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RE-ENTRY AND
ENVIRONMENTAL
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April 15, 1970

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BIOSATELLITE
Project Office

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Dear Mr. Look:

Enclosed are the extra copies of the paper "Biosatellite Environmental Control Coolant Loop System Design" by Robert Ebersole of the General Electric Company.

The paper was presented to the Air Force Office of Scientific Research Symposium in Palo Alto, California, March 21, 1970.

Very truly yours,

Nancy Jamison

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BIOSATELLITE ENVIRONMENTAL CONTROL COOLANT LOOP SYSTEM DESIGN

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General Electric Company
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Philadelphia, Pennsylvania

Presented at the Air Force Scientific Research Symposium on March 21, 1970, in Palo Alto, Calif.

ABSTRACT

This paper presents a functional description of the environmental control coolant loop system design for the 30-day mission NASA Biosatellite program. A two-loop system is described which provides temperature control for the fuel cell power source, cryogenic subsystem, water and urine storage, and the gas management system. The latter provides control of the gaseous environment in the recovery vehicle. It controls temperature, relative humidity, recirculation and filtration of the atmosphere, build up of toxic and/or non-toxic gases and odors, and partial and total pressure of the standard 14.7 psi nitrogen/oxygen atmosphere. Comparison of experimental and flight results with analytical predictions are presented. Extensive thermal vacuum system testing was performed to verify design predictions; good agreement with analysis was achieved.

1. INTRODUCTION

The Biosatellite project has been undertaken by NASA for the purpose of implementing a program of biological experiments in a space environment. Ames Research Center, Moffet Field, California, has responsibility for overall program management and direction. The prime contractor is General Electric Co., Re-entry and Environmental Systems Division, Philadelphia, Penna.

The basic Biosatellite missions are a 3-day mission and a 30-day mission. The experimental objective of the 3-day mission is to investigate the effects of combined weightlessness and radiation on animals, plants, and cells. The experimental objective of the 30-day mission is to study the nervous functions, behavior, metabolism, and cardiovascular function of a primate.

The spacecraft design for each mission consists of an ablative re-entry heat shield, payload capsule, retro-rocket thrust cone assembly, parachute assembly, and adapter section (Figure 1). The spacecraft launch site is the Eastern Test Range, Cape Kennedy, Florida. Recovery of the experimental payloads is a prime objective of all flights.

This paper shall be concerned with the environmental control system (ECS) design for the 30-day mission spacecraft.

2. DUAL LOOP INTEGRATED ENVIRONMENTAL CONTROL SYSTEM

The 30-day mission Biosatellite spacecraft has a dual-loop environmental control system which thermally integrates the life-support gas management assembly (GMA), the hydrogen-oxygen fuel cell power source, the cryogenic subsystem, electronics equipment and experiments, and the water and metabolic waste storage tanks. Figure 2 shows the configuration and pertinent temperature control points of the ECS.

The ECS consists of two circulating coolant loops coupled by an interloop compact heat exchanger. One loop of the ECS provides coolant for temperature and humidity control of the payload capsule atmosphere and coolant for temperature control of the water and metabolic water storage tanks. Temperature and humidity control of the payload capsule atmosphere is accomplished with a liquid to air GMA heat exchanger located in the payload capsule. This heat exchanger is an integral part of the life-support gas management assembly. The capsule air is circulated through one side of the GMA heat exchanger, and the ECS coolant is circulated in counter flow through the opposite side.

The second loop of the ECS provides coolant for temperature control of the fuel cell power source, the cryogenic tankage, electronic equipment and the primate urine experiment package. A radiator for rejection of the spacecraft thermal energy and a regenerative heat exchanger comprise the second loop.

The ECS vehicle thermal design heat loads are 400 Btu/hr minimum and 800 Btu/hr maximum. In addition, the vehicle attitude during orbit is completely random, thus requiring that the ECS be capable of operating over a wide range of orbit thermal environments.

A dual-loop ECS configuration was selected after careful consideration of the system temperature requirements, thermal loads and orbit environments. Tradeoff studies were made considering both single and dual-loop configurations with component by-pass temperature control, regeneration, and radiator by-pass temperature control. The advantages and disadvantages of each were evaluated considering the system flow rate to pressure drop characteristic, precision of temperature control required, effects of system thermal loads, component locations, and orbit environments. The results of these studies showed that a dual-loop configuration with regeneration offered the precision temperature control required for greater variations in vehicle thermal loads and environments than could a single loop. In addition, a dual-loop provided more flexibility to accommodate changes in fuel cell and capsule loads and inlet temperature requirements.

3. ENVIRONMENTAL CONTROL SYSTEMS DESCRIPTION

The primary temperature control functions of the ECS, shown schematically in Figure 2, are to provide coolant at a temperature of 45 ± 3°F to the gas management assembly (GMA) heat exchanger located in the payload capsule, and to provide coolant at a temperature of 55 ± 15°F to the fuel cell power source. In addition to these requirements the ECS also provides coolant for the following temperature control functions:

(1) Maintains the water and metabolic storage tank temperatures above freezing.

(2) Provides heat to condition and pressurize the cryogenic gases to fuel cell operating levels.

(3) Provides electronic equipment and urine experiment thermal control.

3.1 COOLANT

The ECS coolant is Coolanol 25, a silicate ester manufactured by Monsanto Chemical Co. In addition to being a good heat transfer fluid, this fluid has excellent di-electric properties which permit its use in the fuel cell and pump-motor housing, and good fluid lubricity which enhances the operation and life of the pump and motor. Good lubricity is a highly desirable property because the pump has a life requirement of 1000 hours. The fluid has a pour point of approximately -120°F.

A coolant flow rate of 55 ± 10 lb/hr was chosen to satisfy the vehicle temperature requirements and minimize pumping power. The minimum allowable flow rate was set by the fuel cell and payload capsule temperature ranges and thermal loads. Tradeoff studies showed that a minimum flow rate of 45 lb/hr was required to limit the maximum fuel cell temperature to 70°F during maximum vehicle thermal loads and radiator orbit environment. This flow rate results in pumping power requirements of 13 watts under worse case conditions. The corresponding Reynolds numbers are in the range of 10 to 30.

3.2 GMA COOLANT TEMPERATURE CONTROL

The specifications for the primate capsule calls for a laboratory controlled environment in which to perform the biological investigation. The capsule pressure is required to be 14.7 ± 1.5 psi with the gaseous composition of the atmosphere 78.5% N_2, 21% O_2 and 0.5 CO_2. The total volume of the capsule is 6 ft^3. Capsule relative humidity must be kept within the range of 35 to 70 percent and the ambient air within the capsule must be maintained at 75 ± 5°F. Both temperature and relative humidity control are maintained by controlling the temperature of the coolant at the inlet of the GMA heat exchanger. A fan in the capsule circulates the capsule air through the heat exchanger where the capsule heat is transferred to the coolant and the water vapor is condensed in the heat exchanger. To maintain the air at 75 ± 5°F and the relative humidity between 35 and 70 percent the coolant inlet temperature must be held at 45 ± 3°F. The inlet coolant temperature must be less than 48°F in order to pick up the total capsule heat load and reduce the air temperature within the heat exchanger below the dew point to remove the required water. The minimum coolant temperature is maintained above 43°F to prevent low relative humidity in the capsule and allow some margin above the water freezing point of 32°F. The capsule heat consists of primate sensible and latent heat, electrical equipment and environmental effects.

Modulation of the coolant through a liquid to liquid heat exchanger (interloop heat exchanger) maintains the temperature at 45 ± 3°F at the inlet to the GMA heat exchanger. Figure 3 shows a schematic of the temperature control components. A modulating valve, temperature controller, and two temperature sensors are the basic components. The thermal controller contains the control circuits and logic operating the components to provide GMA coolant temperature control. The thermal controller has two modes of operation. In the normal mode, temperature is sensed at the inlet to the GMA heat exchanger and the modulating valve is positioned to by-pass sufficient flow through the interloop heat exchanger to maintain 45 ± 3°F at the sensor. The payload capsule heat is transferred from the air to the coolant in the GMA heat exchanger and rejected to the coolant in the radiator loop via the interloop heat exchanger. The coolant is then circulated through the radiator and the heat rejected from the spacecraft. When the radiator loop is unable to accept the payload capsule heat load and maintain a coolant temperatury of 45 ± 3°F at the GMA inlet sensor, an evaporative water boiler is initiated and the capsule heat is rejected by the boiling water. This condition occurs when the radiator outlet temperature is above 34°F. At this point the coolant ΔT across the interloop heat exchanger is too low to transfer the capsule heat and limit the coolant into the GMA to 48°F. Specifically, the sequence of operation of the thermal controller is as follows:

(1) Sense the coolant temperature at the entrance to the GMA heat exchanger and provide a pulse to the modulating valve when the temperature is out of dead band (45.0 ± 0.5°F).

(2) Initiate water boiler operation when the modulating valve is in the full interloop flow position, the radiator outlet temperature is above 34°F, and the water level in the water accumulator is above the low limit (the water accumulator supplies the boiler with water).

(3) Stop boiler operation when the coolant temperature at the radiator outlet is below 34°F or the water level is below the accumulator low-low limit.

(4) Inhibit the ECS from going into the boiler mode of temperature control during prelaunch operation.

In addition to the temperature control functions described above, the thermal controller also contains the logic for switching from the operating pump to the stand-by pump upon receipt of a signal from a pressure differential switch. The modulating valve consists of a three-way coolant valve, a d-c stepper motor, and gearing. Figure 4 shows a cross-sectional view of the valve. The stepper motor actuates a piston which controls the flow in the two inlet ports. A position switch is incorporated into the valve to indicate that the valve is passing full flow through the interloop heat exchanger. Since a permanent magnet holds the valve position when not being pulsed, the valve does not require power when it is inoperative. The modulating valve and temperature controller were acquired under sub-contract to United Control Corp.

