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HERMODYNAMIC PERFORMANCE TESTING OF THE ORBITER FLASH EVAPORATOR SYSTEM

James R. Jaax\*

Michael A. Melgares\*\*

James R. Frahm+

ABSTRACT

System level testing of the Space Shuttle Orbiter's Development Flash Evaporator System (FES) was conducted at the Johnson Space Center during May/June 1978, and January/February 1979. Testing was performed in a thermal vacuum chamber capable of simulating ambient ascent, orbital, and entry temperature and pressure profiles. The test article included the evaporator assembly, high load and topping exhaust duct and nozzle assemblies, and feedwater supply assembly. Steady state and transient heat load, water pressure/temperature and ambient pressure/temperature profiles were imposed by specially designed supporting test hardware. Testing in 1978 verified evaporator and duct heater thermal design, determined FES performance boundaries and assessed topping evaporator plume characteristics. Testing in 1979 combined the FES with the other systems in the Orbiter active thermal control subsystem (ATCS). The FES met or exceeded all nominal and contingency performance requirements during operation with the integrated ATCS. During both tests stability problems were encountered during steady state operations which resulted in subsequent design changes to the water spray nozzle and valve plate assemblies.

INTRODUCTION

Successful performance by the FES is dependent upon the combined operation of its 4 major assemblies: evaporator core, feedwater nozzles and controllers assembly; feedwater lines, accumulators and heaters assembly; exhaust ducts and heaters assembly, and exhaust duct nozzles assembly. Extensive component level testing of the evaporator assembly had been completed but with simulators for the other assemblies due to the large chamber volume required. Chamber A of the Space Environment Simulation Laboratory at the Johnson Space Center offered the space environment simulation and physical volume necessary for layout of the duct, nozzle and feedwater assemblies of the FES. Special support equipment capable of simulating transient heat load and feedwater pressure and temperature profiles were needed. Hardware to fully assemble and test the FES was obtained. Special structures were provided for assessing orientation and vehicle surface effects. Instrumentation, displays and controls for engineering data and flight performance evaluation were significant drivers on the development of the test facility's data management system. Test conduct followed the test plans allowing deviations to work around hardware and support equipment malfunctions.

\*NASA, Johnson Space Center, Houston, Texas 77058

\*\*Hamilton Standard, Division of United Technologies Corporation, Houston, Texas

+Rockwell International, Houston, Texas 77058

## FLIGHT SYSTEM DESCRIPTION

The FES is the Orbiter's sole heat sink during ascent and down to 30,480m (100,000 feet) altitude during entry on a nominal mission. During orbital operations the FES supplements the radiator system to provide a constant coolant temperature to the Orbiter. The FES removes heat from the Orbiter coolant loops by evaporating in a heat exchanger at low ambient pressure expendable water generated as a byproduct of the fuel cells in the Orbiter electrical power system. The FES is designed to be automatically activated and deactivated as a function of altitude and radiator system performance. Manual control override capability is provided. Water vapor produced during FES operation is discharged overboard through 3 sonic nozzles. Two nozzles are located at positions on the aft fuselage which minimize both the propulsive effects and the particle and gas contamination of the space environment viewed by the payload bay. The FES components are located in the midbody and aft sections of the Orbiter as shown in Figure 1.

The high load and topping evaporators are identical in design. The evaporator, shown schematically in Figure 2, consists of three basic parts; the evaporator core, the water valve/nozzle mounting plate, and the anti-carryover device. The core is a cylindrical dual passage heat exchanger consisting of three concentric cylinders separated by two ruffled finned passages. Evaporant water is sprayed on the inner surface of the core to cool the dual freon loops flowing in the separated finned passages. The water valve/nozzle mounting plate is a pin fin heat exchanger for passing hot freon through to keep the water spray nozzles warm and thereby prevent ice buildup. The anti-carryover plate is a pin fin heat exchanger for passing hot freon through to allow the evaporation of water particles that did not impinge on, or rebound from, the cylindrical wall. The surfaces of the core and anti-carryover device exposed to the water spray are grooved to increase the surface area available for water evaporation. Freon flow through the core is longitudinal from the steam outlet end to the water spray nozzle end of the evaporator. The freon loop having the inside passage (next to the inner cylinder) in one evaporator core has the outside passage in the other evaporator core. On the water valve/nozzle mounting plate are two identical water valve/nozzle assemblies. One assembly consisting of the pulser valves and spray nozzles is dedicated to the primary feedwater supply, and the other is dedicated to the secondary feedwater supply. The feedwater valves are pulsed open at a variable frequency, dependent upon heat load, to meter feedwater to the spray nozzle. The spray nozzles have swirl slots and a swirl chamber to distribute feedwater over the interior surfaces of the evaporators. There are two nozzle sizes: 23 kb/hr (50 lb/hr) installed in the topping evaporator and 61 kg/hr (135 lb/hr) installed in the high load evaporator. Three electronic controllers are used to perform the temperature control function for both the high load and topping evaporators.

