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BRAYTON POWER SYSTEM AND INTEGRATED LIFE SUPPORT SYSTEMS INTEGRATION STUDY

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16. Abstract

A system integration computer study was conducted to determine the compatibility and interactions of the Brayton power system (BPS) and the integrated life support system (ILSS) when operated in an integrated mode. Existing digital and analog models of the BPS were modified to simulate an integration with the ILSS. The prime area of concern was the effect on the BPS of waste heat removal for utilization in various ILSS processes. Results of the study show that the two systems are compatible and that integration results in an increase in overall system efficiency and can be accomplished with no major changes to either system. A hardware integration for further study is not justified until a specific mission is defined.

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SUMMARY

A system integration computer study has been conducted jointly by Lewis Research Center and Langley Research Center. The study was initiated to determine the compatibility and interactions of the Brayton power system (BPS) and the integrated life support system (ILSS) when operated in an integrated mode. Existing digital and analog models of the BPS were modified to simulate an integration with the ILSS. The prime area of concern was the effect on the BPS of waste heat removal for utilization in various ILSS processes.

Data collected during the ILSS testing were combined with subsystem bench test data to provide the information for changes to the BPS computer models. A steady-state digital program was used to determine worst-case interactions obtained by using two methods of heat removal. The information derived was applied to the preliminary design of a heat exchanger to transfer the necessary heat from the BPS to the ILSS process heat loop. At this point the dynamic integrated system was simulated by analog methods to determine the system transient performance. The data are presented for worst-case (steady-state) and dynamic responses in parametric form.

Results of the study show that not only are the two systems compatible but also the added overall efficiency yields a net savings in heat power input.

INTRODUCTION

Systems compatibility is essential for any space mission and candidate systems should be evaluated for potential secondary advantages contributing to the increased efficiency of overall systems. The Brayton power system (BPS) is a major candidate for electrical power generation in several long-term manned mission concepts. The BPS provides waste heat as a byproduct of electrical power generation. The integrated life support system (ILSS) is representative of the life support system requirements in manned mission concepts and includes processes and subsystems requiring heat energy input. Integration of these two major systems with respect to waste heat should, therefore, result in a highly efficient mission concept provided no adverse interactions occur.

The two systems are presently under test and evaluation at the Lewis and Langley Research Centers.

Since physical integration of these two systems would be both time-consuming and expensive, a detailed study was implemented to determine problem areas, define a method of integration, evaluate interactions between the systems, and determine whether physical integration was required to demonstrate compatibility. To accomplish this study, technical personnel from the two centers were assigned to a joint study group.

ILSS test data were evaluated and subsystem bench tests were performed to determine acceptable heat transport temperatures and to evaluate heat transport fluids. A digital computer study was made of the BPS parameters to determine both the suitable limits of operation and the most practical method of heat removal.

The results of these separate efforts were used to define the ground rules for the steady-state computer evaluation of the integrated systems. This part of the study was performed for two heat removal configurations. The data from the steady-state analysis led to the preliminary design of a heat exchanger, the simulation of which was used in a dynamic-analog-computer real-time evaluation. The validity of the mathematical models has been verified by the results of BPS hardware testing at the Space Power Facility, Plum Brook Station, Lewis Research Center, Ohio. (See refs. 1 and 2.)

ABBREVIATIONS

BHXU	Brayton heat exchanger unit
BPS	Brayton power system
BRU	Brayton rotating unit
DC-200	Dow-Corning 200 low-temperature fluid
DC-331	Dow-Corning 331 high-temperature fluid
HSHX	heat source heat exchanger
HX	heat exchanger
ILSS	Integrated life support system
kWe	kilowatt electrical

kWt kilowatt thermal

WHX waste heat exchanger

INTEGRATED LIFE SUPPORT SYSTEMS REQUIREMENTS

The ILSS, under development since 1965 by the NASA Langley Research Center, is an experimental ground facility to evaluate regenerative life support systems for manned space flight. (See ref. 3.) The facility was designed to be self-sufficient with a four-man crew for a period of 90 days. The test bed contains subsystems for thermal control, atmospheric control, water management, waste management, food management, and personal hygiene. An artist's concept of the ILSS is shown in figure 1. A completely integrated system was assumed in the design which included a simulated isotope power supply to provide electrical power and waste heat for the ILSS process systems and a simulated radiator for the rejection of waste heat to space.