Figure 5 shows a sectional view of the temperature sensors. Both temperature sensors are identical except for their calibration temperature range. Each sensor consists of a calibrated thermistor hermetically sealed in a stainless steel housing. The thermistor is electrically connected to the thermal controller.

3.3 FUEL CELL TEMPERATURE CONTROL

The additional primary temperature control function of the ECS is to provide coolant at 55 ± 15°F for fuel cell heat rejection and temperature control. Fuel cell development tests have shown that a coolant between 40 and 70°F is the optimum range for maximum fuel cell life. Temperature control of the coolant between 40 and 70°F is provided by a mechanical temperature control valve and a regenerative heat exchanger (Figure 2). The valve modulates the flow through the regenerative heat exchanger to maintain the coolant temperature out of the valve above 40°F. The valve is so designed that, when the valve outlet temperature starts to drop below 52°F, flow is by-passed through the regenerative heat exchanger where heat is picked up from the warm fuel cell outlet coolant. The fuel cell has an average thermal dissipation of 320 Btu/hr. As the outlet temperature continues to drop, the valve allows more flow through the regenerative heat exchanger, always maintaining the fuel cell inlet temperature above 40°F. This method of control conserves the system thermal energy during minimum orbit thermal conditions, by transferring the fuel cell thermal energy back into the cold radiator outlet coolant, and also attenuates the radiator outlet temperature transients.

The temperature control valve is actuated by a liquid filled element immersed in the coolant which expands and contracts as a result of variation in coolant temperature. This type of valve was selected because it could meet the temperature control and response requirements without requiring power for operation. In addition, it is a simple and reliable design.

The regenerative heat exchanger is a counter flow, three-pass design with an effectiveness of 0.80. Figure 6 shows the dimensions of the heat exchanger.

3.4 SECONDARY ECS FUNCTIONS

The ECS, in addition to the functions discussed above, also provides coolant for temperature control of the following vehicle equipment:

(1) Evaporative boiler water accumulator,

(2) Primate drinking water,

(3) Primate metabolic waste water,

(4) Electronic equipment,

(5) Cryogenic hydrogen and oxygen tanks.

The water and metabolic waste tanks must be maintained above 32°F in order to prevent freezing. This is accomplished by circulating warm coolant through cold plates to which the tanks are mounted. The cold plates are located downstream of the GMA heat exchanger where the temperature range of the coolant is 50 - 75 °F. Two additional cold plates are located at the inlet to the fuel cell to provide a heat rejection surface for the fuel cell electronic equipment and the primate urine experiment packages.

Two electrical heaters are located on the coolant lines of the inlet and outlet of the fuel cell. One heater is a 10 watt orbit contingency heater. The purpose of this heater is to provide additional heat to the coolant to prevent the fuel cell inlet temperature from falling below 40°F during the initial phase of the mission when the fuel cell efficiency is high and the thermal dissipation is low. This heater operates off the fuel cell power bus. The second heater operates off a fuel cell back-up battery and has a capability of 55 watts. The purpose of this heater is to provide the ECS with sufficient heat to maintain the coolant temperature and enable the pumps to continue operating long enough to initiate an early call down if the fuel cell should fail during the mission. The fuel cell provides the major heat input to the radiator coolant loop; loss of this thermal energy would result in a coolant pressure drop above the pump capability due to high coolant viscosities at low temperature.

4. ORBIT RADIATOR DESIGN

Orbit thermal environment analysis for the low inclinations angles to be flown by the Biosatellite showed large variations in heat flux around the spacecraft. In addition, the maximum heat flux can occur over any section of the vehicle with a random spacecraft attitude. A study of radiator configurations showed that the optimum geometry for averaging large heat flux variations around the spacecraft was a cylinder. This resulted in the design of a cylindrical radiator attached to the outer surface of the adapter section of the vehicle. The initial design goals for the radiator heat rejection and outlet coolant temperature requirements were:

(1) Maximum and minimum vehicle thermal loads of 800 and 400 Btu/hr, respectively,

(2) A maximum allowable radiator outlet temperature of 34°F, in order to provide 45 ± 3°F coolant to the primate capsule GMA heat exchanger,

(3) A minimum allowable radiator outlet temperature of -30°F in order to maintain the coolant temperature at the inlet to the fuel cell above 40°F. The -30°F is based upon a regenerative heat exchanger effectiveness of 0.80.

Preliminary analysis to size the radiator showed that the area required to limit the maximum outlet temperature to 34°F resulted in a minimum temperature below -80°F. These low temperatures result in fuel cell inlet temperatures below the 40°F design requirement and also below the freezing point of the fuel cell product water. In order to alleviate this condition and minimize the cold environment effects, the radiator was designed to operate at two different levels of radiating effectiveness. A mechanical valve located at the outlet of the radiator controls the flow between one or four-tube operation. The valve is designed to permit flow in all four radiator tubes when the coolant temperature is above 10°F, and to allow flow in only one tube when the coolant is below -5°F. During maximum thermal conditions, the radiator operates with four coolant tubes and has an effectiveness of 0.96. During minimum thermal conditions, the valve switches to one-tube flow, resulting in an effectiveness of 0.60. In this way the total radiator area is utilized in the hot orbits and only a partial area in the cold orbits (variable area radiator), thus limiting the minimum outlet coolant temperature to -30°F.

The radiator thermal performance was calculated using the General Electric Temperature Control Systems Optimization Computer Program. The results of the radiator thermal analyzes showed that the maximum allowable radiator area consistent with maintaining the fuel cell inlet coolant above 40°F was 24 square feet. The limiting parameter on increasing the area above 24 square feet is the regenerative heat exchanger effectiveness. A higher effectiveness is needed to handle lower radiator outlet temperature. The radiator analysis also showed that, for short periods of time during maximum orbit environments and vehicle heat loads, the radiator outlet temperature increases above the required upper limit of 34°F. This meant that another method of heat rejection was required for short transient periods in order to limit the coolant temperature to 48°F into the primate capsule heat exchanger. The method that was used is an evaporative water boiler. This component will be discussed in a later section.

The optimum radiator configuration determined from the analysis, to meet the fuel cell temperature requirements and minimize water boiler usage during peak thermal conditions, is shown in Figure 7. The radiator consists of four 3/8 inch OD aluminum tubes, brazed to a 0.032 inch aluminum cylinder. The total width of the radiator is 19.5 inches and the diameter of the cylinder is 56.6 inches. The radiator is attached to the outer surface of the adapter section of the vehicle with 24 nylon fasteners. Fourteen layers of aluminized mylar insulation is used between the radiator and spacecraft. The radiator surface is coated with a low α/ϵ inorganic thermal coating to provide a cold sink for heat rejection. The coating was developed by Illinois Institute of Technology Research Institute and designated S-13G. It has an initial α_S of 0.20.

The radiator thermal performance was calculated from a laminar flow heat transfer coefficient based upon a formula developed by H. Housen.

$$h_{(\text{fluid-root})} = \frac{k_f}{d}\left\{4.36 + \frac{0.668(d/l/RePr)}{1+0.04\,[(d/l)RePr]^{2/3}}\right\}\left\{\frac{\mu_B}{\mu}\right\}^{(0.14)}$$

where

Pr = Prandtl number, $\left(\frac{\mu\, C_p}{k}\right)$ fluid

Re = Reynolds number, $\left(\frac{\rho v d}{\mu}\right)_f$

ρ = density of fluid, lb/ft^3

d = inside diameter of radiator tube, ft

μ = viscosity of fluid, lb/ft hr

C_p = specific heat of fluid Btu/lb °F

k = thermal conductivity of fluid Btu/hr ft °F

l = tube length

Comparison of analytical predictions with experimental results showed excellent agreement. The test results and correlations will be discussed in a later section.

5. EVAPORATIVE WATER BOILER

During peak vehicle thermal loads and orbit environments, the radiator cannot maintain the coolant into the GMA heat exchanger below 48°F. During these peak thermal conditions, temperature control for the GMA is provided by an evaporative water boiler which was designed and developed by GE-RESD. The water boiler is located in the coolant line at the inlet to the GMA heat exchanger. The boiler dissipates the primate capsule heat load by boiling fuel cell product water at a low pressure. The conditions which dictate boiler turn-on are as follows:

(1) All the coolant is being by-passed through the interloop heat exchanger. This results in maximum heat transfer to the radiator loop.

(2) The radiator outlet temperature is above 34°F.

(3) The water level in the water accumulator is above the low limit.

When conditions 1 and 2 occur, the radiator can no longer reject the total spacecraft thermal load and maintain the primate capsule within the upper design temperature limit of 80°F. At this point a coolant valve directs flow around the interloop heat exchanger and a signal from the thermal controller enables the boiler to operate and provide the desired temperature control for the primate capsule. Figure 8 shows a cutaway view of the evaporative boiler. The water (after initial start-up) is retained in a reservoir at the bottom of the boiler. Evaporation takes place in a cylindrical vapor chamber directly above the water reservoir. The warm coolant which has picked up the primate capsule thermal energy in the GMA heat exchanger flows into a coolant chamber which surrounds the vapor chamber. The coolant is introduced at the top of the boiler and exits at the bottom flowing over 22 baffles or fins on the outside of the vapor chamber. As evaporation at the wick surface proceeds, due to heat being transferred from the coolant through the baffles and into the wicks, regulated replacement water is induced by capillary action along the wicks.

The water level is maintained in the reservoir by a capacitance sensor in the reservoir and a solenoid water inlet valve. The change in water level is sensed as a change in electrical capacitance, being part of a control circuit which operates the water inlet valve. Wicks at the top and bottom of the water reservoir serve as the capacitor plates. The boiling temperature of the water is controlled by the pressure inside the vapor chamber. A temperature sensor located on the wicks welded to the vapor chamber wall is calibrated to provide a signal to a control circuit which operates a stepping motor to open and close a vapor outlet valve. The valve is designed to be open when a resistance equivalent to a temperature of 40°F is sensed, and to be closed when the temperature is 34°F.

