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SNAP 10A FSM-4 TEST STATUS

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SNAP 10A FSM-4 TEST STATUS

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9/28/04

By

J. BRUNINGS
W. VAUGHN

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ABSTRACT

The SNAP 10A program is oriented to demonstrate space-flight performance of a 500 watt-e nuclear thermoelectric power-generating system. An extensive series of ground tests have been scheduled prior to actual flight operation. The ground test program is subdivided into development, prequalification, and qualification tests at the component, subsystem, and system level. Component level tests have been essentially completed with only a few exceptions, however, endurance tests are continuing. Major systems tests are scheduled which simulate the significant environmental conditions imposed on the power system throughout all phases of the factory-through-flight sequence.

The purpose of the FSM-4 system test is to verify system performance (nonnuclear) throughout a simulated complete factory-to-flight sequence. The FSM-4 system has been fabricated under flight-system quality-control requirements and all components are flight design with the exception of electric core heaters which have been substituted for the active fuel elements. Not all components have completed qualification testing, however, there is substantial test experience to provide confidence in the performance of these components.

This report describes the FSM-4 system test program, schedule, and test objectives. An evaluation of the system test reliability is summarized based on component test data available as of June 1, 1964.

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I. INTRODUCTION

The FSM-4 ground-test unit represents the final system qualification test of the SNAP 10A unit prior to actual flight demonstration. The unit will be subjected to the flight-system acceptance test sequence including NaK loading and thermal reference checks. The unit will then be subjected to qualification level shock and vibration tests simulating the launch environment. Following environmental test, the unit will undergo prestartup orbital test, startup and endurance tests in a simulated space thermal vacuum environment.

The unit is fabricated with flight-design components and it represents the flight-system configuration except for the substitution of electric core heaters for active fuel elements. Therefore, the FSM-4 test simulates all flight-system performance phases and environments in the factory-through-flight sequence on a flight unit except nuclear radiation. A separate nuclear qualification test is scheduled to supplement the FSM-4 test and qualify the reactor.

The reliability of major system components was evaluated based on the results of the component qualification test program and supporting development tests. An evaluation of the facility has shown that the facility equipment reliability is very high, however, major commercial power outages can occur at the Santa Susana test site which can interrupt test operations. Although a major loss of power will cause test shutdown, the overall integrity of the FSM-4 system should not be adversely affected.

The principal test objectives of the FSM-4 test program will be satisfied if the unit successfully survives the launch environment and produces more than 450 watts electrical output during steady-state operation. This power output is equivalent to at least 500 watts output for a flight system operating in space. The probability of meeting test objectives, allowing for facility shutdowns during any portion of the test program, is essentially equal to the probability of the unit itself meeting test objectives. The reliability of the FSM-4 unit is summarized in Table 1 by flight phase.

TABLE 1
FSM-4 ESTIMATED TRUE RELIABILITY

	Launch Survival	Prestartup Orbital Operation	Startup	90 Day Endurance	1 Year Endurance
Cumulative Estimated True Reliability	0.982	0.975	0.942	0.884	0.790

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II. FSM-4 SCHEDULE AND TEST OBJECTIVES

A. INTRODUCTION

There have been several systems fabricated to satisfy the test objectives of the SNAP 10A program (Figure 1).

	FSM-1	FS-1*	FSM-4	FSEM 2A-3
SHOW MANUFACTURING CAPABILITY	X	X	X	
QUALIFICATION SHOCK & VIBRATION	X	X	X	
THERMAL PERFORMANCE	X	X	X	
INSTRUMENTATION PERFORMANCE			X	X
ELECTRICAL COMPATIBILITY				X
CONVERTER PERFORMANCE	X		X	
REACTOR PERFORMANCE QUALIFICATION		X		

*The FS-3 system has been substituted for the FS-1 system to serve as a nuclear system ground test.

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Figure 1. System Test Objectives

1. FSM-1

FSM-1 provided both development and qualification information and satisfied the following system test objectives:

- a) Manufacturing capability was demonstrated by virtue of the successful fabrication and assembly of FSM-1 system. A large number of special techniques were developed to fabricate FSM-1, such as automatic welding of the converter legs to the upper and lower manifold. All phases of titanium fabrication, riveting, forming, handling, and cleaning were developed. Primary tooling, assembly alignment, locating and holding fixtures were developed and successfully used. Certain processes, such as gold foil attachment on piping and converter; and the method of attachment of RTD's were not successful and have been revised.
- b) The qualification shock and vibration program demonstrated the capability of the structure, power converter system, instrumentation, relays, and reactor assemblies to withstand successfully the

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qualification loadings. Much of the equipment exposed to this environment was considered to be developmental, however, substantial structural components and certain instrumentation items were flight components.

