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THERMAL INTEGRATION OF A BRAYTON POWER SYSTEM WITH A LIFE-SUPPORT SYSTEM

II - Transient Analysis

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16. Abstract

An analytical study was conducted to determine the feasibility of integrating a Brayton power system with a four-man life-support system. As part of this study, an analog computer simulation of the Brayton system was utilized to investigate the dynamic effect of the life-support-system varying heat load on the Brayton system. The dynamic effect of the life-support-system thermal load on the Brayton system was minimal.

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THERMAL INTEGRATION OF A BRAYTON POWER SYSTEM WITH A LIFE-SUPPORT SYSTEM
II - TRANSIENT ANALYSIS

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SUMMARY

An analytical study was conducted to determine the feasibility of an integration of the Brayton power system with an existing four-man life-support system. The investigation utilized an analog computer simulation of the Brayton system. The computer simulated the effects of the life-support-system varying heat load on the Brayton system. This report discusses the analog computer simulation techniques and presents the results of this investigation. The analysis showed that the Brayton power-system electrical output remains essentially constant even though the thermal power required by the life-support system does cycle between 4 and 8 kilowatts thermal.

INTRODUCTION

The NASA Lewis Research Center is currently engaged in a program to develop a Brayton power system capable of generating electric power in space. This system is designed to deliver from 2 to 15 kilowatts electric of output power using either a radioisotope or a nuclear reactor as its energy source. The NASA Langley Research Center is currently engaged in a program to develop life-support systems for use in space. As a first step in the evolution of an advanced life-support system, Langley has been conducting tests on a four-man integrated life support system. One application of the Brayton system is to supply both the electrical and thermal powers required by such a life-support system. Additional information related to the Brayton system and the integrated life-support system is contained in references 1 and 2.

A study was jointly conducted by the Lewis Research Center and the Langley Research Center to determine the feasibility of integrating the Brayton system with this life-support system. The study was focused primarily on the capability of the Brayton system to provide the electrical and thermal powers required by the life-support system. In addition, the study examined the necessary modifications to the two systems if they were mated. The life-support-system thermal requirement varies during its operation. An analog computer simulated the transient effects of this heat-load variation on the Brayton system. This report presents the results of this analog computer transient study.

DESCRIPTION AND REQUIREMENTS

Brayton System Configuration

Gas loop. - The heart of the Brayton system is a gas-filled power-conversion loop which is shown in figure 1. This gas loop consists of the Brayton rotating unit (made up of a turbine, compressor, and alternator mounted on a single shaft), a gas recuperator, the heat source, and a waste heat exchanger through which the low-temperature waste heat is removed. Hot gas from the heat source passes through the turbine, generating the required torque to power the Brayton rotating unit. From the turbine exit the gas flows through the high-temperature side of the recuperator and then through the waste heat exchanger. The low-temperature gas flows from the waste-heat-exchanger outlet to the compressor, where the gas pressure is raised. The high-pressure gas then flows through the cold side of the recuperator and back to the heat source, which completes the

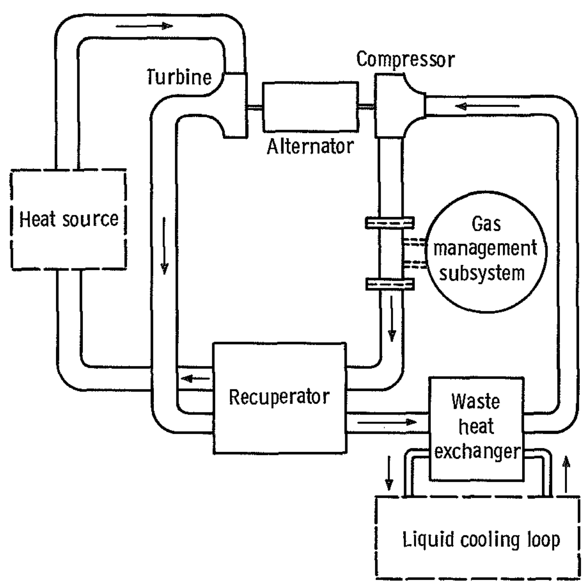

Figure 1. - Brayton gas loop.

cycle. A more detailed discussion of the Brayton system is presented in reference 1.

