS

Early in 1965 a new neutralizer concept was developed at Electro-Optical Systems, Inc., under Air Force Contract AF 33(615)-1530. This device promised long life at high efficiencies, so tests of the new neutralizer approach were started immediately under contract NAS3-5250. These tests were continued in this program, and a neutralizer and neutralizer control system were developed for use on the long tests.

4.1 Neutralizer Operation

Figure 14 is a schematic of an early neutralizer. Electrons are emitted by an externally heated, cesiated tantalum cathode similar in operating principle to the DG engine cathode. Cesium vapor is supplied to the emitter surfaces from a simple laboratory reservoir. The cathode chamber is heated to about 600^{o}C by a sheathed external heater. A small orifice in the chamber, typically 0.006 inch in diameter, faces the ion engine beam.

A discharge is established between the grounded neutralizer and the ion beam, which floats to a positive potential. From this discharge, the ion beam acquires all the electrons it needs for neutralization. The beam potential required to sustain the discharge is typically 8 to 10 volts, much lower than had been obtained previously with conventional thermionic neutralizer cathodes. Even at these low beam potentials, because ions formed in the discharge help overcome space charge effects, the neutralizer may be mounted several inches away from the beam.

The continuous cesium loss with this neutralizer exacts a toll in specific impulse. This penalty may be converted to an increase in required beam power by slightly increasing the engine specific impulse from its original level. Properly contained cathodes of this type have demonstrated emission ratios of over 100 electrons per cesium atom, so the loss of cesium from the neutralizer is expected to be less than

1 percent of the engine flow rate. Flow rates for neutralizers have been found to be as low as 0.84 percent of the engine flow rate.

The power requirements for the neutralizer are due to the cathode and the vaporizer heaters. Both of these may be heat shielded to reduce the power needed.

4.2 Neutralizer Control System

Cathode heater power for the "plasma bridge" neutralizer may be preset. It is anticipated, however, that the large changes in cesium flow rate that are obtained with small vaporizer temperature changes may not be tolerable for long-duration testing.

Control of the vaporizer power requires some form of information feedback. The system parameter which is most dependent upon the cesium flow rate through the neutralizer is the beam potential, normally approximated by the potential of a floating collector in the vacuum facility. As flow rate increases, the beam potential falls. Thus, it is possible to experimentally determine an optimum beam potential. However, for a control system to be realistic, the collector may not be used as the feedback sensor.

Beam Potential Probe

Since a plasma will attach itself to the most positive object it contacts, the "plasma bridge" should very nearly assume the beam potential. Langmuir probing of the low-energy "plasma bridge" should then yield beam potential information without sputtering away during long-term operation as would a probe immersed in the ion beam. Figure 15 shows probe plots taken for two values of "beam" potential with an operating neutralizer. The "beam" for this experiment was a piece of copper screen located about two inches from the neutralizer. The probe used was similar to that shown in Fig. 16.

A probe biased through a 33-ohm resistor from a 12-volt supply will operate along the load line shown in Fig. 15. While a probe operated in this manner will not measure true plasma potential, positive correlation between the probe and beam potentials can be obtained.