- c) Thermal performance, following the simulated launch environment, was demonstrated by application of the anticipated nuclear transient through the use of programmed power to the electrical core heater. System thermal performance characteristics throughout the startup, stabilization, and endurance phases was successful.
- d) Converter performance was successful even though the converter was assembled with first and second generation thermoelectric elements. This test, while developmental in nature, provides confidence in the converter installed on FSM-4, both for reliability and for power performance capability.

2. FS-1

This system is identical to FSM-1 except for the nuclear systems, which are flight type, and the converter which is of a later vintage than FSM-1, but still not flight type. The principal objective of this unit is to provide flight qualification status to the nuclear and associated nuclear components of the SNAP 10A flight systems. This program has been initiated and the FS-1 system is presently loaded with NaK and nuclear fuel and is undergoing acceptance tests.*

3. FSM-4

FSM-4 is identical to the flight systems in every respect except for those items associated with the reactor core. A systematic comparison of these differences is described in Section III.

The factory-to-flight test sequence consists of the following separate phases:

- a) Acceptance – Assembly checkout, system cold reference tests, NaK loading and thermal reference tests, and acceptance level shock and vibration tests

*The FS-3 system has been substituted for the FS-1 system to serve as a nuclear system ground test.

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- b) Launch — Qualification level vibration test and shock loading in each of the three mutually perpendicular axes
- c) Prestartup Orbital Operation — Simulation of solar heat and space temperatures for both the constant sun/constant shade polar orbit and the sun/shade equatorial orbit. Simulation is accomplished by cryogenic walls and radiant heaters inside of a vacuum chamber maintained at about 10^{-4} Torr vacuum.
- d) Startup and Temperature Stabilization — Automatic startup in the space vacuum chamber utilizing command signals and simulating the actual nuclear transient
- e) 90-Day and 1-Year Endurance — The production of thermoelectric power for a 90-day and 1-year period at a level of power level greater than or equivalent to 500 watts in space.

4. FSEM 2A and 3

Electrical compatibility will be satisfied by a test program which integrates the FSEM-3 and the Agena vehicle. This test will be conducted at the LMSC facility at Sunnyvale, California, and monitored by AI. The FSEM-2A system will be used as a development test bed and the results will establish the design margins in FSM-4 and the flight systems instrumentation subsystems.

FSM-4, therefore, occupies a pivotal position in the qualification program and for this reason the accuracy of the technical information and the meeting of qualification objectives will be emphasized throughout the test program.

B. TEST OBJECTIVES

A summary of the FSM-4 system test objectives is presented below:

1. Verify NPU Survival of Launch After Acceptance Test

Verification that the power system can survive the simulated launch phase will be determined by conducting visual and electrical checks on the system throughout this test phase. Circuits that are enabled (active) will be monitored. Relay positions will be determined before and following each qualification axis test to determine if status changes have taken place. Active squibs will be installed and monitored for inadvertent actuation.

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Critical components will be examined following the qualification level test for any defect that would prevent subsequent startup, i. e., structural failure that would prevent components from performing their intended functions. This examination includes checks of the mechanical integrity of the structure, NaK pump, power conversion system, NaK system and control system. The controller, relays, drive motors and harness must show electrical isolation and continuity. The reflector assembly should be mechanically sound with no shift in vessel/reflector position.

In addition, the diagnostic instruments including RTD's, T/C's position switches, and position indicators will be checked for continuity, isolation resistance, and loop impedance.

2. Verify NPU Behavior During Prestartup

The condition of the NPU during this phase will be determined by monitoring the diagnostic instruments associated with NaK system temperatures. The objective is to demonstrate that the NaK contained within the system will not freeze under the worst orbit condition. The orbit conditions will be simulated by means of full-length cryogenic walls maintained at -160°F average temperature and radiant heaters simulating solar heating. A vacuum of about 10^{-4} Torr will be maintained in the test chamber. NaK flow will be established by providing an external current of 40 amps across the pump throat. Temperatures, flow rates, heat shield effectiveness, and temperature transients during orbit operation will be determined and analyzed in terms of the flight system orbit model. Success will be judged by nonfreezing of the NaK under the worst condition. The critical components during the prestartup phase are: pump and battery circuit, heat shield, and NaK system.

3. Verify NPU Behavior During Startup

A remote automatic startup, initiated by a simulated ground command, will be demonstrated during this test. The startup and rise to power temperature ramp rates will be simulated closely by means of an analog programmer.