The ILSS thermal control system includes three interrelated thermal control circuits as shown in figure 2. The process heat circuit (DC-331 loop) transports thermal energy from the fluid heating and pumping unit to the various components which utilize process heat. The cabin air circuit maintains cabin air temperature at a comfortable level for the crew while acting as an intermediate heat sink for the thermal energy generated by the crew and components in the test bed. The primary cooling circuit removes heat from the cabin air through the cabin heat exchangers and transfers the heat to the fluid cooling and pumping unit.

For the purpose of this study, the process heat circuit was of the greatest interest since it represents the thermal load which must be satisfied by process heat from the BPS. A fluid heating and pumping unit is used as the ILSS power system simulator. This unit regulates the DC-331 heating fluid outlet temperature to 204° C (400° F). Because of line losses, the fluid is delivered to the ILSS subsystems at a somewhat lower temperature. The unit simulates a constant temperature source for the heating fluid.

The process-heat circuit flow diagram shown in figure 3 represents the ILSS as originally configured. It can be seen that the process heat is utilized by many components that represent all the major subsystems. The components are grouped in three branches, the process heating fluid flow being divided as shown. The total thermal load was determined from the requirements of the individual components as measured during a 28-day manned test. The thermal requirements of each component vary in a cyclic manner. The average thermal load for each component and the range of thermal load for the total system are shown in table I.

The total thermal load requirements were analyzed as a function of time to determine a typical process heat load profile. This resulting profile, as shown in figure 4, is seen to have a 40-minute cycle which is dominated by the CO_2 concentration unit. This profile is considered to be typical of the thermal requirements which will exist for integrated power and life support systems of the immediate future.

The minimum inlet temperature at which the process heat loop can be operated is determined by the requirements of the CO_2 concentration unit. The CO_2 concentration unit utilizes absorption by a molecular sieve followed by thermal desorption into a CO_2 accumulator. The critical aspect of the molecular sieve operation is the desorption process. A series of tests were run on the ILSS to determine the efficiency of the CO_2 concentration unit at various heating fluid temperatures. (See ref. 4.) These tests indicated that CO_2 concentration in the ILSS chamber with a four-man crew could be maintained at the desired 3.8 torr (0.5 percent) by maintaining the process fluid inlet temperature to the chamber in the 121° to 135° C (250° to 275° F) range. (1 torr = 133 N/m^2.) The test results are plotted in figure 5. If an allowance is made for a line temperature drop, a nominal fluid temperature of 149° C (300° F) at the heat source is needed. A comparison of existing process heat circuit requirements with requirements used in this study is given in table II.

Recent studies (ref. 5) have indicated that water will probably be used in both the heating and cooling circuits of future life support systems. Water is nontoxic, has excellent heat transport properties, and provides the added advantage of storing one common fluid for use in heating, cooling, washing, drinking, and oxygen regeneration subsystems. At the required temperature of 149° C (300° F), water has a vapor pressure of only 462 kN/m^2 (67 psia). Pressurized liquid water was, therefore, chosen as the heat transport fluid for this study.

BRAYTON POWER SYSTEM REQUIREMENTS

The Brayton power system, under development since 1963 by the NASA Lewis Research Center, is a closed-loop, inert-gas cycle power generation system. A schematic representation is shown in figure 6. The heat source for a manned mission will probably be a radioisotope or a nuclear reactor. For initial testing, an electrical heat source is being used.

The Brayton rotating unit (BRU) consists of a turbine, alternator, and compressor mounted on a single shaft.

The Brayton heat exchanger unit (BHXU) assembly consists of a recuperator and a waste heat exchanger (WHX). The high power conversion efficiency of 25 percent to 30 percent is obtained in this system by means of the recuperator which reclaims a large part of the waste heat energy within the gas loop. The remaining waste heat is removed through the WHX by a liquid coolant loop and space radiator.

Heat is injected into the working gas through the heat source heat exchanger (HSHX). The heated gas flows through the turbine providing torque to the BRU. Turbine outlet gas is passed sequentially through the recuperator and WHX and is then compressed.