In addition to the temperature sensor on the vapor chamber wall, there is also a temperature sensor in the coolant inlet line. The purpose of this sensor is to bias the internal sensor at the low heat loads so that sub-cooling and freezing of the boiler does not occur. Coolant flows through the boiler continuously to prevent freezing of the boiler during the non-operational period.

6. MOTOR PUMP

The driving force for circulating the ECS coolant is provided by a dual-element vane pump driven by a two phase a-c motor. The motor-pump unit contains an inverter that converts 26 volt d-c power to 115V, 400 cycle, two phase power. The pumps are redundant and the back-up pump is started when the pressure head across the prime pump decreases below 5 psi. A high pressure relief valve is incorporated into each pump element. Figures 9 and 10 show the coolant flow rate and pumping power versus differential pressure for a coolant temperature of 60°F and a supply voltage of 26 volts. The pumps were acquired under subcontract to Hydro-Aire Division, Crane Co.

7. LIFE SUPPORT GAS MANAGEMENT ASSEMBLY

The gas management assembly (GMA) is located in the primate capsule and controls the gaseous atmosphere in the capsule to provide a laboratory controlled environment. The GMA controls the temperature and relative humidity of the air, the circulation and filtration of the atmosphere, the buildup of trace gases and odors, and the total pressure of the oxygen. It also provides the instrumentation for the measurement of the total pressure, oxygen partial pressure, partial CO_2 pressure, and the temperature and relative humidity.

The GMA receives its coolant supply from the fluid loop ECS located in the adapter. The oxygen is supplied from the cryogenic storage tanks and the nitrogen from a storage bottle in the adapter. The GMA was acquired under subcontract to Hamilton Standard Division of United Aircraft Corporation.

Figure 11 shows a schematic diagram of the GMA. An electrically driven fan is used to circulate the air in the capsule. The air enters the GMA through a particulate filter and flows over the fan into a mechanical temperature control valve. Temperature control of the air is maintained by by-passing air around the heat exchanger as a function of capsule outlet air temperature. The by-passed air flows directly out of the valve into the capsule. The remaining air passes through the heat exchanger where it is cooled and the water vapor removed. The lithium hydroxide CO_2 removal canisters are in a parallel circuit with the fan. The amount of flow through the canisters is controlled with orifices in the lines.

7.1 AIR TEMPERATURE CONTROL

The capsule latent and sensible heat load from the primate, electrical equipment, and contaminate removal equipment is transferred to the ECS coolant in the GMA air to liquid heat exchanger. The mechanical temperature control valve at the heat exchanger inlet is calibrated to flow sufficient air through the GMA heat exchanger to maintain the capsule air temperature between 70 and 80°F. The valve operates through mechanical linkage controlled by a temperature sensing pyrodyne element. The valve is designed to pass the total flow through the heat exchanger during maximum heat load conditions and approximately 50 percent flow during minimum conditions. The maximum air flow rate is 11 cfm.

7.2 HUMIDITY CONTROL AND CONDENSATE DISPOSAL

Relative humidity is controlled by condensing moisture out of the air stream and transferring the water to an evacuated tank in the adapter section. The air by-pass temperature control allows the relative humidity to be maintained between 35 and 70 percent.

Figure 12 shows a schematic of the condensate disposal system. The water condenses on the cold heat transfer surfaces of the heat exchanger and is pushed along the surfaces to the outlet duct. As the water droplets grow in size, the pressure head across the heat exchanger forces them out of the heat exchanger with the existing air. Separation of the condensate from the air is accomplished by means of an elbow in the air duct. The water particles, being heavier than the air, continue in a straight line until they strike the walls of the duct. Collection of the droplets takes place in a section of the duct lined with glass wool wicking. The water is transferred from the wicking to an evacuated tank in the adapter through a water transfer capillary plug. The plug is designed to operate for a downstream pressure 0.3 psia minimum and 9.0 psia maximum.

7.3 CARBON DIOXIDE/TRACE GASES AND ODOR CONTROL

CO_2 partial pressure levels are maintained above 7.6 mm Hg by removing CO_2 from the capsule atmosphere with lithium hydroxide absorption canisters. The hydroxide is contained in two separate canisters each containing approximately 8.5 pounds of chemicals. The capsule air flow is directed into one of the canisters for the first half of the mission, while the other canister is isolated by a diverter valve. At the half-way point of the mission, or when flight data indicates high CO_2 levels, the diverter valve is actuated from a ground signal and the air flow is switched to the second canister. Carbon dioxide partial pressure is monitored constantly so that the maximum allowable level is never exceeded.

Air flow through the canisters is controlled by orifices in the by-pass line and filters in the canisters. The nominal air flow through the canisters is 2.5 lb/hr. Odors and trace gases are removed by a chemical canister and activated charcoal in the lithium hydroxide canisters.

7.4 CAPSULE PRESSURE

The primate capsule total pressure is maintained by a pressure regulator which controls the in-flow of nitrogen during the orbital phase of the mission. During the recovery phase of the mission, pressure is maintained with an oxygen bottle located in the capsule. The nitrogen is stored in a bottle in the adapter section of the spacecraft. The capsule is controlled to a nominal pressure of 14.7 psi. The capsule oxygen is supplied during the orbital phase from the fuel cell oxygen cryogenic storage vessel located in the adapter. Two oxygen partial pressure sensors are used to control an oxygen supply solenoid valve. An oxygen controller is designed to select the higher of two signals and to operate the valve accordingly. The capsule partial oxygen pressure is maintained between 135 and 165 mm Hg.

8. CORRELATION OF FLIGHT AND EXPERIMENTAL RESULTS WITH ANALYTICAL PREDICTIONS

Extensive system thermal vacuum development testing of the environmental control fluid loop was performed to verify analytical design predictions. The tests consisted of subjecting an entire spacecraft to simulated orbital thermal environments in a thermal vacuum chamber. The spacecraft was operated over the entire range of thermal design loads for predicted orbit environments. The orbit thermal environment was simulated using a multiple zone thermal canister that completely enclosed the spacecraft. The canister was divided into separate zones using heaters to simulate the orbital sink temperatures. Figure 13 shows a diagram of the test configuration.

The internal vehicle thermal loads were simulated with d-c heaters controlled to the design levels. Thermocouples were installed both within and on the outside of the fluid loop coolant lines at critical locations. Thermocouples were also installed on all fluid loop components and hardware, including the radiator surface, to record the thermal performance of the complete system.

8.1 THERMAL VACUUM TEST RESULTS

The radiator performance and capability correlated very closely to analytical predictions. Test results verified the analytical and thermal modeling techniques used in sizing the radiator. The radiator coolant outlet temperatures were generally within 3°F of those values predicted using the GE Temperature Control Systems Optimization Computer Program. Figure 14 shows a plot of actual temperature distribution across the radiator during test versus that predicted by analysis. Close agreement was achieved on the predicted temperature level and gradients for tubes 2, 3, and 4. In tube 1, the test results were lower than the predicted value due to a low coolant flow rate resulting from a flow imbalance. The flow imbalance was caused by improper calibration of the radiator two-position valve that switches between 1 and 4-tube flow. This problem was solved by a recalibration of the valve.

The laminar flow film coefficients used in the radiator analysis were also verified during test. The temperature drop across the boundary layer was measured and found, on an average, to be within 4°F of the predicted value. The experimental temperature difference was lower than the predicted, indicating a slightly higher film coefficient than was used in the analysis. Figure 15 shows a plot of predicted coolant film ΔT versus test results. Temperature control of the coolant at the inlet to the fuel cell and GMA heat exchanger was verified for the complete range of design conditions. The thermal controller and modulating valve operated smoothly in response to all temperature changes and thermal loads, and maintained the design requirement of 45 ± 3°F coolant temperature at the inlet to the GMA heat exchanger.

The temperature control valve located at the regenerative heat exchanger outlet performed satisfactorily in by-passing the flow through the regenerator at the required design temperature of 52°F. The thermodynamic performance of the boiler met all the thermal design goals and system requirements. The required GMA inlet coolant temperature of 45 ± 3°F was maintained for all GMA heat loads. Figure 16 shows the boiler performance during vacuum testing. The radiator outlet temperature was increased to 40°F, at which time the GMA inlet temperature reached 48°F and the boiler was initiated. The boiler maintained the GMA inlet coolant below 48°F for GMA heat loads between 309 and 409 Btu/hr. When the boiler was turned on, the radiator outlet temperature decreased until the interloop heat exchanger could transfer the full GMA heat load and maintain the inlet coolant at 48°F. At this point the boiler was turned off. Cycling of the boiler was repeated for both transient and steady state radiator environments to verify performance under extreme simulated orbit environments and heat loads.

8.2 FLIGHT DATA RESULTS

The Biosatellite 30-day spacecraft, designated flight "D", was launched into an Earth orbit on June 28, 1969, carrying a 14-pound primate as its scientific payload. The planned 30-day mission was terminated after nine days when flight data results indicated the primate's life functions were declining. The re-entry vehicle with the primate capsule successfully re-entered and was recovered near the Hawaiian Islands. The adapter section with the fuel cell, cryogenics and thermal control loop remained in orbit and continued functioning for a total of 38-days at which time power was lost.

The fluid loop thermal flight instrumentation consisted of temperature sensors on the coolant lines at the inlet and outlet of the GMA heat exchanger, fuel cell, and orbital radiator. In addition, pressure differential sensors across the pumps were used in order to determine coolant flow rates. The loop instrumentation along with the primate capsule ambient temperature measurements were used to perform heat balances at critical points and verify the fluid loop thermal performance.