NaK pump response in terms of flow rate, and the stepping rate and reactivity insertion of the control drums will be closely monitored. The critical components during this phase are: NaK pump, control system, NaK system, and reflector assembly.

4. Verify Integrated NPU Operation for 90 Days and One Year

After reaching stabilized core outlet temperature (1010°F) following startup, the controller will be commanded off and the core average temperature reduced to about 920°F. This reduction matches the expected reduction in reactor temperature due to hydrogen redistribution effects following the active control period. Those components that must perform satisfactorily for the system to produce 500 watts design electrical output are classified as critical components. In addition, a significant portion of the diagnostic instrumentation must be operable to ascertain the system performance characteristics. Therefore, the critical components during the endurance phase of operation are: NaK pump, NaK system, power conversion system, control system, and a portion of the diagnostic instrumentation.

5. FSM-4 Qualification Objectives

The qualification objective of the FSM-4 system is to demonstrate power performance capability greater than 450 watts for 90 days. This is equivalent to 500 watts for FS-3 in space. In addition, the FSM-4 system should demonstrate the functioning capability of the diagnostic instrumentation. Since redundant diagnostic instrumentation has been provided in the design, qualification objectives are based on at least 50% of the instrumentation being operational for a period of 90 days and that the operable instrumentation is sufficient for diagnostic purposes.

There are also many detail engineering objectives of the FSM-4 system test, however, meeting the two objectives above will establish the satisfactory demonstration of space power unit for flight test.

C. SCHEDULE*

The FSM-4 schedule, as of June 1, 1964, is shown in Figure 2. As of June 1, however, the assembly and checkout had not been completed and completion of checkout will probably be achieved by mid-June. The NaK loading and thermal reference test is scheduled to take about six weeks. The shock and vibration tests, which follow the thermal reference test, are scheduled to take

*Since this schedule was prepared, a failure of an FS-1 expansion compensator during system acceptance test has facilitated the redesign of the flight system compensators. Therefore, the FSM-4 schedule has been delayed pending new expansion compensators.

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Figure 2. FSM-4 Program Schedule

about four weeks. The unit will then be placed in a vacuum tank and undergo prestartup orbital tests and a simulated nuclear startup which should take about two weeks. Following startup, the FSM-4 unit will be maintained at normal operating temperature to demonstrate endurance operation for 90 days and 1 year.

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III. FSM-4 COMPONENT STATUS, AND PERFORMANCE CHARACTERISTICS

A. COMPONENT STATUS

In order for the FSM-4 power unit to serve as a qualification test system, the unit has been built of flight-system components. There are several areas where differences exist, however, these differences do not affect the qualification objectives of the test. In certain areas, flight-type components are not yet available, but they are scheduled to be installed before the qualification tests begin. These items are the main relay box, auxiliary relay box, degradation relay box, temperature switches TS-3 and TS-4 (low-temperature and high-temperature malfunction switches), ELD/ESD timer, and the EABRD (Electrically Actuated Band Release Device).

A preflight ejectable heat shield is currently being modified to reflect the flight design, revised thermal coating, revised pivot block brackets, and electrical connectors. The shield will be used during the pre-orbital startup tests and during acceptance and qualification vibration and shock tests. The shield will be adequate for these tests even though it is not considered a flight quality shield.

Several detailed variations exist between the FSM-4 unit and the flight systems which stem from the use of electrical cartridge heaters in place of a normal fuel loading. These differences are considered minor. Figure 3 (a and b) summarizes the differences between the FSM-4 qualification test unit and the flight systems FS-3, -4, and -5.

B. PERFORMANCE CHARACTERISTICS

The performance characteristics of the FSM-4 unit, under ground test conditions, is summarized in Figure 4. Reactor power (electric power input) is regulated during the startup and endurance phases of system operation to correspond with the actual performance characteristics of a flight reactor operating under space conditions. During the three-day active control period, core power is regulated to achieve a core outlet temperature of 1010°F. At this temperature, the FSM-4 pump will circulate 13.2 gpm and the system will reach thermal equilibrium at an average reactor temperature of 944°F. The corresponding converter output is 503 watts-e.

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COMPONENT	FLIGHT SYSTEM	COMMENT
CORE HEATERS	NO	FUEL SIMULATION
REFLECTOR ASSY	YES	STAND OFFS
CONTROL SYSTEM	YES	RELAY BOXES TO BE REPLACED
NaK SYSTEM	YES	G-SPRINGS REACTOR OUTLET TUBE
PUMP	YES	MOUNTING VARIATIONS
P C S	YES	—
STRUCTURE	YES	—

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a.