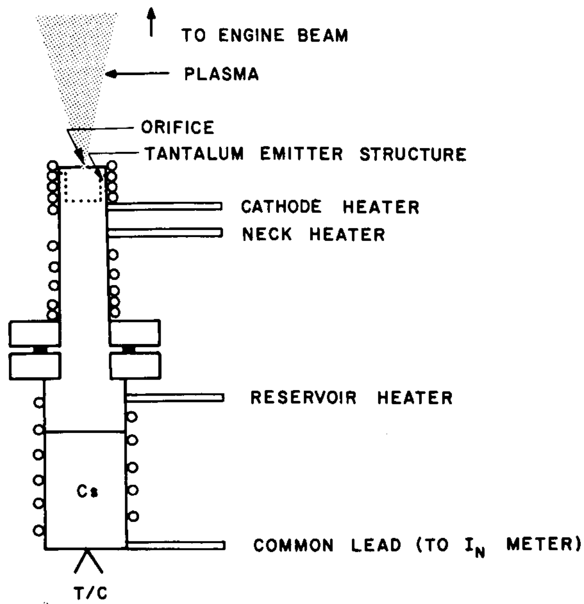
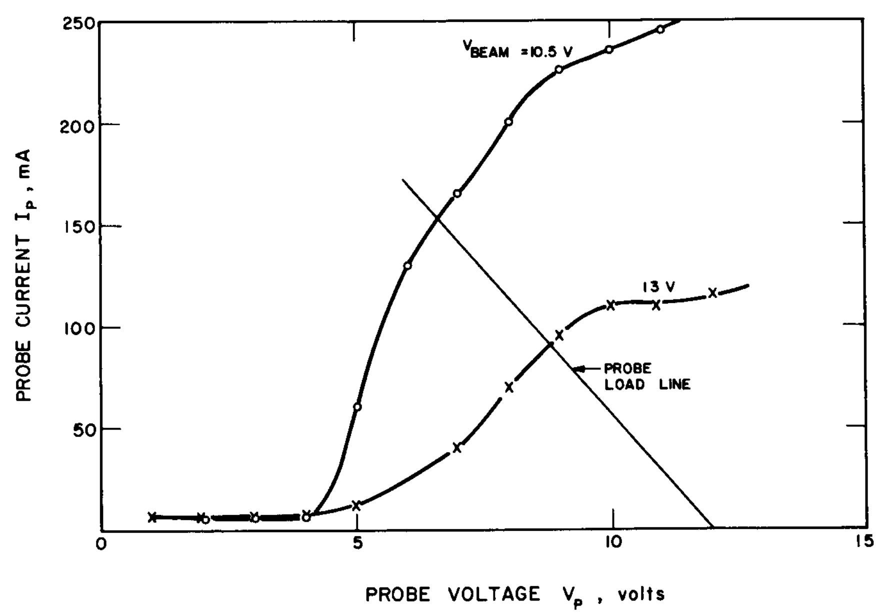


FIG. 14

"PLASMA BRIDGE" NEUTRALIZER

FIG. 15

"PLASMA BRIDGE" PROBE CHARACTERISTICS



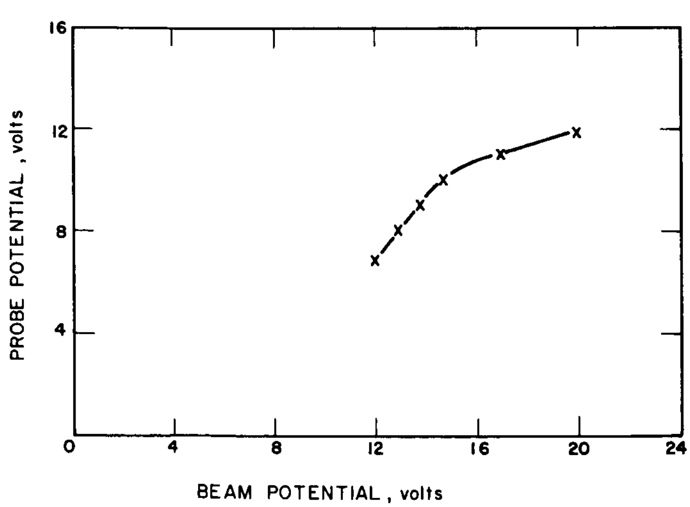


FIG. 16

PROBE POTENTIAL CORRELATION

Figure 17 shows the correlation obtained with a 400-ma constant current source applied to the "beam." These data were taken as the vaporizer was allowed to cool, causing the "beam" potential to rise. An automatic vaporizer feedback control was synthesized based on the results of these tests.

4.3 Prototype Neutralizer

The neutralizer shown in Fig. 16 consists of a zero-g feed system and an externally heated, cesiated tantalum cathode. A long narrow vaporizer section was used to minimize heat losses.

The prototype neutralizer, shown in Fig. 18 without the probe, was tested with the DG engine. Table III lists the operating parameters obtained.