8.2.1 Primate Capsule Thermal Performance

The primary requirement of the environmental control fluid loop is to provide a medium for rejection of the primate capsule waste heat and control of the capsule relative humidity. Both of these objectives were successfully met during flight. The fluid loop is required to maintain the coolant to the GMA heat exchanger at 45 ± 3°F. Figure 17a shows the GMA inlet temperature varied between 43.5 and 44.5°F between launch and R/V separation. Figure 17a also shows that the temperature rise of the coolant through the heat exchanger was approximately 9°F during the beginning of the mission and declined to approximately 7.5°F at separation. This is a change in ΔT of 1.5°F. During ground thermal vacuum testing there was a temperature rise of 11°F during the maximum environment case and 8.5°F during the minimum environment, or a change in ΔT of 2.5°F. During thermal vacuum testing, internal thermal loads were held constant and there was no noticeable change in the primate load, thus indicating a fairly constant internal heat load to the GMA heat exchanger. The change in GMA ΔT during this time was caused by the change in external environment and was as predicted. Design limits allowed a heat addition of 44 Btu/hr during maximum orbital environments and a heat loss of 30 Btu/hr during minimum environment, or a change in GMA ΔT of 3°F.

The maximum and minimum orbit design environments were based upon a 56 degree β angle (angle between the sun's rays and the orbit plane) and a 0 degree β angle, respectively. Figure 18 shows that during flight the β angle at launch was 43 degrees and at de-orbit 7 degrees. Based upon the ratio of the β angle change during flight to that used for design, the GMA ΔT should have decreased 1.5 to 2°F during the flight. Since a 1.5°F decrease in GMA ΔT during flight was experienced, this verifies the validity of the design environments as well as proper performance of the re-entry vehicle thermal coatings and insulation system.

The only difference between test and flight data that was evident in the GMA coolant temperatures was that of total heat load. The ground test data showed a ΔT of 11°F of which 1.5°F was external environment heat load. The remaining ΔT of 9.5°F or 227 Btu/hr is attributable to metabolic and electrical equipment heat generated in the capsule. Subtracting the external heat load during flight, a GMA ΔT of 8°F or 191 Btu/hr was the result of internal heat generation. Thus, during flight, the GMA heat load was always in the lower end of the design range of 160 to 350 Btu/hr.

In addition to the fluid loop flight temperature sensors, there were also five temperature sensors in the primate capsule. All five sensors were used to measure the capsule air temperature. Two of the sensors were located in the primate head and chest area (incentive points); one sensor was located in the primate foot area; and two sensors were used to monitor GMA inlet and outlet air temperature. The orbital temperature data for the five capsule temperature sensors showed all temperatures to be within specification throughout the mission. Figure 19 shows a summary of the primate capsule temperature and environmental conditions during both orbit and recovery.

8.2.2 Fuel Cell Thermal Performance

The system design requirement is for the coolant loop to maintain fuel cell inlet temperature between the limits of 40 and 75°F. Figure 17a shows that the fuel cell coolant inlet temperature remaining fairly constant at 53°F for the first five days of the flight. This indicates that the total system heat load was high enough to keep the temperature control valve within the controlling range. From the fifth day on, the temperature of the fuel cell inlet gradually declined to a minimum value of 46°F during the seventh day and then increased again to a maximum of 55°F during de-orbit. The low temperature of 46°F was caused by a reduction in system heat load due to the turning off of the primate urine experiment package and associated electronics.

A fuel cell average electrical load of 104 watts was estimated based upon a calculated average fuel cell waste heat rejection of 245 Btu/hr. None of the fuel cell inlet coolant contingency heaters were required during the flight even though the urine experiment was turned off. Thus, an adequate design margin was available in the system for minimum heat load conditions.

8.2.3 Radiator Thermal Performance

The radiator inlet and outlet temperatures during flight from launch until R/V separation are shown in Figure 17b. The figure shows the orbital cyclic fluctuation on a 24-hour period, since the ground station received that data once each orbit. The figure also shows that the minimum outlet temperature during each orbit was 5°F. The maximum outlet temperature was 18 - 20°F at the beginning of the mission and gradually decayed with the decreasing external environment to 11°F of de-orbit. The constant minimum outlet temperature of 5°F was a result of the two position valve coming into its control range at this point.

During thermal vacuum ground testing, the maximum radiator outlet temperature was 46°F and 12°F during the maximum and minimum orbit environments. If a ratio of the β angles during flight to those during test is made, a predicted maximum radiator outlet temperature during flight would be 36°F. This prediction should be valid, since the radiator heat loads during the test and flight were approximately equal. The discrepancy between flight data and prediction is not that great however (only 16°F) and could readily be accounted for by the unknown orientation of the vehicle and by conservative values used for the radiator thermal coating properties during design. Furthermore, at de-orbit, when the vehicle orientation was known, the radiator outlet reached a maximum value of 26°F. This is in exact agreement with the results obtained during ground testing for a test condition with equal heat loads and similar radiator environments. Thus, the radiator's performance indicated that it also had adequate design margin in the low heat load and environment condition. The system design thermal loads were 400 to 800 Btu/hr compared with the flight average of 530 Btu/hr. The radiator performance also demonstrated that the predicted environments used for design and test were valid.

8.2.4 Evaporative Water Boiler Flight Performance

During the flight, boiler operation was never initiated. The vehicle system heat load was never high enough to require the reserve cooling capacity of the boiler. Flight data results showed that early in the mission the total system heat load was as high as 700 Btu/hr. However, this was for a short duration and the system thermal capacitance prevented boiler turn-on conditions from being reached. The total system heat load gradually fell to an average of 530 Btu/hr for the remainder of the mission.

9. SUMMARY

The Biosatellite 30-day spacecraft met or exceeded all environmental design requirements. Shirt-sleeve conditions were maintained in the primate capsule throughout the entire mission. Temperature variations within the primate static envelope was limited to 68 to 81°F and relative humidity was maintained between 42 and 56 percent.

The two-gas standard atmosphere system supplied a laboratory environment for the primate. During the on-orbit portion of the mission, the capsule's total pressure ranged between 13.7 and 14.7 psia with partial oxygen pressures of 143 to 156 mm Hg., versus system requirement ranges of 13.2 to 16.2 psia and 135 to 165 mm Hg., respectively.

Toxic gas levels were maintained significantly below specification requirements. In particular, CO_2 concentrations ranged from 0.3 to 4.2 mm Hg, versus an allowable range of 0.2 to 7.6 mm Hg.

The flight demonstrated the capability of industry working in conjunction with government and the Bioscience community to successfully integrate a complex spacecraft experiment.

This work was carried out by the General Electric Co. with the support of the NASA, Ames Research Center under Contract NAS2-1900.

BIOGRAPHY

Robert Ebersole

Education: BSME Bucknell University 1960
Graduate studies: University of Pennsylvania, University of Maryland and Penn State University

Mr. Ebersole is currently Supervising Engineer, Environmental Control System, Design, with the General Electric Company, Re-entry and Environmental Systems Division. In this position Mr. Ebersole is responsible for the environmental and thermal control of all RESD product lines. This includes orbiting satellites, planetary satellites, and re-entry spacecraft and missiles. Prior to this, Mr. Ebersole was a thermal control Design Engineer in the GE-RESD Thermodynamics Operation.

Mr. Ebersole has worked on all types of passive, semi-passive, and active thermal control systems for both orbiting and re-entry spacecraft. He performed basic system selection studies and thermal design support on a hardware basis. The major programs Mr. Ebersole contributed to include Biosatellite, Discoverer, Mark 6 and Mark 12 re-entry systems and numerous classified military programs.

Mr. Ebersole is a member of Tau Beta Pi and Pi Mu Epsilon honorary societies.