COMPONENT	FLIGHT SYSTEM	COMMENT
EJECT HEAT SHIELD	NO	THERMAL CHARACTERISTICS w/FS DESIGN
PYROTECHNICS + PIN PULLERS	YES	—
WIRE & CONNECTORS	YES	—
RADIATION SHIELD	YES	—
EMMISSIVITY COATINGS	YES	—
DIAGNOSTIC INSTRUMENTATION	YES	—
MALFUNCTION & FAIL INSTRUMENTATION	YES	TS-31 TS-41 NOT INSTALLED TIMER TO BE REPLACED
SHUT DOWN	YES	EABRD — TABRD —

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b.

Figure 3. FSM-4 Component Status Comparison

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	Start	90 Day	1 Year
Reactor Outlet Temperature (°F)	1010	992	998
Average Reactor Temperature (°F)	944	920	920
Flow (gpm)	13.2	12.0	11.0
Power Output (watts-e)	503	461	442
Average Radiator Temperature (°F)	630	606	606
Core Power (kwt)	41.3	39.9	40.4
Overall Efficiency (%)	1.22	1.15	1.09

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Figure 4. Expected FSM-4 Performance

Following the three-day active control period, the reactor power output is decreased to yield an average reactor temperature of 920°F. This reduction in core temperature corresponds to the expected reduction in the flight system reactor due to reactivity losses from hydrogen redistribution following the active reactor control period.

The average reactor temperature is maintained at 920°F during the 90-day and 1-year endurance test. 920°F is the expected average reactor temperature of a flight system reactor throughout the endurance phase of operation. The corresponding electrical power output is 461 watts at 90 days and 442 watts at 1 year.

Flow degradation of the NaK pump is gradual, approximating 0.25 gpm/1000 hr. Maintaining a constant average reactor temperature causes an increase in reactor outlet temperature climbing slowly from a value of 980°F to 998°F at the end of 1 year. Reduced power output during endurance operation is attributed to converter degradation.

Figure 5 compares the FSM-4 power output operating under ground test condition to the power output expected from a flight system (FS-3) operating under actual flight conditions. At an average core temperature of 920°F, the expected nominal power produced by FS-3 varies from 530 watts initially to 502 watts at the end of 1 year. For FSM-4, the initial expected power output is 503 watts during the active control period reducing to 442 watts at the end of 1 year. No uncertainty band exists during the active control period for FS-3, as it does for

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FSM-4, since the initial FS-3 power output is established at 570 watts by adjustment of the core outlet temperature (estimated to be 1010°F) during system acceptance tests. The uncertainty in the initial power output on FSM-4 results from establishing the controller temperature cutoff at 1010°F. The degree of power output uncertainty shown is approximately a $\pm 1\sigma$ band or about $\pm 3\%$ of the nominal converter output. The gradual spread of power in both FS-3 and FSM-4 results from a $\pm 1\sigma$ uncertainty in converter degradation with time. The upper curve in both cases is 4%, the center curve is the assumed normal degradation rate and is 5.5%, and the lower curve represents a maximum degradation of 7.0%. Most of this degradation occurs during the first few hundred hours of operation. The difference between the FSM-4 and flight system power output is approximately 10% due to the correction for ground-test environmental conditions.

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Figure 5. FSM-4 Performance Characteristics

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IV. FACILITY DESCRIPTION

The FSM-4 system will be subjected to a complete simulated factory-through-flight sequence of test operations. Following acceptance test (NaK loading and thermal reference test), the system will be subjected to qualification level shock and vibration tests simulating the launch environment. After completing the simulated launch environmental tests, the unit will undergo prestartup orbital tests and a simulated startup and will demonstrate endurance operation.

The qualification level shock and vibration tests will be conducted in Environmental Test Laboratory (Building 27). The environmental test equipment consists of a 30,000-lb-force electromagnetic shake table and its appropriate controls. Two independent limiter circuits are provided to automatically cut off power to the shake table if the table input inadvertently exceeds specified levels.

NaK loading, thermal reference test, prestartup orbital test, and startup and endurance operation will be conducted in the Building 032 FSM-4 Thermal Vacuum Test Facility. This facility consists of the following major systems.

A. VACUUM SYSTEM

The vacuum system (Figure 6 and 7) consists of the following major components: a test chamber constructed in three sections with a rubber seal where sections are joined, two electric motor-driven mechanical vacuum pumps, one oil diffusion pump, necessary shutoff valves in the outgassing line, and two readouts. The diffusion pump and one roughing pump is used to pump down the chamber. The second roughing pump is in standby. However, once the chamber has been pumped down, either of the roughing pumps are capable of maintaining a vacuum of sufficient magnitude that shutdown of test would not be necessary as long as one pump is operable. The pumps are redundant from a reliability standpoint as testing does not begin until the chamber has been pumped down to the required vacuum. A schematic of FSM-4 vacuum pumping system is illustrated in Figure 7.