The BPS is capable of a maximum output power of 15 kWe at 1200 Hz. The output power can be varied by changing the system gas pressure and the alternator field current.

Three methods to remove waste heat energy for use outside the system were considered. The first method was to extend the plumbing in the radiator loop and pass the process fluid through the ILSS before going to the radiator. This procedure would not violate the integrity of the gas loop but would complicate the radiator loop, particularly if redundancy is required or if the fluid (DC-200) used in the radiator loop is not compatible with the needs of the ILSS process heat loop. This approach was not considered further. The second method was to place a gas-to-liquid heat exchanger between the recuperator and the WHX. The third, and most promising method, was to add a liquid-to-liquid heat exchanger in the radiator loop. This procedure would permit the use of a different heat transport fluid within the ILSS loops and have less effect on the Brayton loop parameters because of the natural time lags associated with each thermal transfer.

The two preferable methods discussed involve the use of an additional heat exchanger. If the temperature loss across the heat exchanger is assumed to be 28° C (50° F), the temperature in the Brayton loop at the point the process heat is to be extracted must be at least 176° C (350° F) in order to provide the process heat temperature required for the ILSS. From figure 7(a) it can be seen that under nominal operating conditions, the temperature of the WHX gas inlet is 172° C (342° F) and liquid coolant outlet is 158° C (316° F). The first step, therefore, was a parametric study of the Brayton loop to determine the variations of temperatures and pressures required to increase the waste heat rejection temperature. This increase could be accomplished most readily by either increasing the compressor inlet temperature by decreasing the radiator area or by reducing the effectiveness of the recuperator.

Figures 7 and 8 show the effects of compressor inlet temperature variations on system parameters. Alternator output power was held constant at 9.4 kWe and turbine inlet temperature was held at 870° C (1600° F). This condition was obtained by variations in heat input, gas pressure, heat rejections, and coolant mass flow rates. Figure 7(a) shows that a heat rejection temperature of 176° C (350° F) can be obtained from the gas circuit with a compressor inlet temperature increase of about 5.6° C (10° F) over the design point of 26° C (80° F). An increase of about 22° C (40° F) in compressor inlet temperature would be required if the heat were removed from the radiator loop at this 176° C (350° F) temperature by a liquid-to-liquid heat exchanger.

Figure 8 shows that the operating point associated with the liquid-to-liquid heat exchanger is less efficient than with the gas-to-liquid exchanger, but both operating points are well within the capability of the system.

The effects of reducing recuperator effectiveness are shown in figure 9. Figure 9(a) shows the radiator coolant rejection temperature can be increased by reducing recuperator effectiveness, but the crossplotted 176° C (350° F) line of figure 9(b) shows an additional small reduction in conversion efficiency. This method then offers no advantage over the simple method of raising compressor inlet temperatures.

INTEGRATION GROUND RULES

The requirements of the ILSS and the range of off-design operation of the BPS determined a set of ground rules for the computerized integration. By specifying water as a heat transport fluid, with an acceptable temperature of 149° C (300° F), the integrated system can be represented as shown in figure 10. Both the gas-to-liquid and liquid-to-liquid heat exchangers were considered as alternate methods. The most desirable heat removal method is by means of a liquid-to-liquid heat exchanger in the BPS radiator loop; however, both heat exchanger systems were studied. The ground rules or assumptions were as follows:

(a) A constant power heat source was assumed.

(b) The inert gas used was a helium-xenon mixture with a molecular weight of 83.8.

(c) Both of the added heat exchangers had a temperature loss of 28° C (50° F).

(d) The average heat load of the ILSS was 6.0 kWt with a variation of ± 2.0 kWt. A condition of zero heat load was also examined.

(e) The turbine inlet temperature was set at 870° C (1600° F) with an ILSS heat load of 6.0 kWt.

(f) The gross alternator power output was set at 9.4 kWe with an ILSS heat load of 6.0 kWt. The power was distributed as follows: ILSS, 6.5 kWe; Brayton, 1.4 kWe; and Margin, 1.5 kWe.

The integration study was performed in two steps:

(1) Digital: A steady-state evaluation of the effects of ILSS thermal loading on the BPS performance. For each change in load, the BPS was allowed to reach its steady-state operating levels. These studies were made for both a liquid-to-liquid heat exchanger in the radiator loop and for a gas-to-liquid heat exchanger in the gas loop.