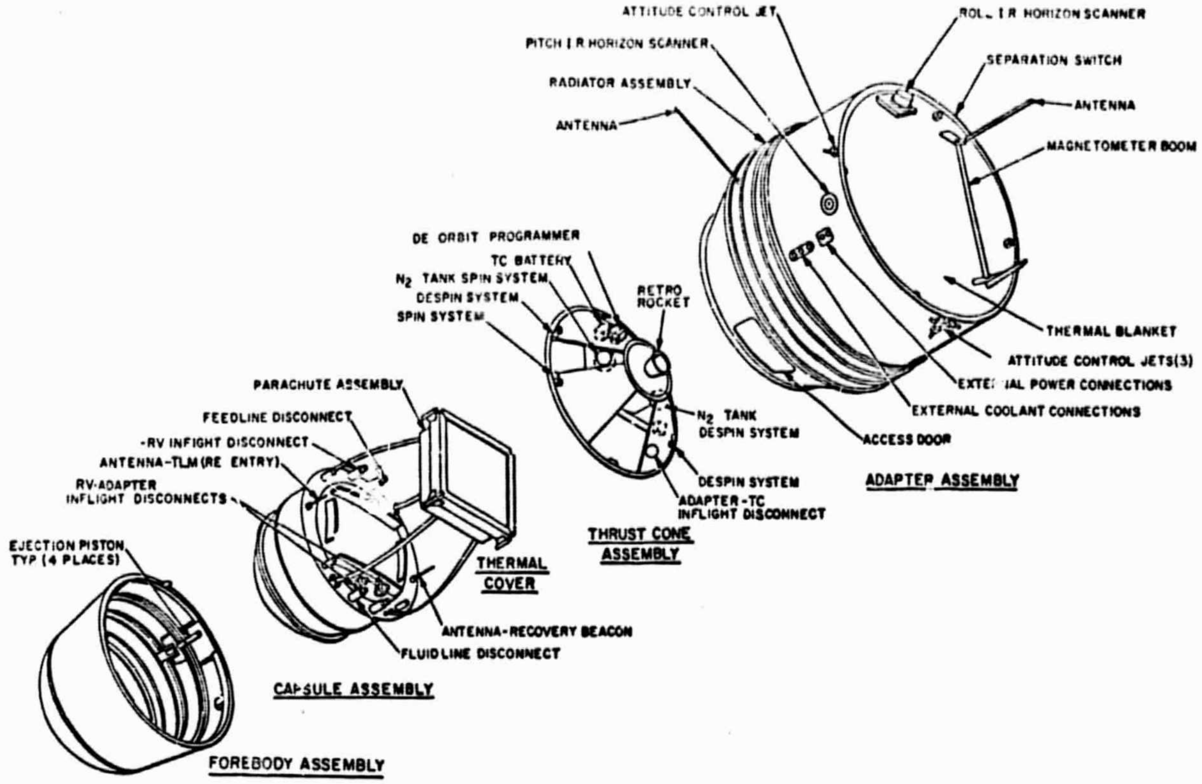

Figure 1. Biosatellite Spacecraft Configuration

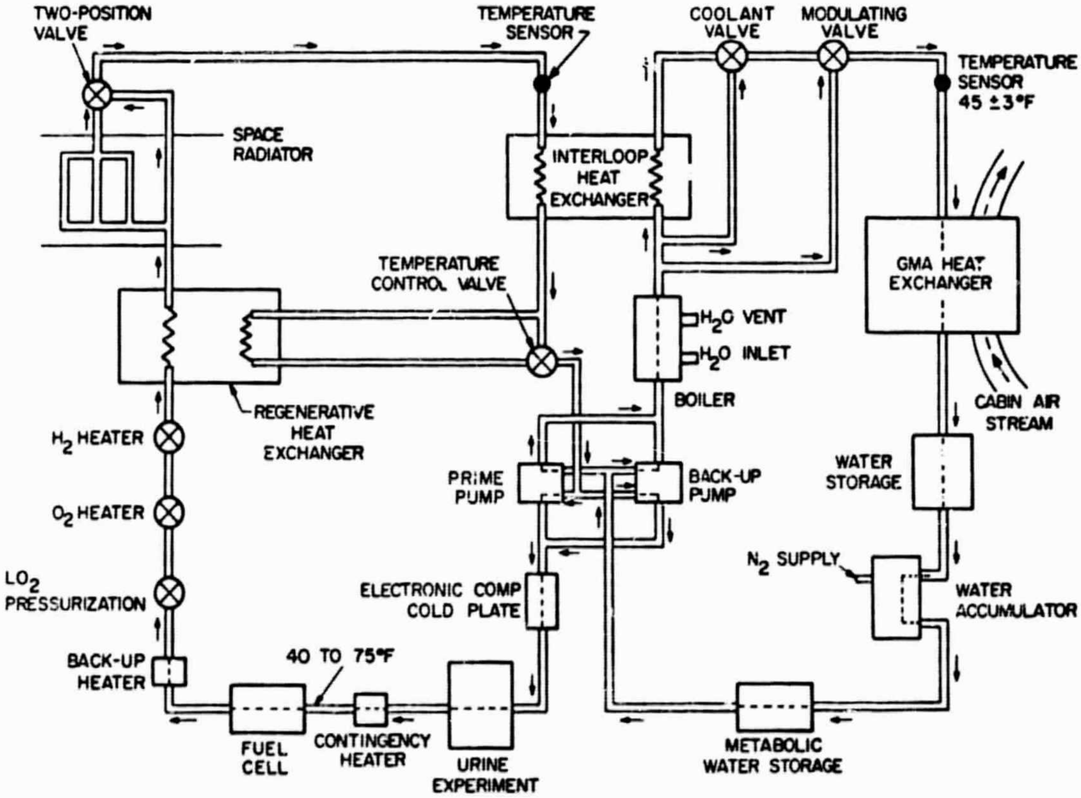

Figure 2. Environmental Control Liquid Loop

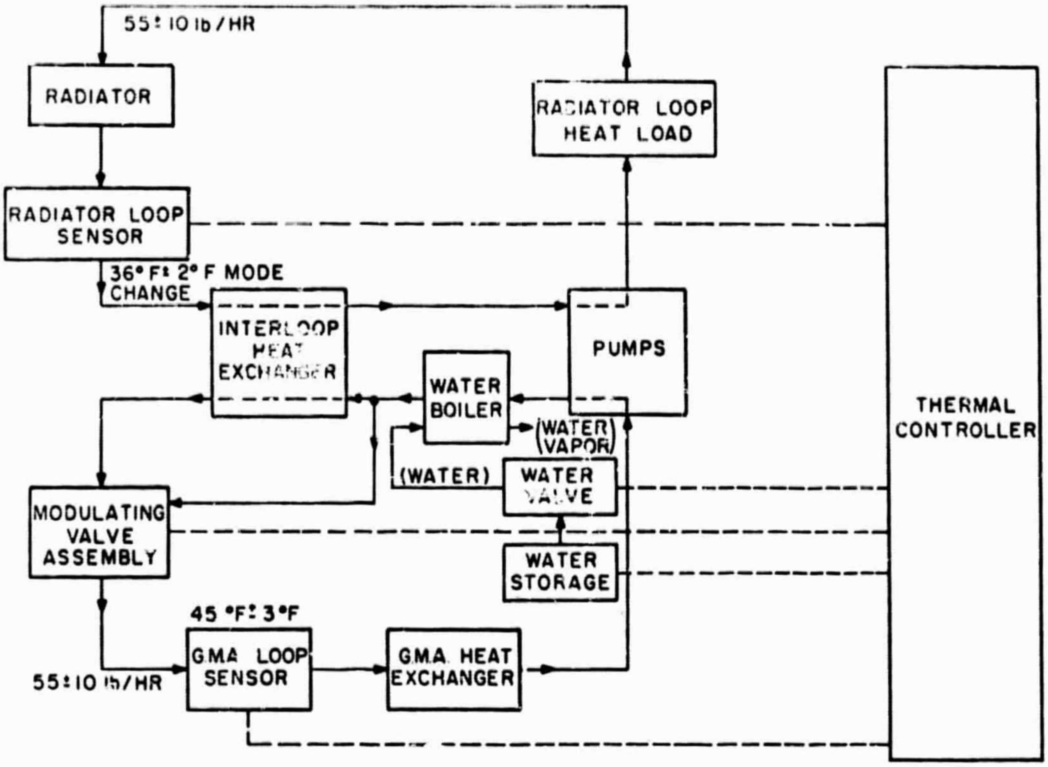

Figure 3. Thermal Controller and Modulating Valve Schematic Diagram

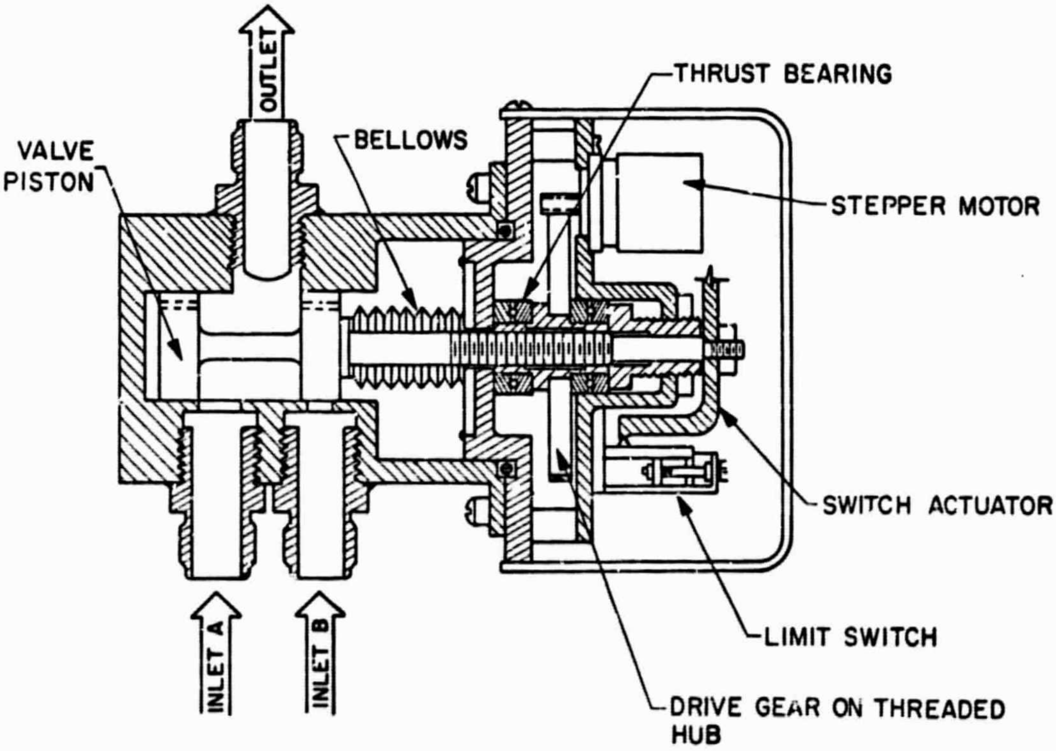

Figure. 4. Modulating Valve

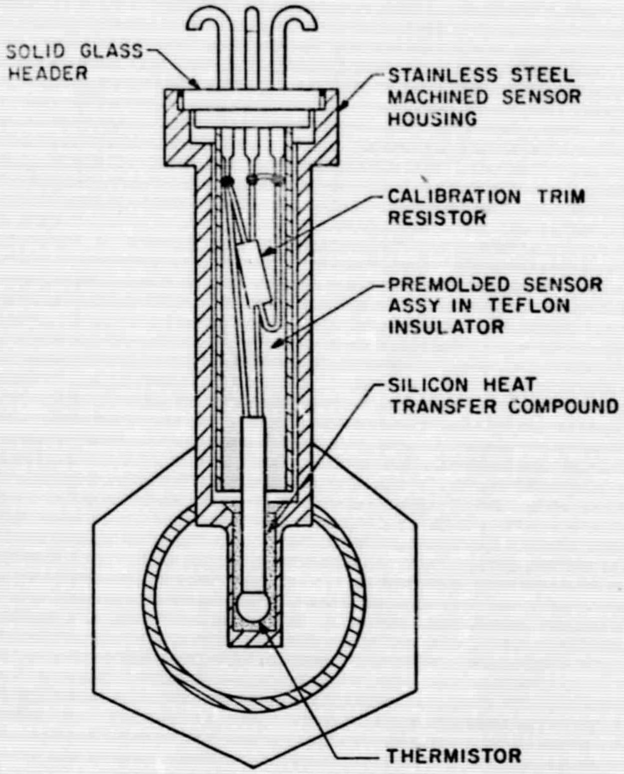

Figure 5. Thermal Controller Coolant Sensor

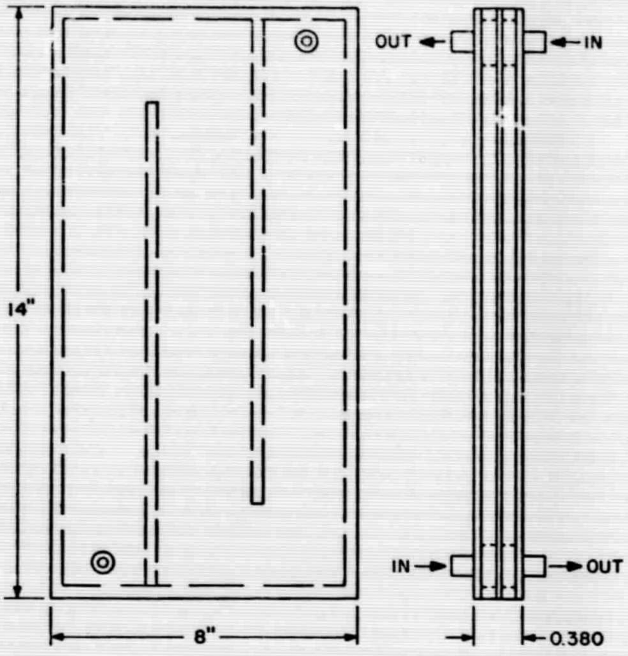

Figure 6. Regenerative Heat Exchanger

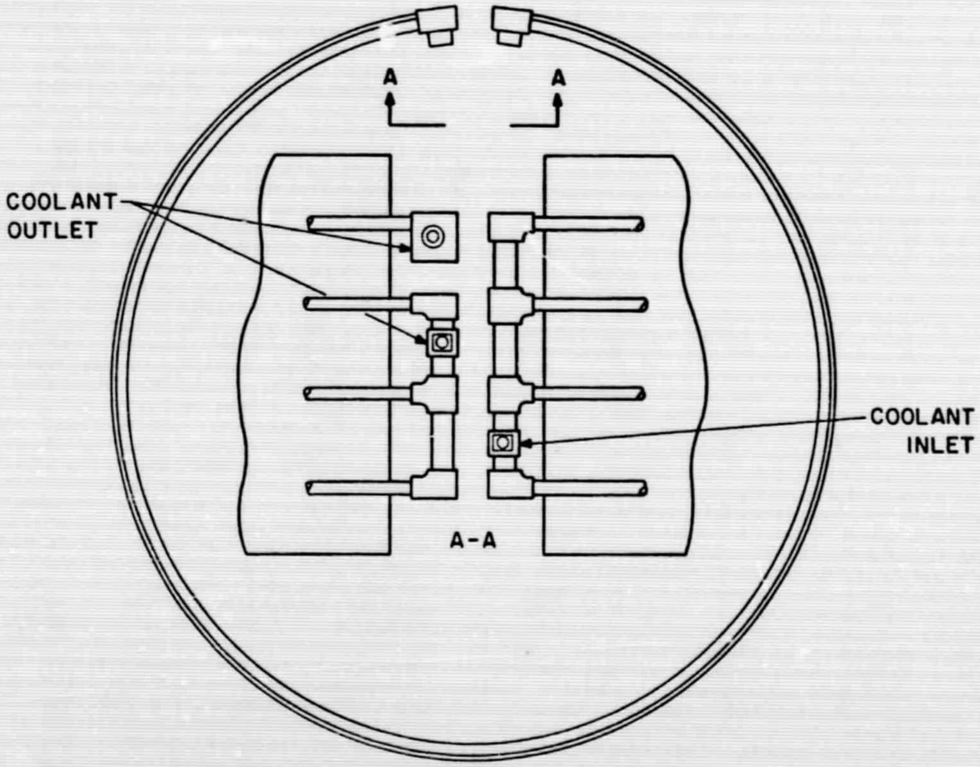