The overboard venting of the steam generated by the FES is accomplished by two insulated and electrically heated ducts as shown schematically in Figure 3. The high load evaporator has a nominal 0.15m (6 in) diameter, 2.29m (90 in) long duct with two 90-degree bends. The topping evaporator has a non-propulsive exhaust duct system composed of a 0.15m (6 in) diameter, 2.08m (82 in) long section with one 90-degree bend and two 0.1m (4 in)

diameter, 4.32 m (170 in) long sections with three 90-degree bends; both of which terminate with sonic nozzles. Water that is not evaporated in the evaporator is called carryover. It results from the spray nozzle dribble volume, steam drag effects on the main water spray, deflection of water particles, and inefficiency of the evaporator process. The exhaust duct heaters are sized to handle up to 3 percent water carryover. The exhaust duct heaters are divided into zones with individual zone configurations and power requirements. The ducts are insulated to minimize environmental heat losses.

The FES feedwater supply system contains the primary and secondary feedwater lines and accumulators. A detailed description of the FES is provided in Reference 1.

### TEST FACILITY

Both tests were conducted in Chamber A of the Space Environment Simulation Laboratory. A schematic representation of the test article layout for the 1978 test is shown in Figure 4. A similar layout, without the equipment for plume distribution assessment, was used in the 1979 test. Test article elements were mounted at floor level elevation inside the chamber as shown in Figure 5. Special test support elements supporting the test article were located on the first and third levels around the chamber. Roughing, cryogenic and diffusion pumping was used to obtain  $1.3 \times 10^{-4}$  N/M<sup>2</sup> ( $10^{-5}$  torr) chamber pressure. Up to 11 diffusion pumps were activated to handle the water vapor load during FES operation. The chamber's entire liquid nitrogen shroud was cooled to liquid nitrogen temperature to obtain the required environment for FES plume measurements, duct heater assessment and FES water vapor collection. One zone of helium was used to maintain chamber pressure. Ten controlled partial chamber repressurizations down to 200 N/M<sup>2</sup> (15 torr) were conducted simulating the ambient pressure environment during a typical Orbiter entry profile. A slower (12 hour) method, sublimation repressurization, using dry nitrogen and heaters to minimize water condensation in the thermal blankets of the test article, was used to bring the chamber to sea level conditions. During repressurization television operation was prohibited to prevent corona effected damage. Facility chilled water, hot water, cooling water and compressed air were supplied to elements of the test support equipment. Special user AC and DC power requirements were supplied by a 400 Hertz motor-generator set and regulated power supplies.

### TEST ARTICLE

For both tests development, and inhouse FES hardware were assembled in a test configuration which represented the total flight system.

The development evaporator assembly contained flight-type high-load and topping cores, feedwater valves and nozzles and electronic controllers. Between tests a modified design of the topping feedwater nozzles was installed

to obtain a better water spray distribution for improving low control temperature performance. During the 1979 test the topping feedwater nozzles were coated with thermal grease and an insert (shim) which recessed the water nozzles to be flush with the valve plate was installed to obtain better thermal conductivity and minimize possible icing nucleation sites within the core. A thermal blanket of multilayer insulation protected the assembly from the chamber environment.

A feedwater supply assembly duplicating the dual 30.48m (100 feet) stainless steel lines of the flight configuration was provided. Accumulators simulating the function of the flight accumulators were included in both tests. Thermal conditioning of the water in the feedwater lines, simulating orbital conditions, was provided by multilayer insulation, electric heaters and a counterflow concentric tube heat exchanger. A combination of computer and set point controlled heater circuits protected the feedwater system during nonflowing periods.

The exhaust duct heater assembly was installed such that steam flow would never be opposed to gravity (vertical upward), only horizontal and vertical down. Both the high load and topping ducts were equipped with heaters subdivided into discrete zones. Each heater circuit was individually powered by a computer controlled power supply. During the 1979 test heater density and temperature control bands were preset at the levels planned for the early Shuttle flights. A special 20 watt heater blanket was wrapped around the high load duct system to replace the function of heaters failed during the 1978 test.