(2) Analog: A dynamic system response evaluation with ILSS heat loads cycling. Based on results obtained in the digital study, a preliminary design was made for the liquid-to-liquid heat exchanger only.

COMPUTER SIMULATION RESULTS

The steady-state digital program yielded the maximum variation in power system performance under the influence of a range ILSS heat loads. Figures 11 and 12 show the performance of a system rated for a 6 kWt process heat load. The limits of the ILSS heat profile at 4 kWt and 8 kWt were also treated as constant loads, as was the effect of zero ILSS heat load, which simulates the removal of all life support thermal loads.

Figure 11 shows pertinent BPS temperature variations and electrical output against ILSS heat loads for the liquid-to-liquid heat exchanger. Over the range of ± 2 kWt about the 6 kWt point, there is very little change in electrical power output because the temperatures within the BPS rise and fall with output heat variations. The turbine inlet and compressor inlet temperatures have opposite effects within the gas loop and therefore tend to cancel their individual reactions. The net effect is an electrical power variation of less than 1.0 percent.

If heat loads are removed entirely, turbine inlet temperature rises over the design point by 24° C (43° F) which is within the design limits of the power system.

The same approach was taken for a gas-to-liquid heat exchanger. The corresponding curves are plotted in figure 12. Generally, gas loop temperatures in the recuperator and compressor can be kept lower, but the excursions caused by ILSS heat load variation are greater.

The only point of concern for either heat-removal method is the rise in turbine inlet temperature. This temperature could be reduced to an acceptable value by lowering the turbine inlet temperature operating point.

Since the use of a liquid-to-liquid heat exchanger showed advantages both in physical implementation and in smaller gas loop variations, a preliminary design of the heat exchanger was made. The mathematical model could then be represented by analog circuit methods and included in a real-time dynamic study on an analog computer. The same ground rules were held but the ILSS heat load profile was applied as shown in figure 13. As could be expected, the gas loop parameter variations were smaller than those seen under steady-state conditions. For example, T_1 in figure 13 represents the temperature of gas at the outlet of the recuperator. The peak-to-peak variation is 2° C (4° F). The same parameter "Gas inlet" in figure 11 shows an 8° C (15° F) variation under steady-state heat loads. The computed temperature of the ILSS water is 149° C $\pm$ 9° C (300° F $\pm$ 17° F) cyclic, as shown by T_5. This variation is acceptable and would not affect normal ILSS operation.

Perhaps one of the most significant advantages of the integration of these two systems can be realized by redefining efficiency. As can be seen from figure 8, operation with compressor inlet temperature at 47° C (117° F) rather than at the design value of 27° C (80° F) causes the overall engine conversion efficiency to drop from 29 percent to 27 percent. This efficiency figure is defined as

$$\text{Efficiency} = \frac{\text{Electrical power output}}{\text{Heat source input}}$$

By using 9.4 kWe as the electrical power output in both cases, the required heat source input at 29 percent efficiency is 32.4 kWt and 34.8 kWt at 27 percent. At the lower percentage figure, an additional 2.4 kWt must be supplied from the heat source to obtain 9.4 kWe at the alternator terminals. But, the ILSS is being supplied with 6 kWt that would have otherwise had to be furnished from some other source, such as a separate isotope process heat loop. By redefining efficiency as

$$\text{Efficiency} = \frac{\text{Electrical power out} + \text{Thermal power out}}{\text{Total heat source input}}$$

the efficiency figure becomes 44.2 percent for the integrated system and 40.2 percent unintegrated. Hence, the integration increases the overall efficiency by 4 percent.

CONCLUDING REMARKS

This integration study was performed to investigate the interaction of two major space flight systems when operated in an integrated mode and to determine the necessity of an actual integration of hardware. The integration of these two systems can be performed if (1) The Brayton power system (BPS) is operated in a slightly off-design mode and (2) the integrated life support system (ILSS) uses water at approximately 149° C (300° F) as a process heat transport fluid.

To accomplish this integration the following BPS changes would be made:

(1) A liquid-to-liquid heat exchanger would be installed in the BPS radiator loop. (Installation of a gas-to-liquid heat exchanger within the gas loop would be expensive and would result in greater BPS parametric variations and is not recommended.)