Figure 7. Radiator Configuration

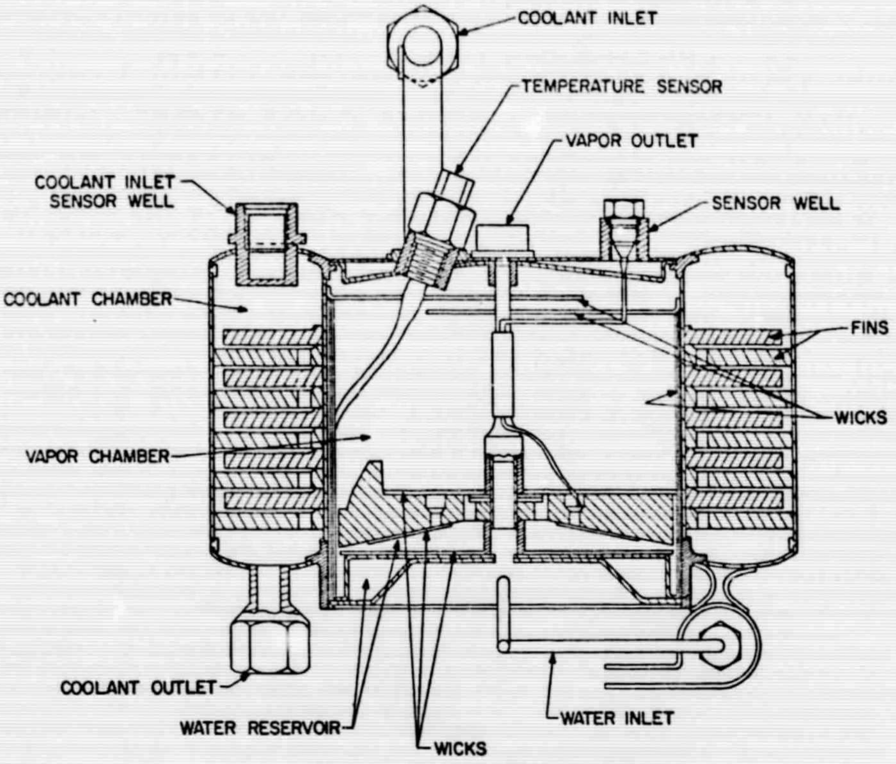

Figure 8. Evaporative Boiler

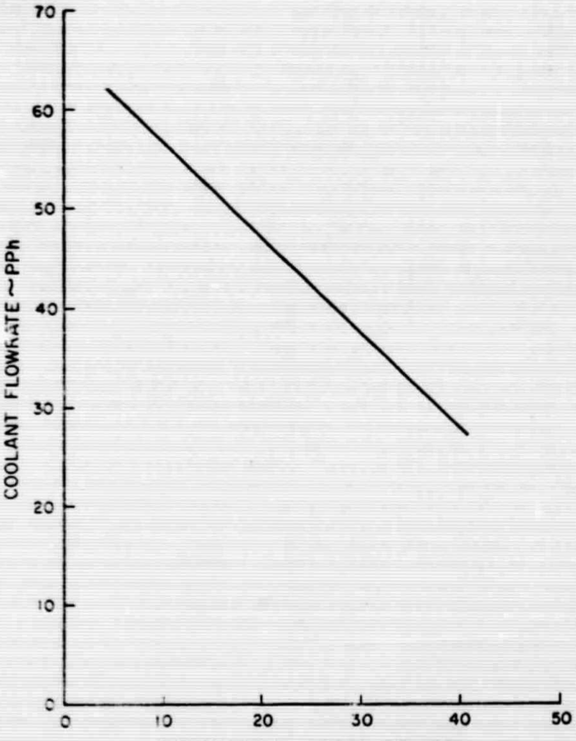

Figure 9. Coolant Flow Rate vs. Differential Pressure

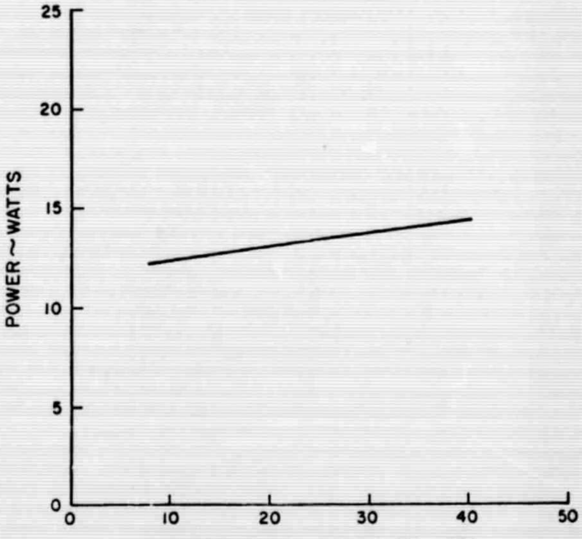

Figure 10. Pump Power vs. Differential Pressure

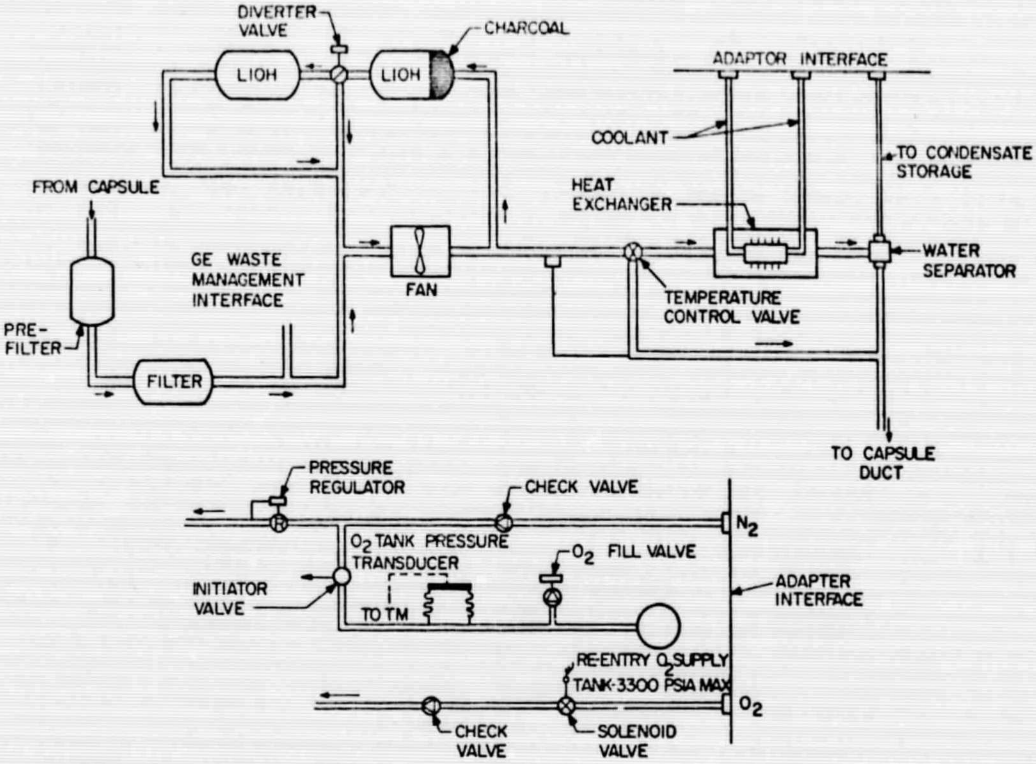

Figure 11. Life Support Gas Management Assembly

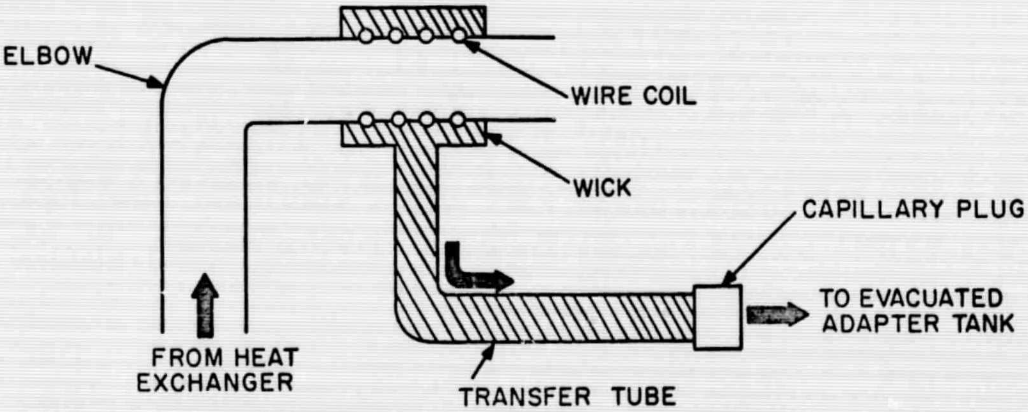

Figure 12. Condensate Disposal System

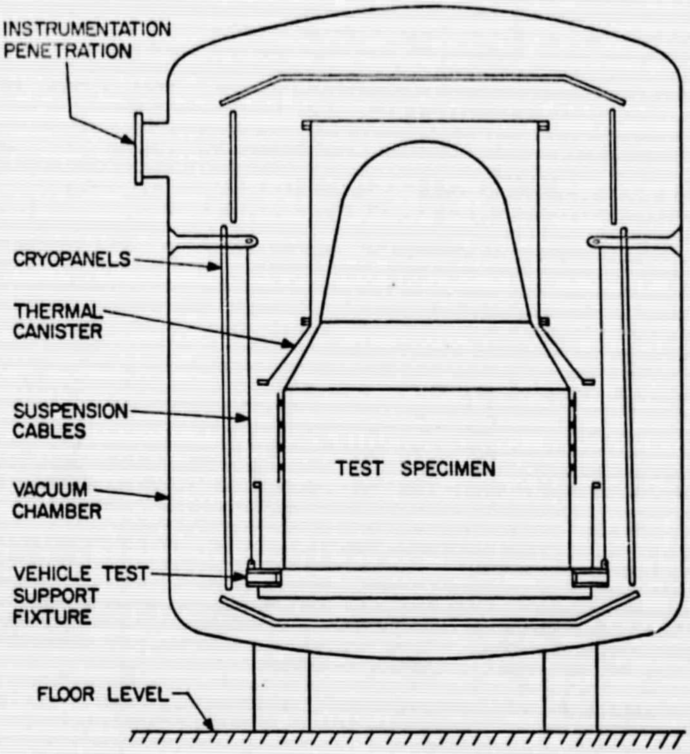

Figure 13. Thermal Vacuum Test Configuration

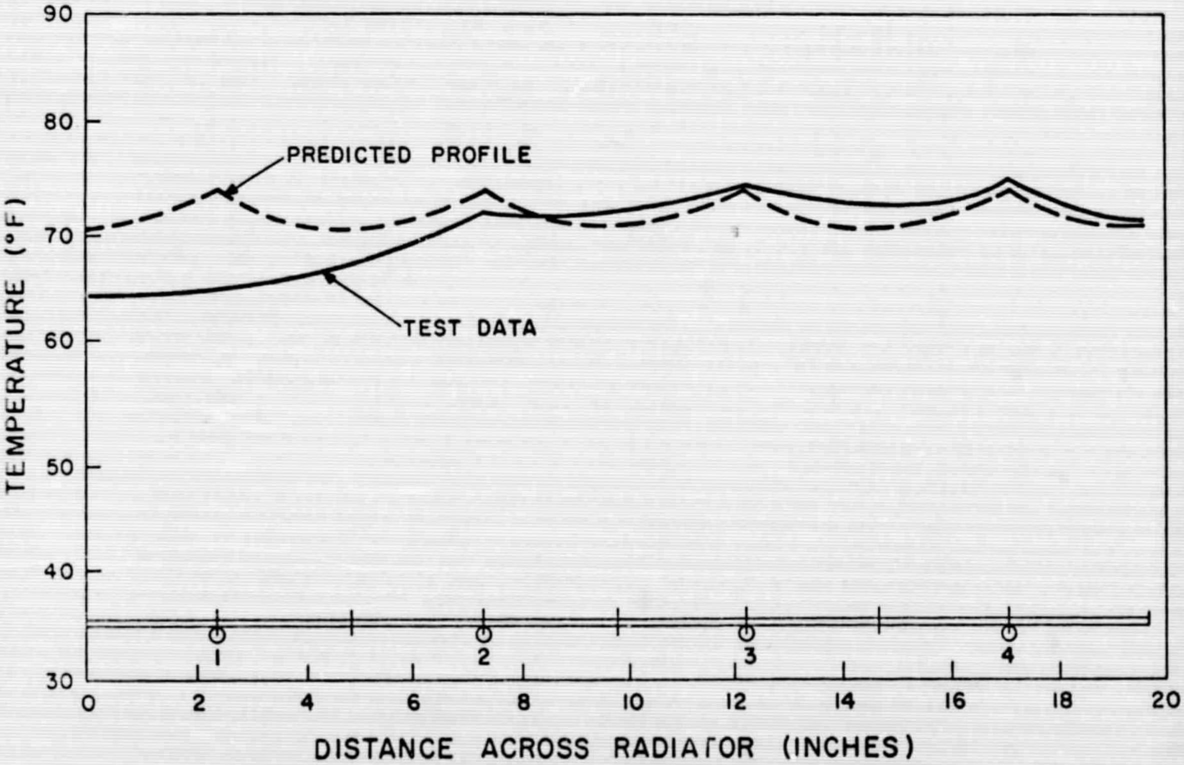