During the 1978 test one topping nozzle was oriented to exhaust into the main chamber volume for plume measurements. The other nozzles in the 1978 tests and all nozzles in the 1979 test were oriented to exhaust behind the chamber cold walls. In addition, in the 1979 test four liquid nitrogen panels were installed between the FES ducts and the center of the chamber to ensure that the water vapor plumes impinged directly upon the cold walls.

#### TEST SUPPORT HARDWARE

Several independently controlled support systems were provided to simulate the various Orbiter fluid, thermal, electrical and structural interfaces with the FES.

The Orbiter Coolant Thermal Simulator delivered Freon-21 at rates up to 1361 kg/hr (3000 lb/hr) per loop at temperature ranges of -1 to 66°C (30 to 150°F) to simulate the full spectrum of Orbiter ATCS operating conditions and heat loads. Manual and automatic (drum recorder) temperature control capable of introducing FES inlet temperature ramps of 1.7°C (3°F) per second was provided. Two coolant loops were provided, with provision to stop flow in either loop.

The Flash Evaporator Feedwater Supply simulator delivered deionized water from two 0.04m<sup>3</sup> (10 gallon) tanks at pressures up to 10.4 x 10<sup>5</sup> N/M<sup>2</sup> gage (150 psig) and rates up to 91 kg/hr (200 lb/hr) to the FES. Manual

controls capable of simulating the ascent and entry pressure transients and electronic weight scales for measuring water consumption rates were provided. Both primary and secondary water systems were provided.

A Feedwater Thermal Conditioning System conditioned the feedwater to provide 7.2°C (45°F) to 66°C (150°F) delivered water to the FES at demand rates up to 91 kg/hr (200 lb/hr). Computer and set point controllers were used to introduce ramps up to 5.6°C (10°F) per minute, multilayer insulation blankets and 21 electrical heaters provided freeze protection for the feedwater lines during no-flow test periods. A 9 kW heater and a liquid nitrogen heat exchanger were available to trim the water temperature.

A FES power and control console provided electrical and control interfaces to the FES. This console provided the normal Orbiter control functions, special test control functions, specific failure mode operations and special monitoring equipment for FES operation and evaluation.

The FES was mounted on a multi-orientation support stand. The aluminum structure permitted configuration of the FES evaporators in three different orientations: vertical up, vertical down, and horizontal. This permitted the study of gravity effects on evaporator performance. The stand was thermally isolated from the evaporator, exhaust ducts, and chamber floor by teflon pads.

Two adjustable Orbiter fuselage surface simulators were provided in the chamber adjacent to one of the topping evaporator exhaust duct nozzles to study the effect of plume characteristics on Orbiter structure and payloads.

During buildup, servicing, and operation of the FES test, additional test support equipment was provided.

- a. In chamber closed circuit television coverage by 6 cameras of the 3 FES exhaust nozzles and Orbiter surface simulators.
- b. Vacuum pump with cryo trap and micro gage for servicing the freon and water loops.
- c. Helium leak check test equipment.
- d. Gas analyzer, first aid, and protective equipment for handling leaks or spills of Freon-21.
- e. Heaters and temperature controllers to maintain FES exhaust duct pressure instrumentation lines above 50°F.
- f. Wang 2200 Mini-Computer system for off-line processing of test data for anomaly investigations and FES water carryover determination.

#### DATA MANAGEMENT

The test facility's Flexible Data System (FLEX) Hewlett Packard 2117 computer provided the real time control and data acquisition/process/display services for both tests. Raw data from temperature, pressure, flow rate, frequency, current and voltage instrumentation was simultaneously displayed, used in calculations and stored.

## Instrumentation

Extensive engineering test instrumentation was installed for the 1978 tests to obtain performance data on the evaporator core, duct heater system and water vapor plume. Much of this instrumentation was removed for the 1979 test as the test program matured from detailed component performance assessment to system interaction with other ATCS systems assessment. The 1979 test instrumentation was used to obtain detailed system performance data and evaluate the timeliness and meaningfulness of flight data. The following is a summary of the thermal performance instrumentation required for the test article and support equipment for both tests.

	1978 Test	1979
Surface Thermocouples	200	48
Immersion Platinum Probe	6	24
Current transducers	71	25
Voltage transducers	21	17
Turbine flowmeters	5	2
Baratron pressure sensors	6	6
Pressure transducers	25	6
Frequency	1	1

Thermal performance test instrumentation was sampled at 2, 3, 5, 10, 15, or 30 seconds intervals depending on the dynamic response required from the measurements. Special high response pressure transducers monitored by high speed stripchart recorders were included to detect feedwater and steam pressure transients in both tests.