Liquid loop. - A liquid heat-rejection loop is used to remove the waste heat from the Brayton gas loop and to provide cooling for the Brayton alternator and electronic equipment. The presently envisioned configuration of the Brayton liquid loop is shown schematically in figure 2. It contains three flow paths, two radiators, and a single liquid pump. Recirculating Dow-Corning 200 fluid flows from the pump through the three parallel flow paths. Flow path 1 passes through the waste heat exchanger, where it removes heat from the gas loop; through the high-temperature radiator, where it rejects this heat to space; and back to the pump. Flow path 2 passes through the Brayton alternator, the low-temperature radiator, and back to the pump. Flow path 3 passes through the electronic package cold plates, through the low-temperature radiator, and back to the pump. The flow rates in each of the flow paths are fixed at their rated values by metering orifices in each of the three paths. Two identical liquid loops are provided, only one loop being active at any time and the other being redundant. The exact configuration of flow paths 2 and 3 is highly dependent on the mission of the Brayton system. For example,

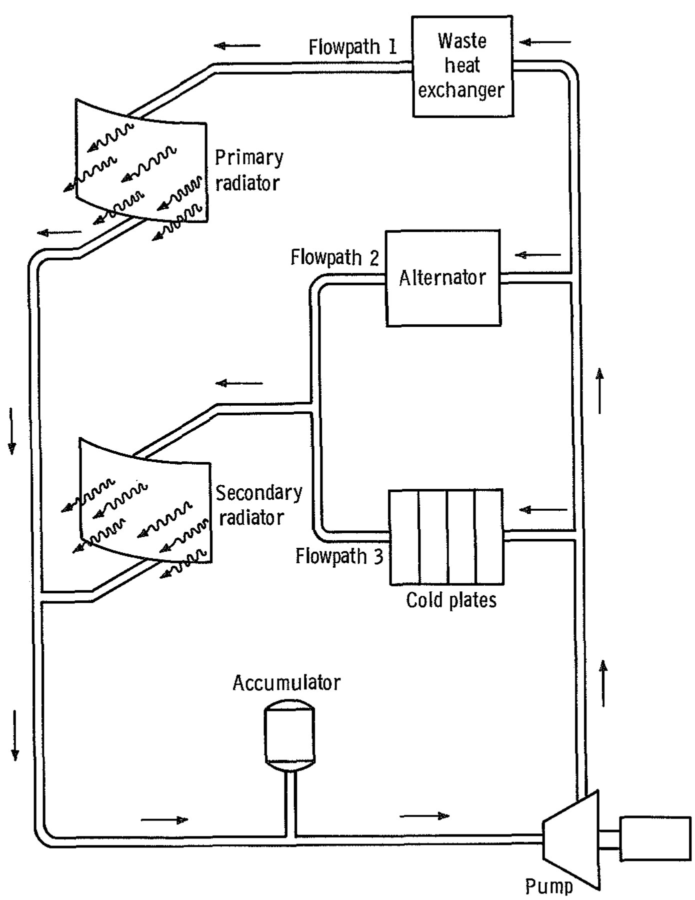

Figure 2. - Brayton liquid cooling loop.

if it were used with a life-support system, a common liquid cooling loop might be used for the Brayton electronics and the life-support-system electronics.

Life-Support-System Configuration

A detailed description of the present configuration of the life-support system is contained in reference 2. In brief, the life-support system performs the following functions: (1) atmospheric control, (2) thermal control, and (3) food, water, and waste management. It also contains all the controls and instrumentation required for the operation of its equipment. Presently these systems are installed in a spacecraft test hull with laboratory and living space appropriate for a four-man 1-year mission. The life-support system depends on a space power system to provide all the electrical and thermal power required to perform its functions.