The seals used between the chamber sections are a butyl rubber composition. Samples have been tested to higher vacuum than required in the FSM-4 tests. A successful vacuum was maintained during the 90-day test of the FSM-1 system using these seals.

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Figure 6. Environmental Chamber

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Figure 7. Vacuum Pumping System SNAP 10A FSM-4

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The valves in the outgassing line to each pump are capable of sealing the lines and isolating the chamber. With the valves closed and at the estimated leakage and outgassing rate from the FSM-4 system, a period of three hours of testing can be conducted without any pumping before the vacuum in the chamber is reduced to a level which would require that the test be secured. Therefore, the test could be shut down if both pumps malfunctioned or power was lost and pumping could not be reestablished before the lowest allowable vacuum level was reached.

B. POWER SUPPLY

The facility power is supplied by the main plant commercial line and the power is utilized to operate the facility test equipment as well as supply power directly to the electric core heater. This power supply is backed up by a "battery stack" which can operate for approximately 20 minutes at full power. A manual switch is provided to switch from the commercial line to the battery stack. A battery charger is utilized to keep the batteries charged and the charger operates through a timer arrangement which switches every 8 hours from one portion of the battery stack to another.

C. COOLING WATER SYSTEM

The cooling water system cools the vacuum chamber, vacuum pumps and refrigeration systems. The system is a closed water loop which rejects heat to a cooling tower. Flow and pressure are supplied by a centrifugal pump. A second pump is provided in parallel for redundancy. The cooling tower uses a recirculating water pump and a blower to cool the water in the closed loop. Experience has shown that the blower is not required except on extremely hot days. Therefore, the loss of the blower would not seriously affect the test even on a hot day. A spare motor for the blower and a spare recirculating pump-motor unit is available.

The facility main water source is at a temperature of from 70 to 80°F and it can be used for emergency cooling in the event of a failure of the closed loop system. Any credible outage of this system should not require more than two hours to repair. It is estimated that the test could operate without any cooling for this length of time.

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D. REFRIGERATION SYSTEMS

Two refrigeration systems are utilized in the thermal vacuum test facility. The Freon system (Figure 8) is provided to cool the FSM-4 instrument compartment and the diffusion pump cold baffle. A liquid nitrogen system (Figure 9) is also provided to cool the cryogenic panels which are only utilized during the prestartup orbital tests.

The Freon system is a standard mechanical refrigeration system. There are two parallel units, with by-passes around the filters and manual control valves which can be used if the automatic expansion valves malfunction. The system could be shut down for a short period, if necessary.

The liquid nitrogen system refrigeration is only used during the prestartup orbital tests to provide simulated space temperatures within the vacuum tank.

E. LOAD BANK

The power generated by the FSM-4 converter is dissipated in a rheostat which is nominally set at the converter matched load resistance. The loss of the rheostat would cause a small change in system temperatures but it would not cause damage to the FSM-4 unit. Load bank replacement or repair is possible which adds to the reliability of the item.

F. INSTRUMENTATION AND CONTROLS

All instrumentation will be carefully calibrated and, where possible, calibrated to N.B.S. standards. Instruments of 1% or better accuracy have been utilized and care will be taken to use the same instrument for the same readout each time a reading is taken. This will eliminate problems of difference in readings due to differences in meters.

A visual dynamic display of converter leg temperatures and other dynamic parameters will be observed on a 17-in. cathode ray tube during the NaK loading.

A test console is provided to simulate the functions of the ground checkout equipment and to provide simulated commands normally received by the power unit from the command system. This console is equipped with several power supplies for system operation; i.e., dc for pump start and 400 cps, 115 volt,

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Figure 8. Schematic Freon System SNAP 10A FSM-4

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Figure 9. SNAP 10A FSM-4 Liquid Nitrogen System to Support Cryogenic Walls

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3 Ø for position indicator circuits. An event marker monitors all circuits. Lamps are used to indicate position of relays, switches and other contracts. A group of switches is included for distribution of dc power.

A control console regulates and monitors the thermal functions of the power system and the facilities. This console contains instruments and alarms for checking the following items:

- 1) Chamber cooling water flow
- 2) Temperature-recorder with 40-channel switch to backup Data
Logger
- 3) Cooling water to diffusion pump
- 4) Temperature on the diffusion pump
- 5) Main cooling water flow
- 6) Core outlet temperature of NPU
- 7) Vacuum in chamber
- 8) Voltages - by use of 100-point indicator to backup Data Logger.