(2) The radiator fluid would be operated with an increase in operating temperature, and thus the temperature of the compressor inlet gas would be increased.

Integration creates no disadvantageous operating modes and results in an increase in overall systems efficiency. In view of the data collected in the course of this study, there are no major problems foreseen in the integration of these two systems. However, a hardware integration for further study is not justified until a specific mission is defined.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., March 19, 1971.

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TABLE I.- ILSS THERMAL LOAD REQUIREMENTS

	Average thermal load		Flow rate	
	kWt	Btu/hr	kg/sec	lb/hr
Branch 1:				
Feces dryer	0.211	720	0.005	40
Wash water heater	0.133	454	0.005	40
Branch 2:				
CO_2 concentration unit	2.619	8 930	0.0202	160
Branch 3:				
CO_2 reduction unit	-0.102	-347 (heat gain)	0.0126	100
Water recovery unit 1	1.121	3 822	0.0076	60
Water recovery unit 2	0.459	1 565	0.005	40
Food water heater	0.208	710	0.0126	100
Miscellaneous losses	1.509	5 146		
Average net thermal load on fluid:				
Heating and pumping unit	6.159	21 000		
Minimum thermal load	4.399	15 000		
Maximum thermal load	7.919	27 000		

TABLE II.- PROCESS HEAT CIRCUIT REQUIREMENTS

Parameter	Existing	Proposed
Process heat fluid	DC-331	H_2O
Fluid temperature:		
Source	204° C (400° F)	149° C (300° F)
Return	112° C (233° F)	111° C (231° F)
Fluid pressure	448 kN/m^2 (65 psia)	483 kN/m^2 (70 psia)
Fluid flow rate	0.0378 kg/sec (300 lb/hr)	0.0378 kg/sec (300 lb/hr)
Process heat load – nominal . .	6.2 kWt (21 000 Btu/hr)	6.2 kWt (21 000 Btu/hr)