Plume performance instrumentation included 2 particle spectrometers to detect ice particle formation in the chamber, 9 quality crystal oscillators to measure surface contamination, 4 ionization gages to determine plume flow field characteristics and 3 baratron pressure transducers to measure low pressures in the  $1.3 \times 10^{-2} \text{ N/M}^2$  ( $1 \times 10^{-4}$  torr) range.

## Real Time Processing

FLEX software for the 1978 test was configured to acquire and process 896 real measurements, calculate 156 pseudo measurements and compute stimuli for 100 control channels for the test article, support equipment and facility systems. Formats for 37 pages were defined and available for display at 12 interactive terminals with CRT's. Data displays could be made into hard copy through "instantaneous" system SCOOPS (upon keyboard command). A similar software capability was provided for the 1979 test.

During both tests team members maintained data logs, recording real time observations and impressions of test article performance. FLEX made a permanent record of real and pseudo measurements on test history magnetic tapes for post-test point data evaluation. During the test, 24-hour processing of selected portions of the test history tapes was provided by the IDSD (Institutional Data Systems Division) on the UNIVAC 1110 and 1108 EXEC 8 computer systems. Post-test time history plots of key parameters for assessing selected component performance were prepared by IDSD from the FLEX test history tape for selected test points. Microfilm and hard copy were provided of each plot.

## TEST CONDUCT

Chamber occupancy for the 1978 test began in August 1977, and ended in June 1978 after 4 weeks of testing. Test article fluid charging began in March 1978 followed by 1 week of ambient checkout and 4 weeks of vacuum checkout testing. The test article and stand was removed in June then re-installed in August in Chamber A for the 1979 test buildup. Test article fluid charging for the 1979 test began in late December 1978 followed by 2 weeks of ambient checkout testing and 2 days of vacuum checkout testing. FES performance testing was completed during the 3 week "open loop" test period. The test article was reconfigured for "closed loop" testing. A 3 day vacuum checkout test preceded the 4 days of "closed loop" testing where FES performance as part of the integrated ATCS was assessed.

The 60 members of the 1978 test team manned 15 stations, providing 24 hour coverage with three 8 hour shifts. The control room had 6 stations including the test director responsible for the conduct of the test, technical supervision and control of the systems within the test article, operation of the test support and facility systems and real time assessment of the test article's performance. A similar layout of stations and responsibilities for FES operations was maintained for the 1979 test. During both tests standard hardline communication network protocol was observed by all test team members and a voice record tape of all communication channels was obtained.

During the 1978 test one control room CRT station displayed FES "flight" data in addition to engineering test information. This concept was expanded for the 1979 test, whereby at one CRT station, flight measurements identical to the flight data format were used by a "flight controller" test team member to monitor ATCS performance, including the FES, during mission simulations.

Steady state and transient heat load profiles based on pretest analytical predictions were used to assess FES capacity, water carryover, controller response, heater design, flight instrumentation adequacy, and plume characteristics (1978 test only). Timelining of the 224 steady state and 42 transient test points in the 1978 test followed the guidelines that test points requiring similar conditions shall be grouped in priority order and that proceeding from one group to another shall take the path of minimum change in existing conditions. All vertical FES assembly orientation testing was grouped into the first test week. Weekend reconfiguration allowed horizontal orientation to start the following week. Chamber pressure, chamber temperature, feedwater temperature and "ice free" duct pressure were the most time consuming parameters to establish. Using "drum plotters" to input transient heat load profiles for the FES provided uniform repeatable stimuli for the transient test points. High risk test points which "stressed" the test article or were predicted to result in ice buildup were conducted at the end of each test week. During each test point selected parameters were monitored continuously to minimize ice buildup in the test article. Test article hardware performance problems required almost daily assessment of the test timeline as diagnostic and problem solving test conditions were integrated into the test conduct.

The 1979 test included 21 open loop test points for performance mapping and constraint definition and 30 closed loop test points for assessment of FES operation with the integrated ATCS. Timelining guidelines were similar to those used in the previous test. All tests were conducted with the FES in the horizontal position.

## TEST RESULTS

The system level tests of the FES achieved all planned test objectives, demonstrated that the FES meets or exceeds most performance requirements, and demonstrated the full compatibility of the FES hardware and controls within the Orbiter ATCS. During the conduct of both tests, hardware and procedure deficiencies were identified which have resulted in design and operation changes that improve FES performance and recommendations for reducing FES weight, power and volume requirements and are described in Reference 2.