The controller for controlling power to the core heater is on this console as well as a manual override capability. The meters for monitoring power applied, the load bank and running time meters are located on this console. A Data Logger with a 300-data-point capacity is used for recording calibration, input, and output data of the entire test.

Pictures of the FSM-4 Test Console, Control Console and Data Logger are shown in Figures 10, 11, and 12 respectively.

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Figure 10. FSM-4 Test Console

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Figure 11. FSM-4 Control Console

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Figure 12. FSM-4 Data Logger

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V. FSM-4 RELIABILITY EVALUATION

A. INTRODUCTION

A reliability evaluation has been undertaken to ascertain the probability of the FSM-4 unit satisfactorily surviving the factory-through-flight test sequence and produce useful electric power under simulated space conditions. The following system performance characteristics were used as the success criteria in preparing this evaluation:

1. Launch

The FSM-4 unit must survive the simulated launch phase and be capable of starting up and producing power. Five performance characteristics must be satisfied before the FSM-4 unit satisfactorily passes the environmental test. They are:

- a) Maintain structural integrity
- b) Maintain electrical continuity
- c) No inadvertent operation of control system
- d) No leaks in piping system
- e) Eighty-five percent diagnostic instrumentation functional.

The FSM-4 unit must survive the simulated launch phase without sustaining structural damage which would prohibit the system from starting up and producing power. In addition, electrical continuity must be maintained. Inadvertent operation of the control system could result in the firing of live squibs since the squib bus is armed during the launch phase. A NaK leak would constitute a failure in accordance with the above criteria. As a result of the redundancy in diagnostic instrumentation, 15% of the diagnostic instrumentation may be nonfunctional at the conclusion of the environmental test and still satisfy the success criteria.

2. Prestartup Orbital Operation

Following booster burnout, a signal is received by the power unit from the ascent timer directing current to the expansion compensator squibs and pin pullers which, in turn, releases the compensators for NaK volumetric expansion.

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Successful operation of this system is achieved if both expansion compensators are released, however, one expansion compensator can provide the necessary expansion volume.

During the prestartup orbital phase, NaK temperatures must be maintained between the NaK freezing temperature (14°F) and 250°K. NaK freezing could restrict flow in the power conversion system and prevent power generation following reactor startup. Exceeding the upper temperature limit could cause premature actuation of the heat shield ejection switches or deteriorate the heat shield squibs.

The additional performance characteristics that must be established for the FSM-4 unit to pass the prestartup orbital phase are:

- a) No leaks in piping system
- b) No control system operation
- c) Maintain electrical continuity
- d) Eighty percent diagnostic instrumentation functional.

3. Startup

The startup phase is initiated by a ground command received by the Agena vehicle which in turn directs power to the NPU. Receipt of this signal triggers the following events:

- a) Coarse control-drum pin-puller squibs are fired releasing the control drums.
- b) The spring-loaded coarse control drums snap to their full in position.
- c) The startup controller is energized.
- d) The fine control drums step inward at a controlled rate.

Following the reactor criticality, the reactor undergoes an initial power transient and the NaK temperature rapidly rises to about 400°F. During this transient, the ejectable heat shield switches are actuated and simulated heat-shield pin-puller squibs are fired. The system then rises steadily in temperature and power to normal operating conditions. The actual startup transient in the FSM-4 system is simulated by an automatic core electric power program.

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The following performance characteristics must be satisfied for the FSM-4 unit to pass the startup phase:

- a) Control system functions
- b) Heat shield release activated
- c) Converter output ≥ 450 watts
- d) No inadvertent operation of malfunction and failure circuitry or shutdown devices
- e) Deactivation of control system after three days
- f) Seventy-five percent diagnostic instrumentation functional.

4. 90-Day Endurance

During the 90-day endurance test, the average NaK temperature in the FSM-4 unit will be controlled at a value greater than 905°F. This temperature level corresponds to the minimum expected temperature from a flight reactor operating under space conditions. The corresponding performance characteristics must be satisfied for the FSM-4 unit to pass the 90-day endurance phase are:

- a) Converter output ≥ 450 watts
- b) Converter voltage ≥ 22.5 volts
- c) No inadvertent operation of malfunction and failure circuitry or shutdown devices
- d) Fifty percent diagnostic instrumentation functional.