Electrical requirements. - Figure 3 shows the experimentally determined electrical power requirements of the life-support system. The system requires both 400-hertz and

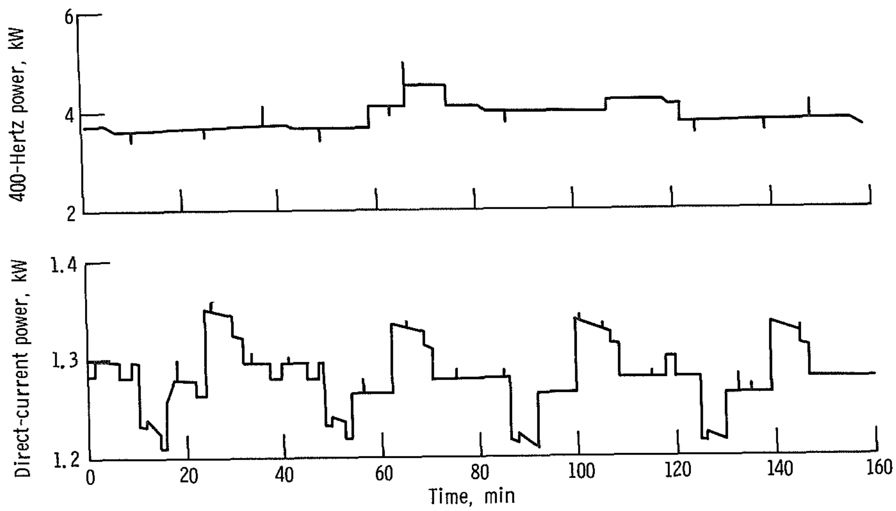

Figure 3. - Electrical requirements of life-support system.

28-volt-dc electrical power. The nominal electrical power requirements is 5.2 kilowatts electric with peaks as high as 5.8 kilowatts electric. A steady-state analysis (ref. 3) shows that the Brayton system in its present configuration could readily supply the electrical requirements of the life-support system.

Thermal requirements. - Figure 4 shows the experimentally determined thermal power requirements of the life-support system. The nominal thermal requirement is approximately 6 kilowatts thermal. This thermal energy requirement is not constant but

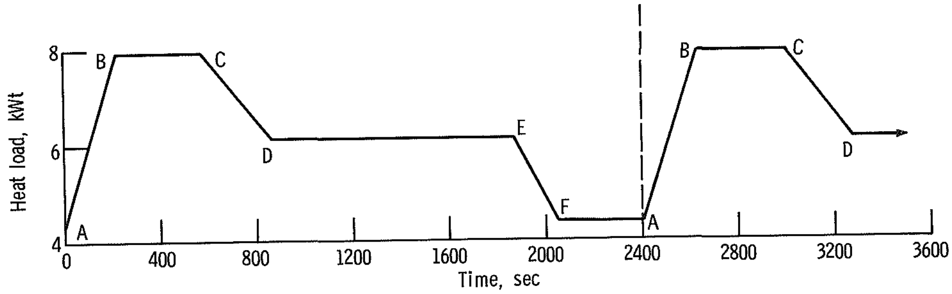

Figure 4. - Thermal power requirements of life-support system.

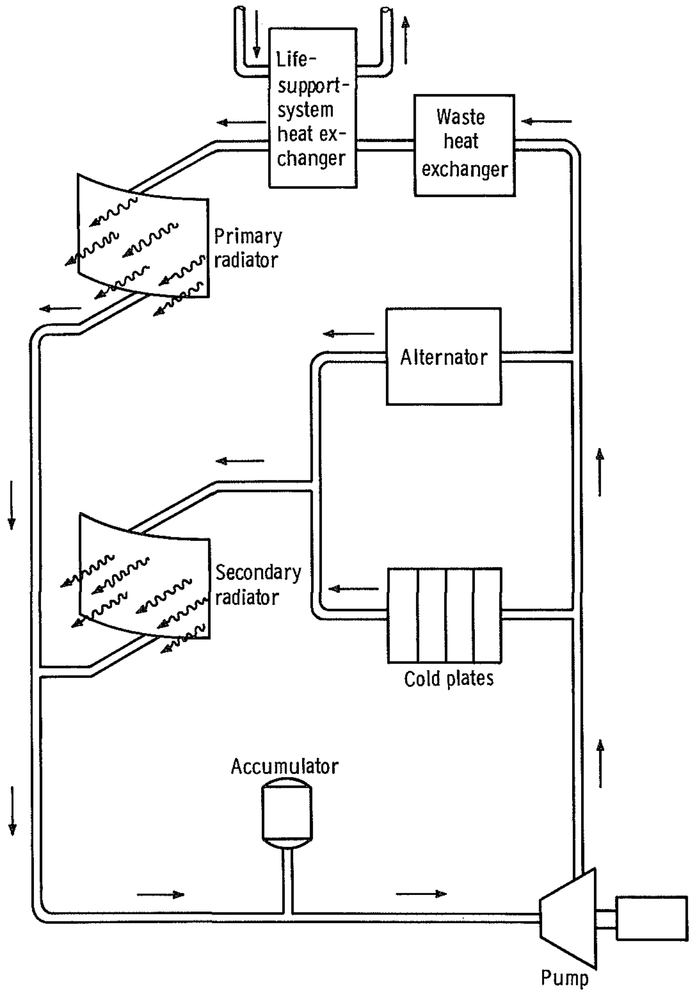

Figure 5. - Brayton liquid cooling loop with life-support-system heat exchanger.