Testing in 1978 concentrated on verifying the system design and determining the FES operating boundaries. Steam backpressure (boiler pressure) is a critical parameter in the operation of the FES. Initial testing provided the data for determining and verifying the topping exhaust nozzles throat diameter for obtaining the design on-orbit backpressure in the evaporator core. The remainder of the testing was dedicated to determining the thermodynamic performance of the FES during all planned and contingency FES operating modes, verifying topping evaporator plume characteristics. The topping evaporator performed successfully in both vertical and horizontal orientations. Instabilities in feedwater pressure (water hammer) during FES operation were confirmed and the effectiveness of an accumulator in reducing this effect verified. Maximum performance capability for all operating modes exceeded design requirements. However, significant problems were encountered during orbital simulations at moderate heat loads which subsequently resulted in a design change to the topping evaporator water spray nozzles. Unstable FES performance was observed during extended operation with feedwater temperatures above 38°C (100°F). Although many FES shutdowns occurred and ice verified to be in the core and ducts, each FES restart was successful when feedwater was below 38°C (100°F). Flight instrumentation was found adequate for monitoring FES status but inadequate for early detection (before FES shutdown) of an icing condition in the cores and ducts. Exhaust ducts and nozzle heaters thermal design was determined to be conservative and power density redistribution, fewer heaters and lower control temperatures were recommended. Topping evaporator plume characteristics were compatible with Orbiter design requirements. Periodic solar orientation of the Orbiter should prevent buildup of frost (particles less than 1 micron) observed on the fuselage simulator. Minimal thrust imbalance from the ducts was noted during topping evaporator operation.

For the 1979 test the FES was included with flight-type and functionally simulated portions of all systems within the Orbiter ATCS. Maximum thermodynamic performance test points verified that FES performance with the new topping evaporator water spray nozzles still exceeded design requirements. The FES met or exceeded all performance requirements during operation with the integrated ATCS. Testing verified with few identified shortcomings the



adequacy of proposed flight procedures, instrumentation, displays and controls for nominal and contingency operations. Coolant temperature instabilities encountered during high load evaporator operation at low heat loads resulted in a design change to the water spray nozzle and valve plate. Procedures were successfully developed and demonstrated for clearing ice out of the topping evaporator core and startup of the topping evaporator after inhibiting on orbit. Exhaust ducts and nozzle heater performance using the OV102 Orbiter power density was adequate but inefficient. A redistribution of the topping evaporator heaters would prevent non-iced heater zones from exceeding 177°C (350°F) after FES shutdown should ice collect at a thermostat location.

#### CONCLUSIONS

The FES development test program provided the data necessary for design verification and operational certification of the Orbiter FES. The successes, limitations, and shortcomings identified during the tests have resulted in a safer design with much greater understanding and confidence in the FES during normal and contingency operations. Through the daily coordination and cooperation by user and test facility personnel both tests were successfully planned and conducted with minimal impact on technical objectives and within financial constraints.

#### REFERENCES

1. Jaax, J. R., "Orbiter Active Thermal Control Subsystem Description and Test History," Crew Systems Division CSD-SH-126, Johnson Space Center JSC 11295, July 20, 1978.
2. Jaax, J. R., "Integrated Active Thermal Control Subsystem Test Final Report," Crew Systems Division CSD-SH-143, Johnson Space Center JSC 14182, August 24, 1979.