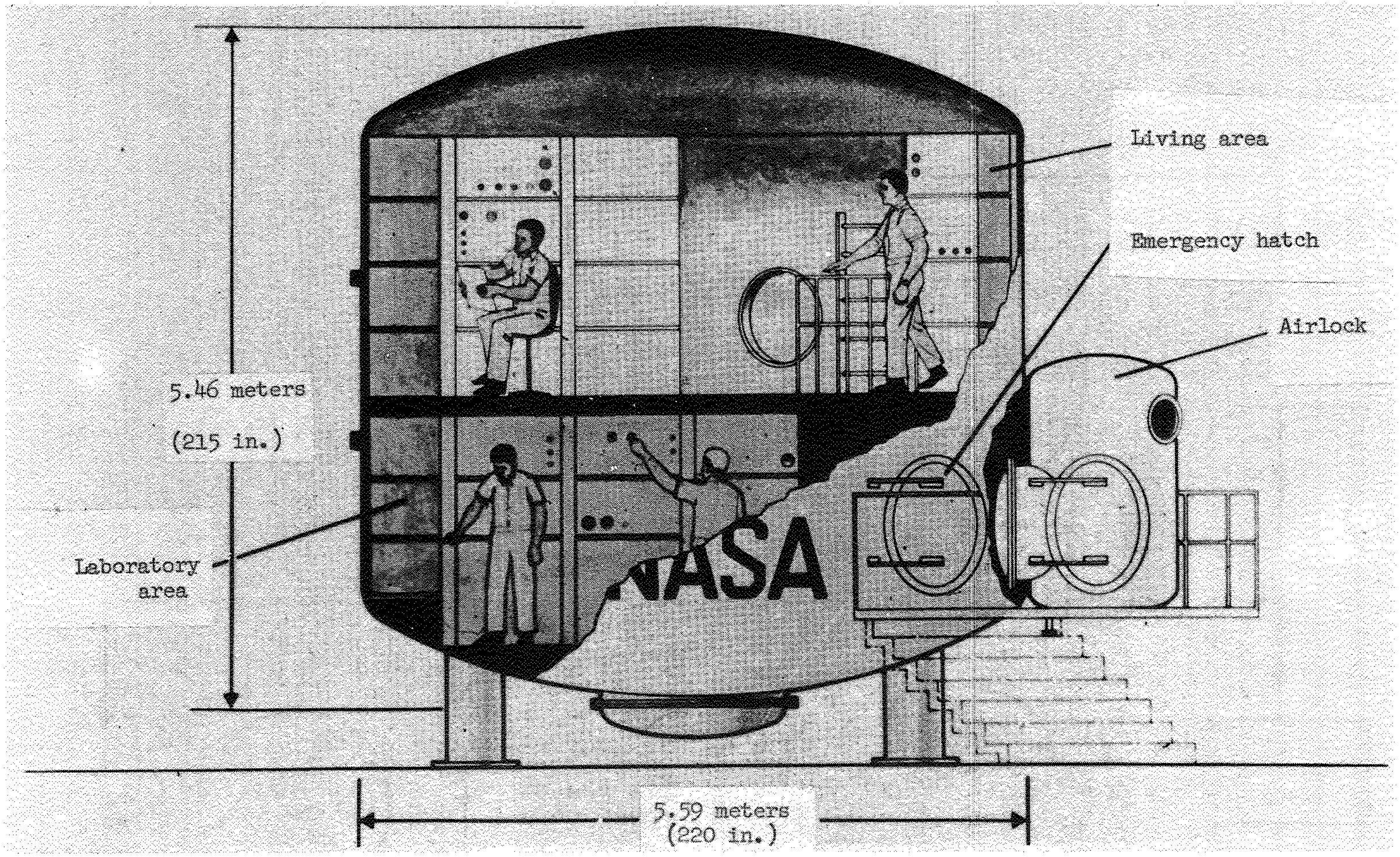

Figure 1.- Artist's concept of ILSS.