continuously cycles between 4.4 and 7.9 kilowatts thermal with an average period of 40.2 minutes. Recent experiments at the Langley Research Center have determined that the required thermal energy can be provided by heating the life-support-system fluid (water) to temperatures of 300° F (422 K) or higher.

Brayton - Life-Support-System Thermal Interface

Several methods of integrating the Brayton system and the life-support system are investigated in reference 3. Considerations of the required modification to present Brayton and life-support-system hardware indicated that the simplest means of providing the thermal power requirements of the life-support system was to insert a heat exchanger in the high-temperature flow path of the Brayton liquid loop. Digital computer studies indicate that Brayton system waste heat could be transferred to the life-support system through this heat exchanger at a nominal 300° F (422 K). Figure 5 shows the position of this heat exchanger in the Brayton liquid loop. As part of this integration study, a conceptual design of a heat exchanger which could be used to transfer waste heat from the Brayton system to the life-support system was undertaken. This effort resulted in the conceptual design of a lightweight tube-in-shell heat exchanger shown in figure 6. The effectiveness of this heat exchanger is predicted to be approximately 0.70. Its tube bundle weight is calculated to be approximately 50 pounds (23 kg).

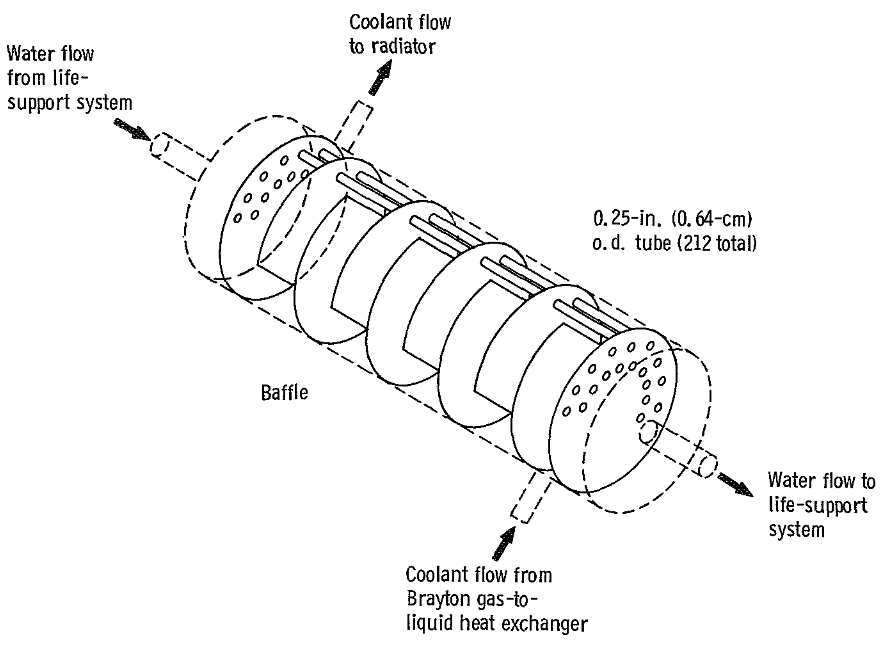

Figure 6. - Brayton - life-support-system interface heat-exchanger concept (liquid to liquid). Tube bundle: length, 19.5 inches (49.5 cm); outside diameter, 5.5 inches (14 cm); weight, 50 pounds (23 kg); material, stainless steel.

ANALOG COMPUTER SIMULATION

An analog computer simulation of the entire Brayton system, including the conceptual heat exchanger in the Brayton liquid loop, was used in this study. A simulation of the Brayton liquid loop was developed and combined with an existing analog simulation of the Brayton gas loop. This gas-loop simulation is described in reference 4. Included in the gas-loop simulations are dynamic models of the Brayton rotating unit, the gas recuperator, and the gas side of the waste heat exchanger.