Figure 14. Temperature Distribution Across Radiator

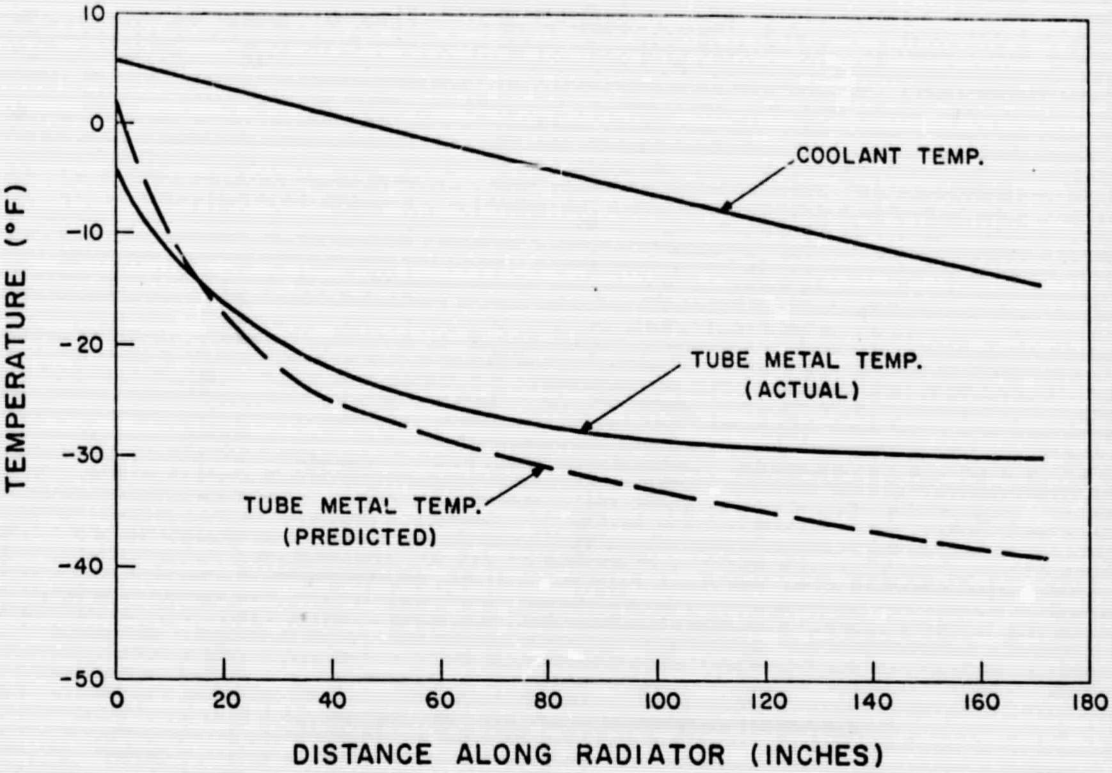

Figure 15. Comparison of Predicted Coolant Film ΔT

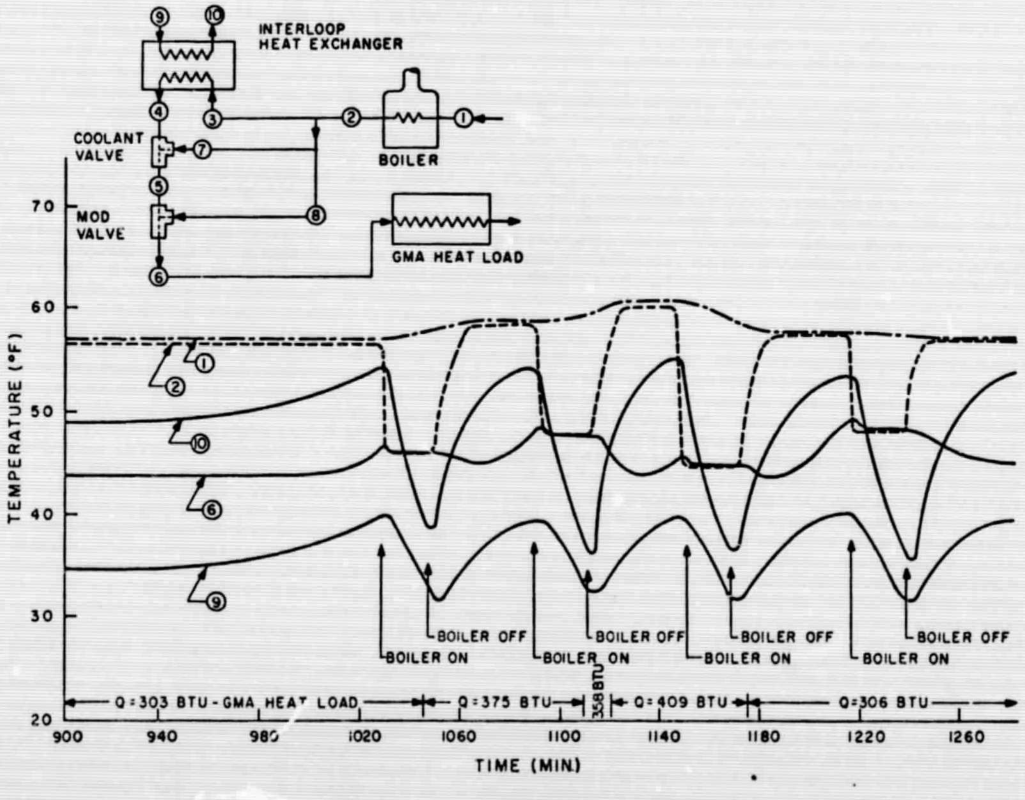

Figure 16. Boiler Test Performance

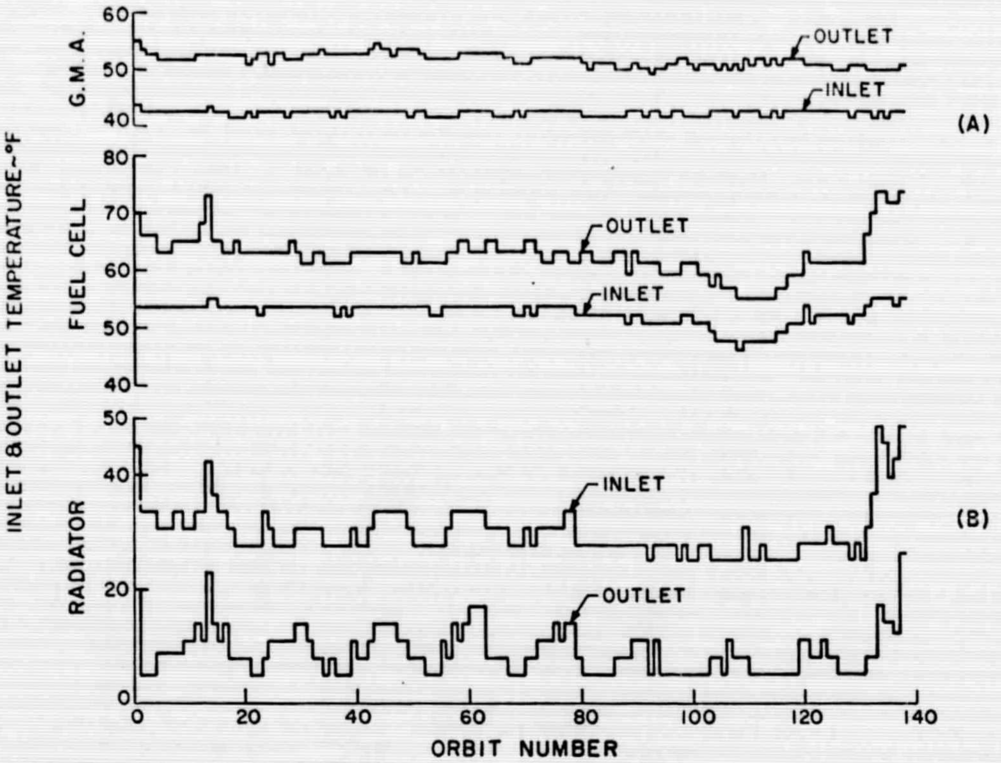

Figure 17. Flight Temperature Data

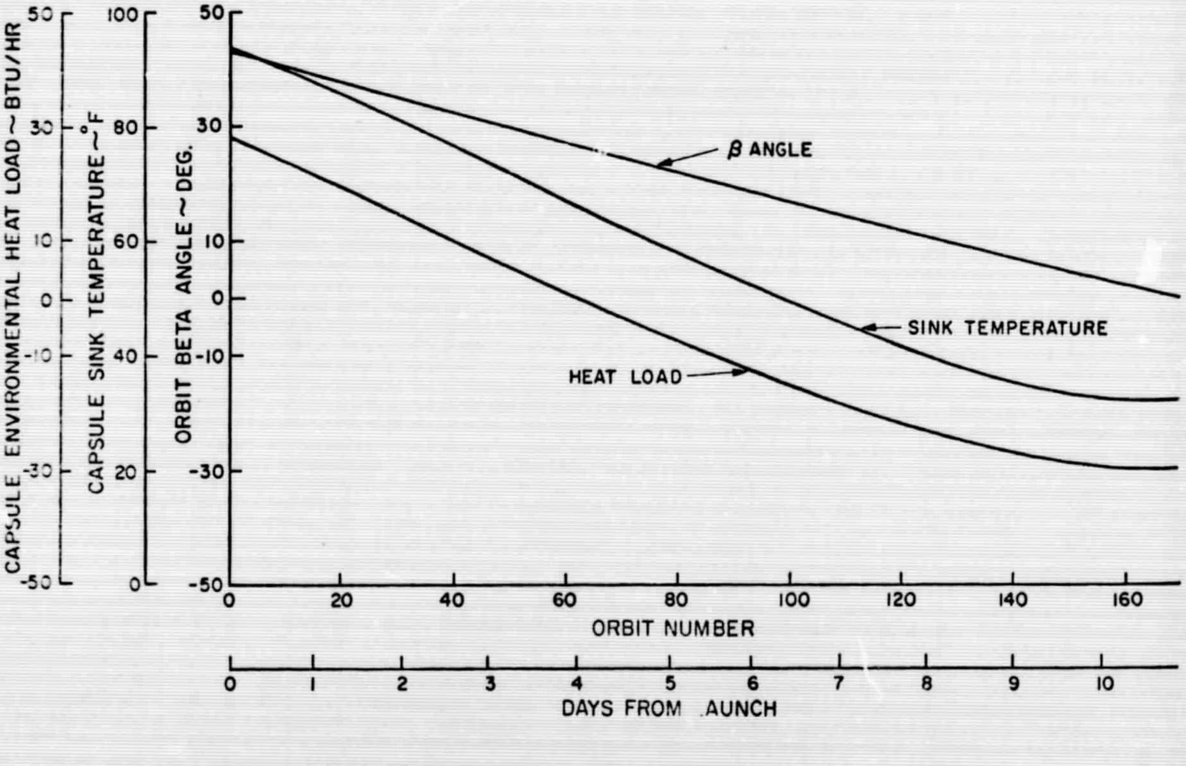

Figure 18. Predicted Capsule Environmental Heat Loads and Sink Temperatures

Environment	Units	Mission Objective	Flight Range
Capsule Total Pressure	psia	13.2 to 16.2	13.7 to 14.7
Recovery Total Pressure	psia	13.2 to 16.7	15.0 to 15.4
Capsule Incentive Temp.	°F	70 to 80	70 to 71.2
Temperature Recovery	°F	50 to 100	74.5 to 80.0
Temperature Gradient Across Primate	°F	67 to 83	67.6 to 81.0
Maximum Temp. Gradient in any one Orbit	°F	Not to exceed 13	69.8 to 81.0
Capsule Relative Humidity	percent	35 to 70	42.1 to 56.8
Capsule Partial O_2 Pressure	mm Hg	135 to 165	142.9 to 158.7
Recovery Partial O_2 Pressure	mm Hg	105 to 260	175 to 200
Capsule Partial CO_2 Pressure	mm Hg	0.2 to 7.6	0.30 to 4.22
Recovery Partial CO_2 Pressure	mm Hg	0.2 to 7.6	0.52

Figure 19. Gas Management Performance Summary