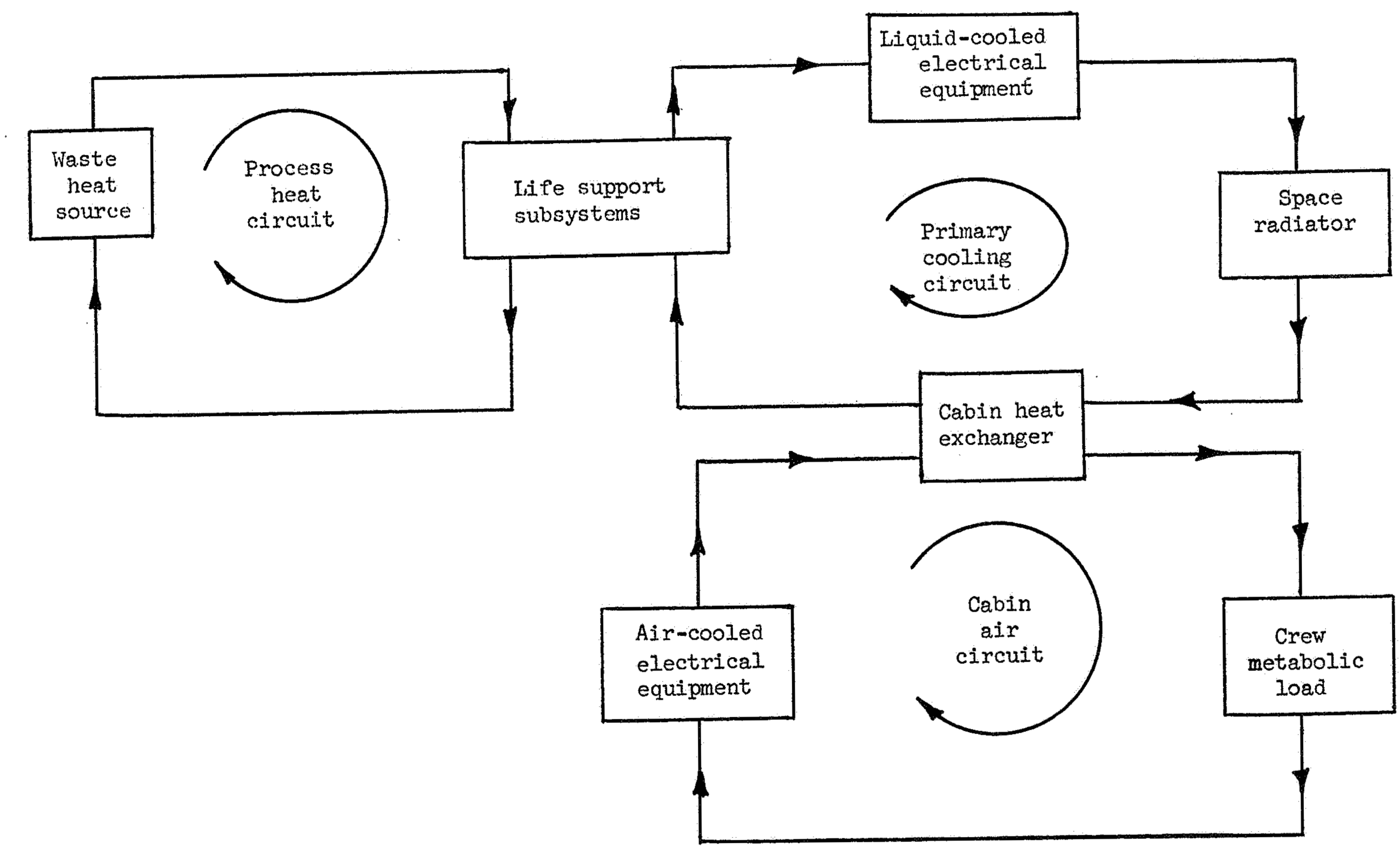

Figure 2.- Integration of thermal control circuits.

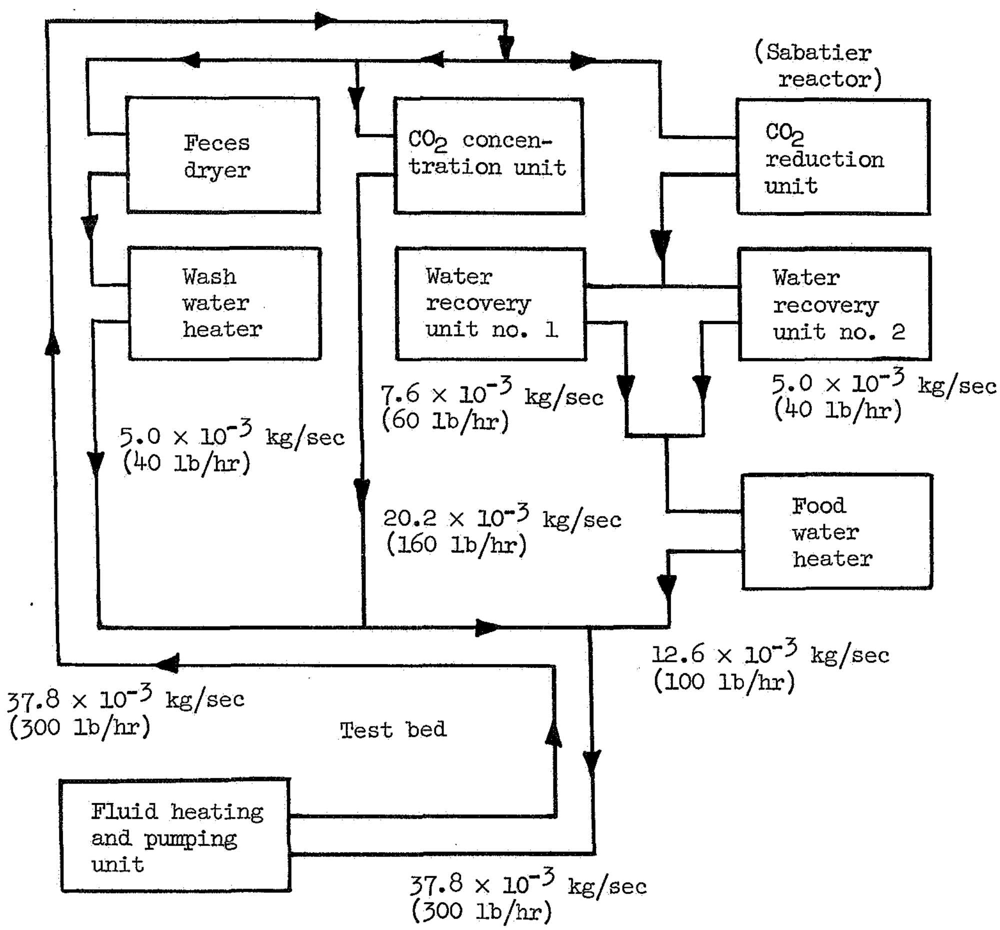

Figure 3.- ILSS process heat (DC-331) circuit flow distribution.