A new liquid-loop simulation was developed. For the purposes of this study, only flow path 1 (fig. 3) was simulated. It is in this flow path that the life-support-system heat exchanger will be located. Therefore, it is this flow path that will show the main effects of the integration of the two systems. Because the flow rate is maintained constant during operation of this loop, only a simulation reflecting loop temperature dynamics was needed.

The liquid-loop simulation included dynamic models of the life-support-system heat exchanger, a space radiator, and the liquid side of the waste heat exchanger.

The procedure used in developing the dynamic analog computer model of each of these components was as follows:

(1) Separate digital computer programs which simulated both the steady-state and dynamic performance of each component were written.

(2) Steady-state performance maps for each component were obtained from the digital computer models.

(3) Analog computer circuits which duplicate these maps were developed and incorporated into the analog simulation.

(4) Step changes in each of the input variables were introduced into the dynamic digital computer simulations.

(5) The responses of the component outlet temperatures to the step changes in inlet variables were plotted.

(6) Analog computer circuits which approximated these responses were developed and incorporated into the analog simulation.

The heat-exchanger models were then interconnected in proper sequence and checked as a complete system. The liquid-loop heat-rejection simulation thus programed provided excellent steady-state accuracy together with a good dynamic response using a minimum of analog equipment.

RESULTS

A complete analog computer simulation of the Brayton gas loop and the Brayton

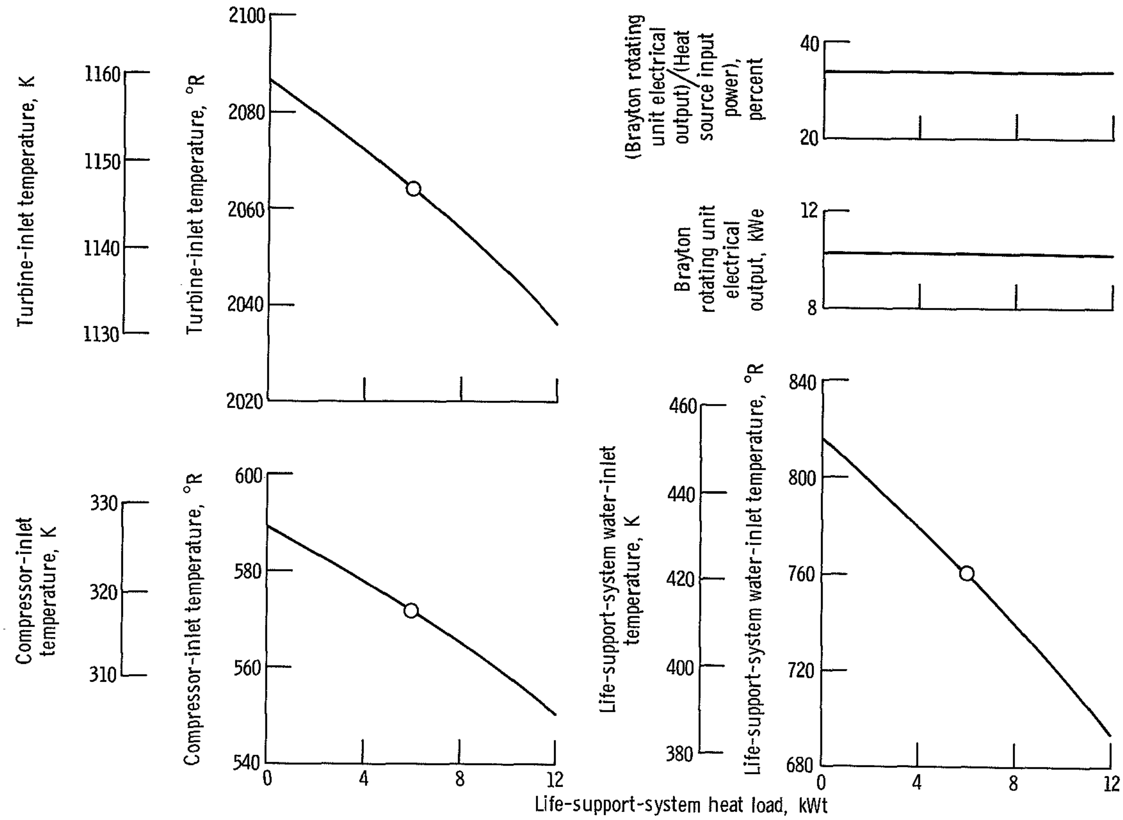

Figure 7. - Effects of life-support-system heat-load variation on water-inlet temperature, turbine-inlet temperature, and compressor-inlet temperature. Prime radiator area, 260 square feet (24.25 m^2); coolant mass-flow rate, 0.15 pound mass per second (0.068 kg/sec); source thermal input, 30 kilowatts; working gas, helium-xenon at molecular weight of 83.8; total gas mass, 1.035 pounds mass (0.470 kg); water flow rate, 0.0833 pounds mass per second (0.0378 kg/sec).