5. One-Year Endurance

The FSM-4 unit will be operated for a period of 1 year to demonstrate the endurance capability of the unit. The following performance characteristics that must be satisfied for the FSM-4 unit to pass this endurance phase are:

Converter output ≥ 450 watts

Converter voltage ≥ 22.5 volts

B. FSM-4 RELIABILITY

The probability of the FSM-4 unit surviving the simulated launch phase and producing useful electric power output was estimated by combining the performance

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reliabilities of each major system component. The performance requirements for each major component during each flight phase was established in accordance with the overall reliability success criteria. Actual performance characteristics, as determined through qualification testing, was compared with these performance requirements to establish an estimated true reliability for each component. The methods used for evaluating the power conversion system reliability and the thermoelectric pump reliability are described. The estimated true reliability of each major component is summarized.

1. Power Conversion System

The principal failure mode of the power conversion system, which has been established through development and qualification testing of the thermoelectric modules, results from a pellet failure causing an open circuit. The status of qualification testing of the flight type modules (Type V) as of June 1, 1964, is summarized in Table 2.

TABLE 2
TYPE V MODULE TEST* RESULTS

972 Elements submitted to launch S and V without failure
972 Elements submitted to startup cycles without failure
948 Elements submitted to endurance have completed 1000 hr of thermal vacuum test of which
756 Elements completed 2000 to 3000 hr with 1 failure @ shutdown and
472 Elements completed 3000 to 6500 hr without failure

*Endurance test represents three million element hour of operation.

Based on binomial statistics, the demonstrated element failure rate and demonstrated converter reliability was evaluated as shown in Figure 13. The estimated true element failure rate and the estimated true reliability for the FSM-4 converter was evaluated based on demonstrated performance. These estimated values are also summarized in Figure 13. The estimated true converter reliability is slightly less than the demonstrated reliability because of additional handling seen by the modules during fabrication of a complete converter and the poor vacuum which the modules see during system test.

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2. Thermoelectric Pump

Although no performance data existed as of June 1, 1964, on the exact flight pump configuration, there was considerable development and prequalification test data upon which to base a reliability evaluation. A summary of significant pump performance data is illustrated in Figure 14. A large fraction of the pump test data was classified as qualification test data because of the similarity between these pumps and the flight pump design.

	LAUNCH	STARTUP	90 DAY	1 YEAR
DEMON. ELE. F.R.	0.0007	0.0007	(0.0005)* 0.0012	(0.0021)* 0.0048
DEMON. REL. FROM F.R.	0.995	0.995	0.993	0.935
EST. TRUE ELE. F.R.	0.0007	0.0014	0.0019	0.0055
EST. TRUE REL.	0.995	0.992	0.985	0.916

*NO FAILURES

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Figure 13. PCS Reliability Evaluation

	LAUNCH	PRE-ORBITAL OPERATION	STARTUP		ENDURANCE		DEGRADATION gpm/1000hrs
			PUMPS	CYCLES	PUMPS	HOURS	
DEVELOPMENT							
PUMP 1→8, FD 1&2	5	7	10	60	10	40,000	1
PUMP 012, 019, 020, 021	1	4	4	14	4	2600	2
PRE-QUALIFICATION							
FQ 1-4, FS-1 & FSM-1	5	6	6	50	5	12,400	1
	(0.3 gpm LOSS)	(0.65 gpm @ 400 AMPS)					(0.6 FOR FSM-1)
QUALIFICATION							
FQ-5 PUMP 010, 011, 013, 015, 016, 017, 018	7	8	8	50	8	26,300	0.35
	(0.6 gpm LOSS)	(0.45 gpm @ 40 AMPS)		(NO LOSS)			

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Figure 14. TE Pump Data

Based on the significant pump test data, and on binomial statistics, the demonstrated TE pump reliability and estimated true reliability of the pump for each flight phase was estimated. These values are summarized in Figure 15. The minimum pump performance characteristics which were used as the basis for evaluating pump reliability are also summarized in Figure 15. The estimated true reliability is considerably higher than demonstrated reliability. This conclusion is reached since the minimum pump performance characteristics represent a 3-sigma variation from the nominal pump performance characteristics.

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	LAUNCH	PRE-ORBITAL OPERATION	STARTUP	90 DAYS	1 YEAR
EQUIV. PUMPS TESTED WITH NO FAILURES	7	8	21	18	4.4
SUCCESS CRITERIA	<2 gpm LOSS	>0.2 gpm FLOW	<0.5 gpm LOSS	<2 gpm/1000 hr	<1 gpm/1000 hr
DEMONSTRATE RELIABILITY	0.917	0.850	0.813	0.783	0.715
EST TRUE RELIABILITY	0.999	0.996	0.994	0.990	0.984

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Figure 15. TE Pump Reliability Evaluation

lative probability that the FSM-4 unit will survive the launch phase and produce greater than 450 watts electrical output for 90-days and 1-year endurance operation.