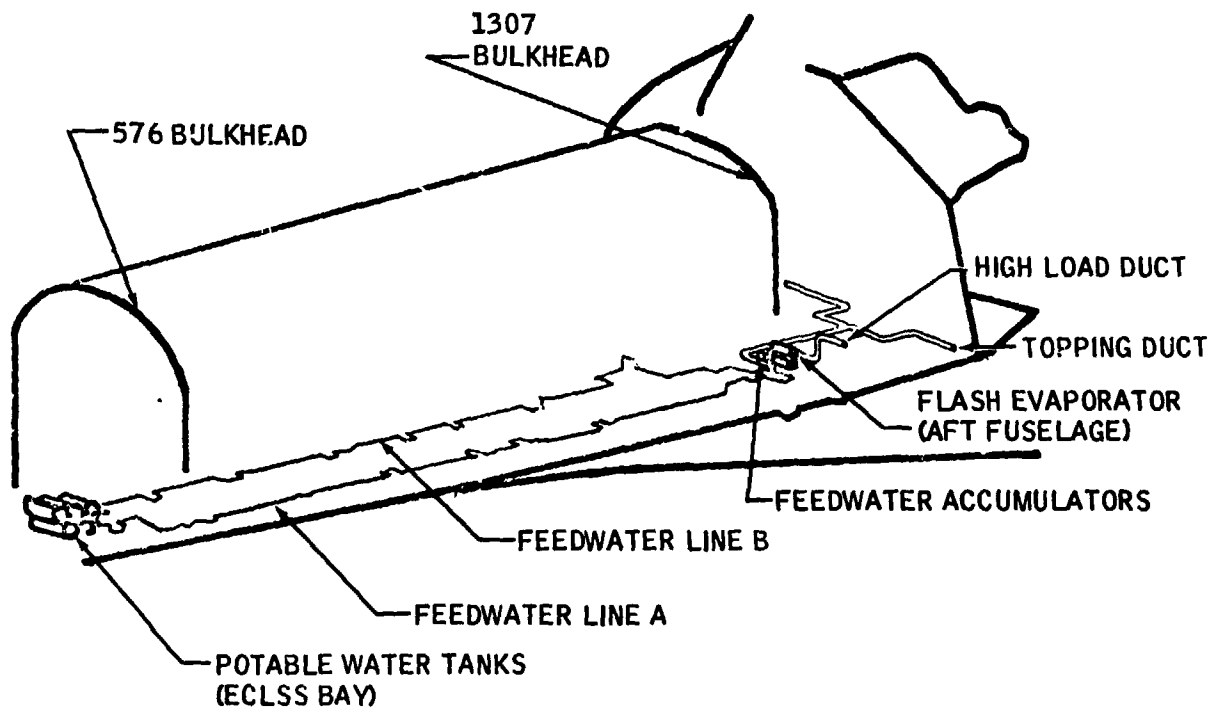


Figure 1 Flash Evaporator System Location in Space Shuttle

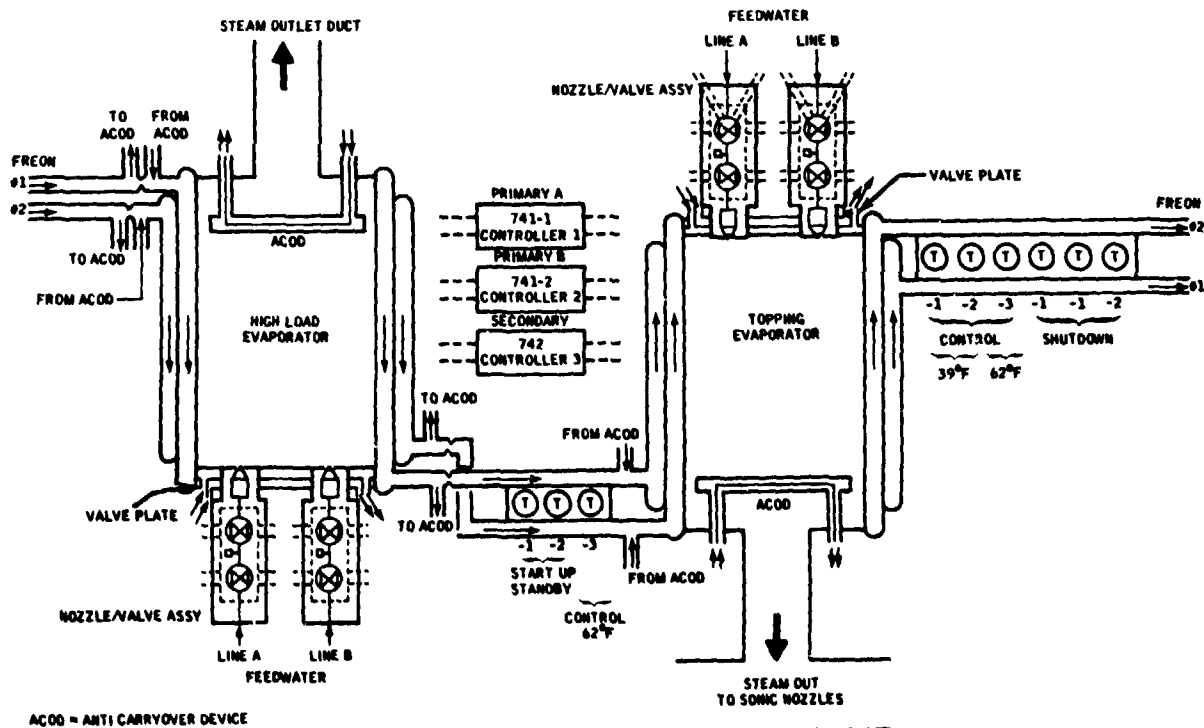