liquid loop was used to study the transient behavior of the Brayton system when used to power the life-support system. For all test runs, the compressor discharge pressure was set at a nominal 40 psia (27.6 N/cm^2), and the heat source thermal input was set at a constant 30 kilowatts thermal (simulating an isotope source).

Steady-state performance was computed for a range of heat loads to the life-support system. The effects of the heat-load variation on key parameters are shown in figure 7. As can be seen in this figure, the life-support-system water-inlet temperature, the turbine-inlet temperature, and the compressor-inlet temperature all decrease with increasing life-support-system heat load. Since the turbine- and compressor-inlet temperatures are both changing in the same direction, the effect on the Brayton electrical power output is very small. These results compare very closely to the results obtained from the steady-state digital computer study in reference 3.

The analog computer simulation was run through three consecutive life-support-system heat-load cycles. Figure 8 shows the variations in the life-support-system water-inlet temperature, the Brayton compressor-inlet temperature, and the Brayton

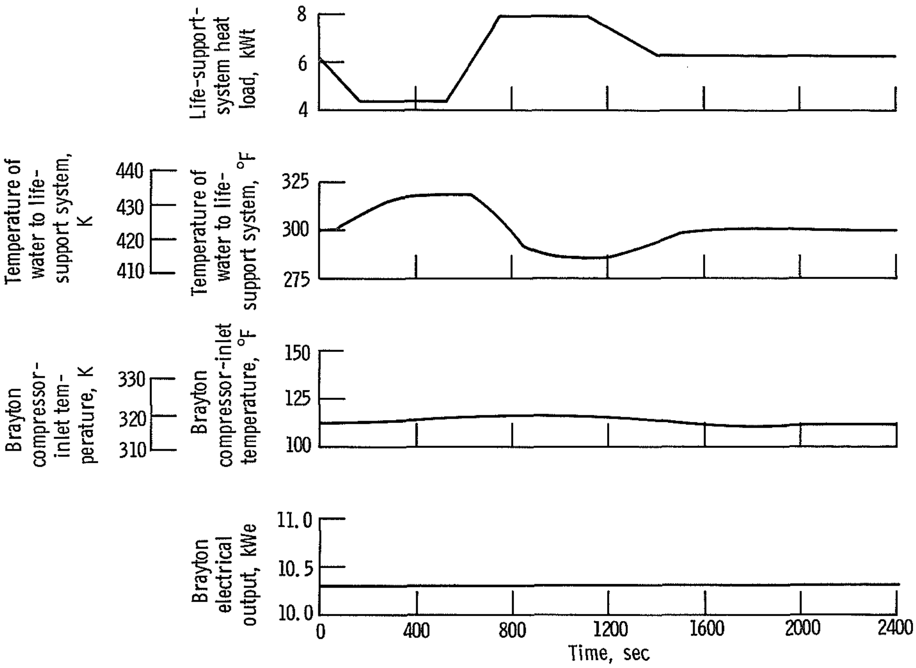

Figure 8. - One cycle of life-support-system process-heat load (typical).

electrical output during the third cycle. The variations in these parameters were identical during each of the three cycles, due primarily to the fact that each cycle terminates with the heat load at a constant level for approximately 1000 seconds. This period is long enough that the system essentially comes to steady state at the end of each cycle. The compressor-inlet temperature varied only slightly from 106° to 118° F (314 to 321 K) during the heat-load cycle. The life-support-system water-inlet temperature varied between 283° to 317° F (412 to 431 K). Throughout the runs the electrical output remained constant.