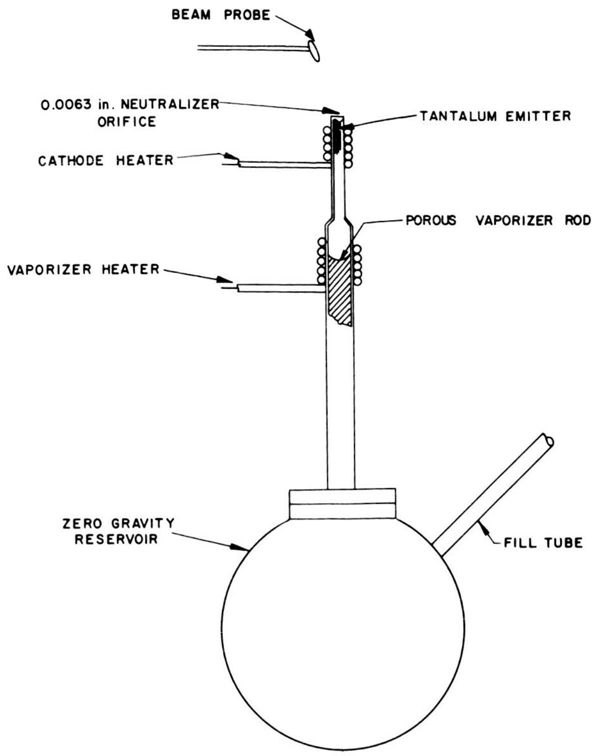


FIG. 17

PROTOTYPE NEUTRALIZER DESIGN

FIG. 18

PROTOTYPE NEUTRALIZER

TABLE III

NEUTRALIZER OPERATING PARAMETERS AND TOTAL EQUIVALENT POWER

Cathode Heater Power, P_K		3.9 watts
Vaporizer Heater Power, P_V		10.2 watts
[1]Emission Current, I_N	0.4 ampere	
[2]Beam Potential, V_B	9.5 volts	
Perveance Power, $V_B\ I_N$		3.8 watts
[3]Cesium Flowrate (percent of Engine Flowrate), η_{cs}	1.0 percent	
Slope of Engine P/T vs I_{sp} Curve at 5000 seconds, ^{sp}K	17 watts/lb-sec	
Engine Thrust, T	6.77 mlb	
Engine Specific Impulse, I_{sp}	5050 seconds	
Neutralizer Flowrate Penalty in Equivalent Power, $(\eta_{cs}\ K\ T\ I_{sp} \times 10^{-5})$, P_{cs}		5.8 watts
Total Neutralizer Power		23.9 watts
Neutralizer P/T Penalty		3.5 kW/lb

1. Correlation between engine beam current and neutralizer emission current was within 5 percent.
2. Potential of isolated collector in the vacuum system.
3. Estimated from previous tests.

5. QUALITY ASSURANCE

EOS Report 6954-QAP-1, "Quality Assurance Plan — Revised," was prepared and submitted to NASA/Lewis. This report included the Quality Control Manual and the Inspection and Test Plan Outline for NASA/Lewis Contract NAS3-7112. The equipment log and failure report formats were also included.

Shop traveller activity during the first quarter was primarily concerned with DG-1 engine and zero-gravity feed system support. Equipment logs were issued for both control systems. Five standing assembly requests are active as follows:

DG-1 engine
20-pound feed system S/N 1
Neutralizer assembly S/N 1
1/2-pound feed system S/N 1
1/2-pound feed system S/N 2

The following test procedures were released:

6954-03-1) Feed System Assembly and Test Procedure
6954-02-1) Magnet Coil Check, Air
6954-02-2) Cathode Check, Air
6954-02-3) Reliability Engine Component Weights
6954-02-4) Electrode System Check, Air
6954-02-5) Neutralizer Inspection and Test Procedure

Additional welding, brazing, and processing instructions were released to control new procedures developed under this contract.

6. PLANS FOR NEXT QUARTER

The 2000-hour engine system will be performance-mapped and the 2000-hour test will be started. Following the choice between the electromagnet and permanent magnet engines for the 4000-hour test, the engine system will be performance-mapped and the 4000-hour test will be started.