Figure 2 FES Evaporator Assembly Schematic

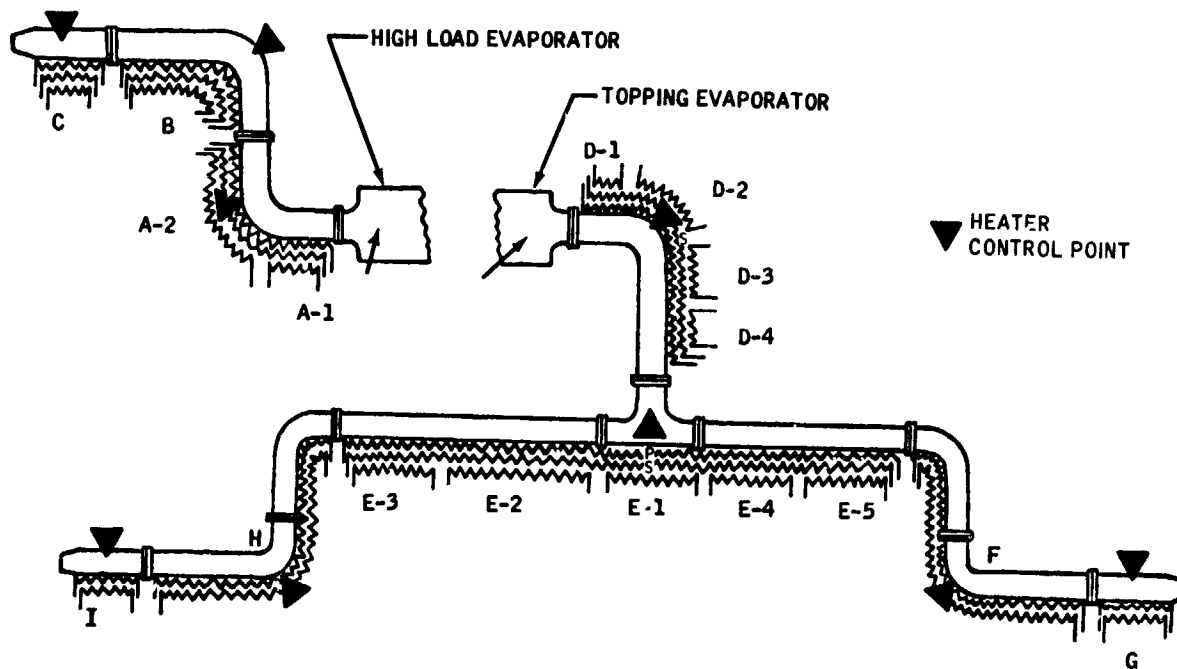


Figure 3 FES Duct and Nozzle Heater Schematic

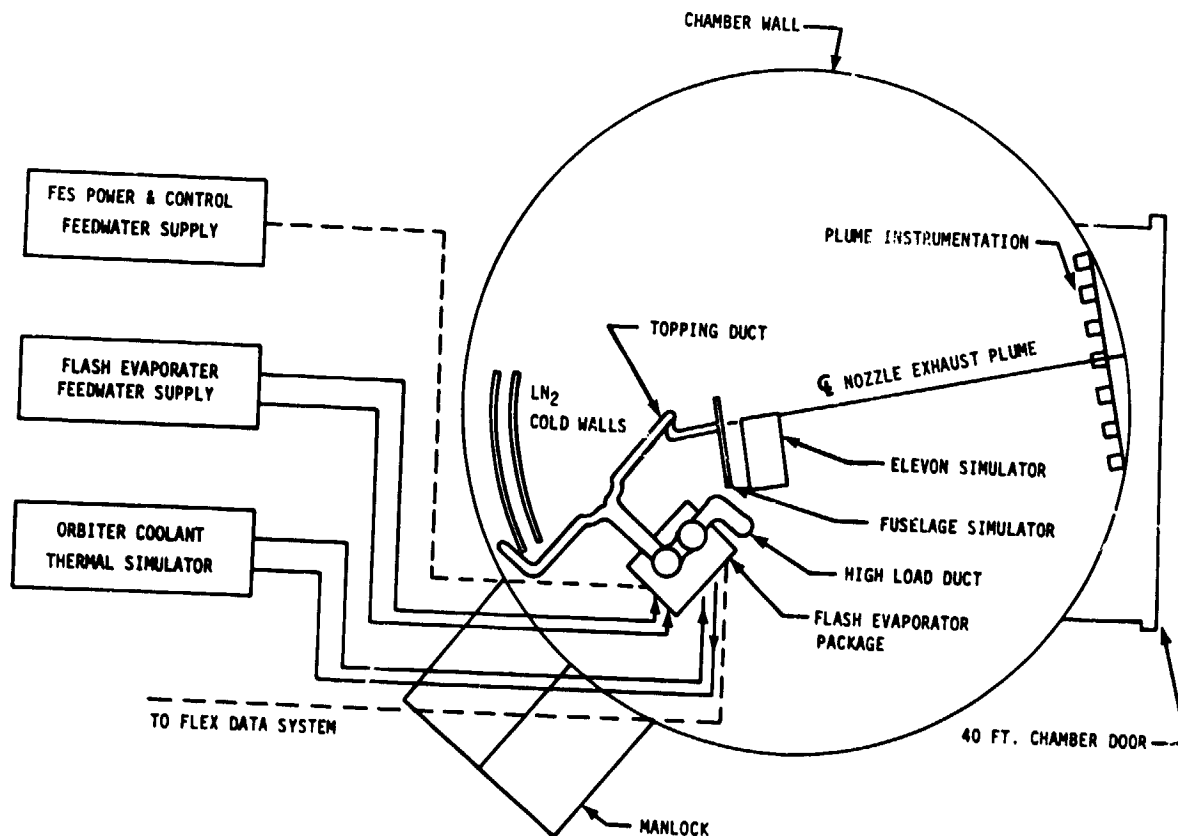