A study of the effects of a life-support-system startup on the Brayton system was made. The startup procedure was assumed to be as follows:

(1) The Brayton system is brought to its design operating point (30-kWe heat input and a nominal 40-psia (27.6-N/cm^2) compressor-outlet pressure).

(2) The life-support-system water-loop flow rate is brought to its design value and the water temperature is allowed to stabilize.

(3) The life-support-system equipment is brought on line, which results in a removal of heat from the Brayton system.

In order to determine if there is any pronounced effect of a life-support-system startup on the Brayton system, a very severe heat-load application was investigated. The life-support-system heat load was assumed to be ramped from zero to its maximum of 8 kilowatts thermal in 100 seconds and then held at that level until all transients subsided. As can be seen from figure 9, the temperature of the water supplied to the life-

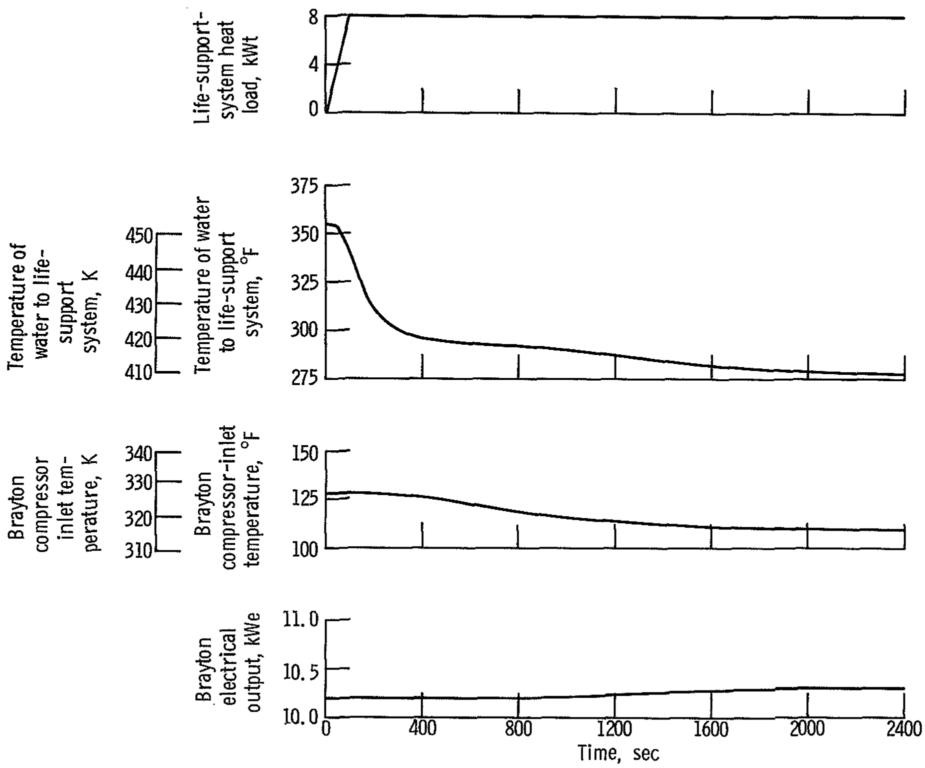

Figure 9. - Life-support-system startup transient.

support system drops slowly from 355° to 277° F (452 to 409 K). The Brayton compressor-inlet temperature dropped from 129° to 103° F (327 to 312 K). The Brayton electrical output remained nearly constant.

CONCLUDING REMARKS

The Brayton system can supply both the electrical and thermal power required by the life-support system. The technique of transferring Brayton waste heat to the life-support system by means of a heat exchanger in the Brayton liquid loop does transfer the required thermal energy at the required temperature during the life-support-system heat-load transients. The life-support-system water can be heated to the required temperature with an acceptable variation during the thermal cycle. In addition, by using this technique, the isotope-powered Brayton system electrical output is not affected by the life-support-system heat-load cycle. The reason for this is that the relatively large thermal inertias of the Brayton radiator and waste heat exchanger tend to almost completely damp out any Brayton gas-loop temperature transients caused by the life-support-system heat cycle. The investigation also showed that no major effect on the Brayton system is expected during the startup transient of the life-support system.

Lewis Research Center,
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