3. FSM-4

The reliability of each major system component was evaluated using binomial statistics. The results are summarized in Figure 16. These reliability values are presented cumulatively by phase and the product of the component reliabilities represents the cumulative probability that the FSM-4 unit will survive the launch phase and produce greater than 450 watts electrical output for 90-days and 1-year endurance operation.

	LAUNCH SURVIVAL	PRE-STARTUP ORBITAL OPER.	STARTUP	90 DAY	1 YEAR
REFLECTOR ASSY	0.999	0.999	0.995	0.984	0.981
STRUCTURE	0.998	0.998	0.997	0.996	0.995
NaK SYSTEM	0.998	0.997	0.987	0.980	0.970
PUMP & BATTERY	0.999	0.996	0.994	0.990	0.984
P C S	0.995	0.994	0.992	0.985	0.916
CONTROL SYSTEM	0.997	0.997	0.986	0.975	0.974
EJECT. HEAT SHIELD	0.999	0.997	0.997	0.997	0.997
RADIATION SHIELD	0.999	0.999	0.998	0.996	0.994
DIAGNOSTIC INSTR.	0.999	0.998	0.993	0.983	0.958
CUMULATIVE ESTIMATED TRUE RELIABILITY	0.982	0.975	0.942	0.884	0.790

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Figure 16. NPU Estimated True Reliability
(For Continuous Operation)

C. FACILITY RELIABILITY

The reliability of each test facility subsystem was evaluated using standard failure rate data for industrial and process equipment.

The reliability of the Environmental Test Facility (Building 027) was judged to be unity since the automatic control system is backed up by two independent limiter circuits and manual shutdown capability. Failure of the environmental test equipment or loss of facility power does not affect the overall test reliability since there are no requirements for extended continuous test runs. If

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a test is interrupted due to a facility outage, the test can be restarted from that point without rerunning that portion of the test which was already completed.

The results of thermal vacuum testing is more dependent on facility availability. A facility-caused shutdown should not adversely affect the integrity of the FSM-4 unit, however, a shutdown will interrupt an endurance run and possibly mask long term degradation data on major system components.

The reliability block diagrams for the FSM-4 vacuum system and the electrical power system are illustrated in Figures 17 and 18 respectively.

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Figure 17. FSM-4 Vacuum System Reliability

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Figure 18. Electrical Power System

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The vacuum system reliability is estimated at 0.986 for startup plus one year of continuous operation. The power system reliability, however, is only 0.018 for startup plus one year. This low level of reliability is attributed to the probability of experiencing a major commercial power outage which cannot be over-ridden by the battery bank. A summary of the thermal vacuum facility reliability is presented in Figure 19. It is evident from Figure 19 that the reliability of the other major systems is very high and that the facility reliability is controlled by the availability of commercial power.

90 DAY REL.

$$R_{\text{sys}} = R_1 \times R_2 \times R_3 \times \dots \times R_7$$

$$R_{\text{sys}} \times R_8 = \text{PRE-START}$$

<u>PHASE</u>	<u>R_{sys}</u>
START UP + 3 DAYS	0.964
START UP + 90 DAYS	0.336
START UP + 1 YEAR	0.013
PRE-START UP ...	0.963

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Figure 19. FSM-4 Facility Reliability

D. FSM-4 SYSTEM TEST RELIABILITY

The preceding sections illustrate that the probability of the FSM-4 unit surviving the launch environmental and producing greater than 450 watts electrical output is very high. The reliability of the FSM-4 test equipment is also very high, however, the overall probability of achieving continuous endurance

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operation is controlled by the availability of commercial power at the Santa Susana test site. Past experience indicates that there could be an average of four major power outages over a period of one year which could cause temporary suspension of FSM-4 testing. These shutdowns should not affect FSM-4 system integrity and, therefore, the probability of the FSM-4 unit surviving the launch environment and achieving an integrated one-year endurance run is essentially the reliability of the FSM-4 unit itself or 0.79. The probability of the FSM-4 unit successfully meeting test objectives by flight phase is illustrated in Table 3.

TABLE 3
FSM-4 SYSTEM TEST RELIABILITY

	Cumulative Estimated True Reliability
Launch Survival	0.982
Prestartup Orbital Operation	0.975
Startup	0.942
90-Day Endurance	0.884
1-Year Endurance	0.790

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