Figure 4 Layout of Flash Evaporator System in Test Chamber A

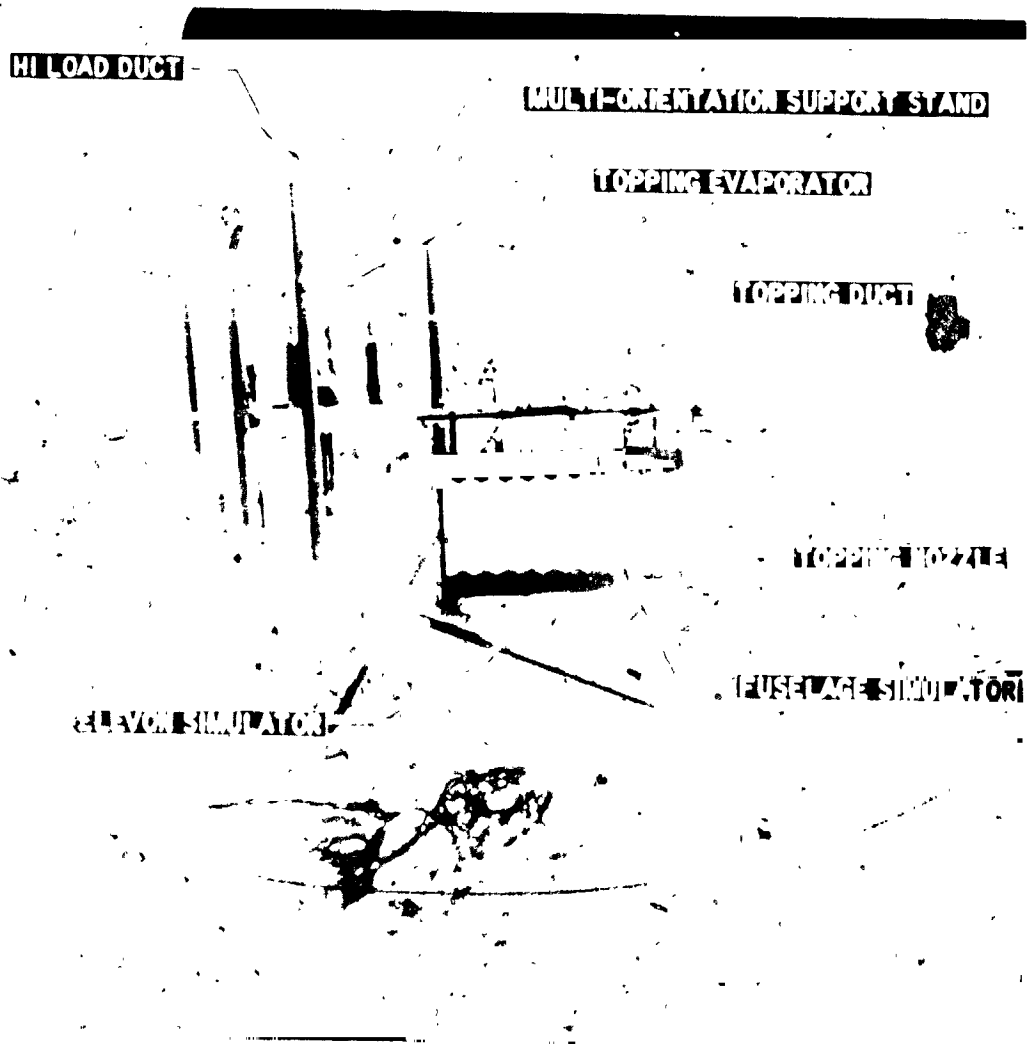


Figure 5 FES Test Setup in Chamber A