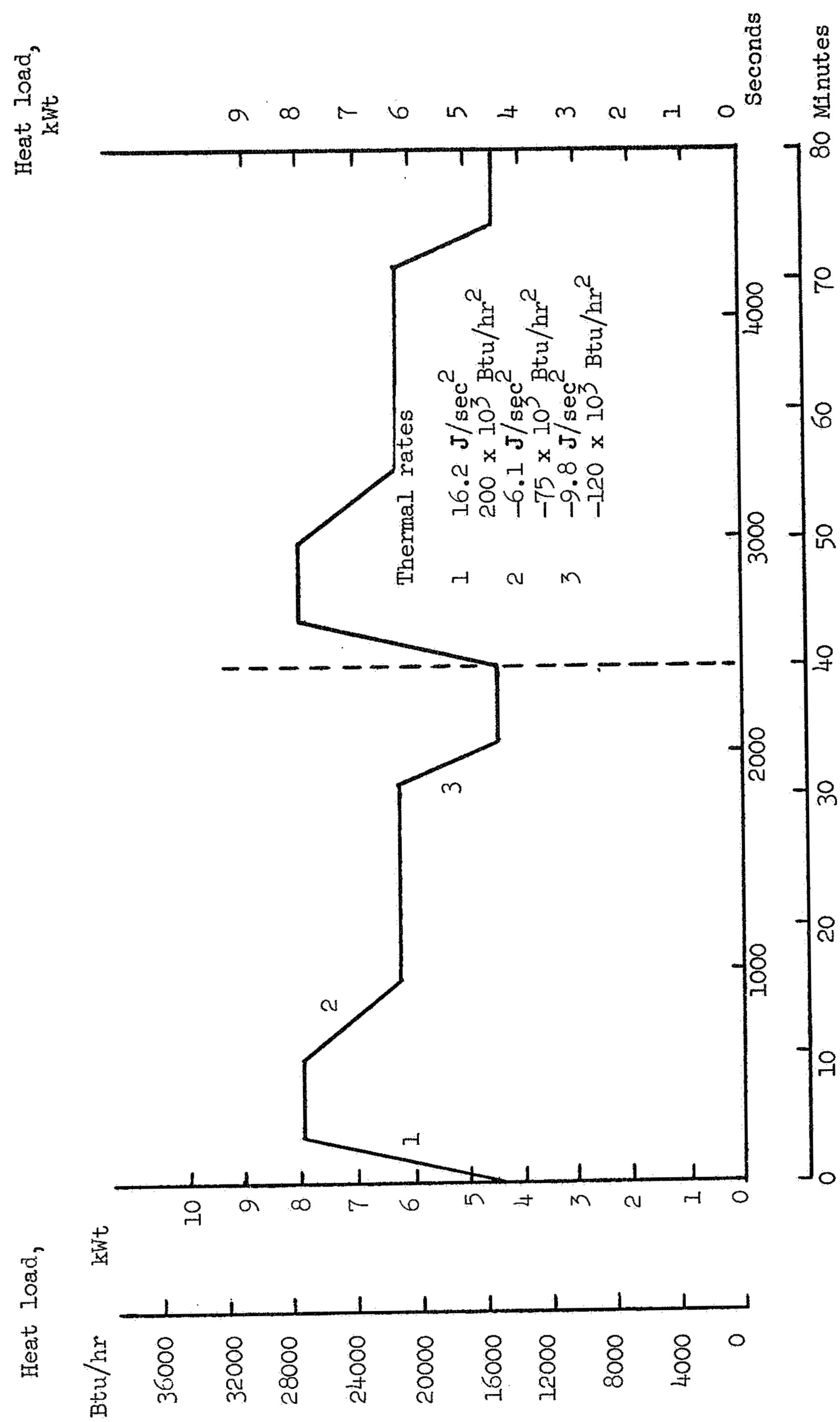

Figure 4.- Process heat load profile.

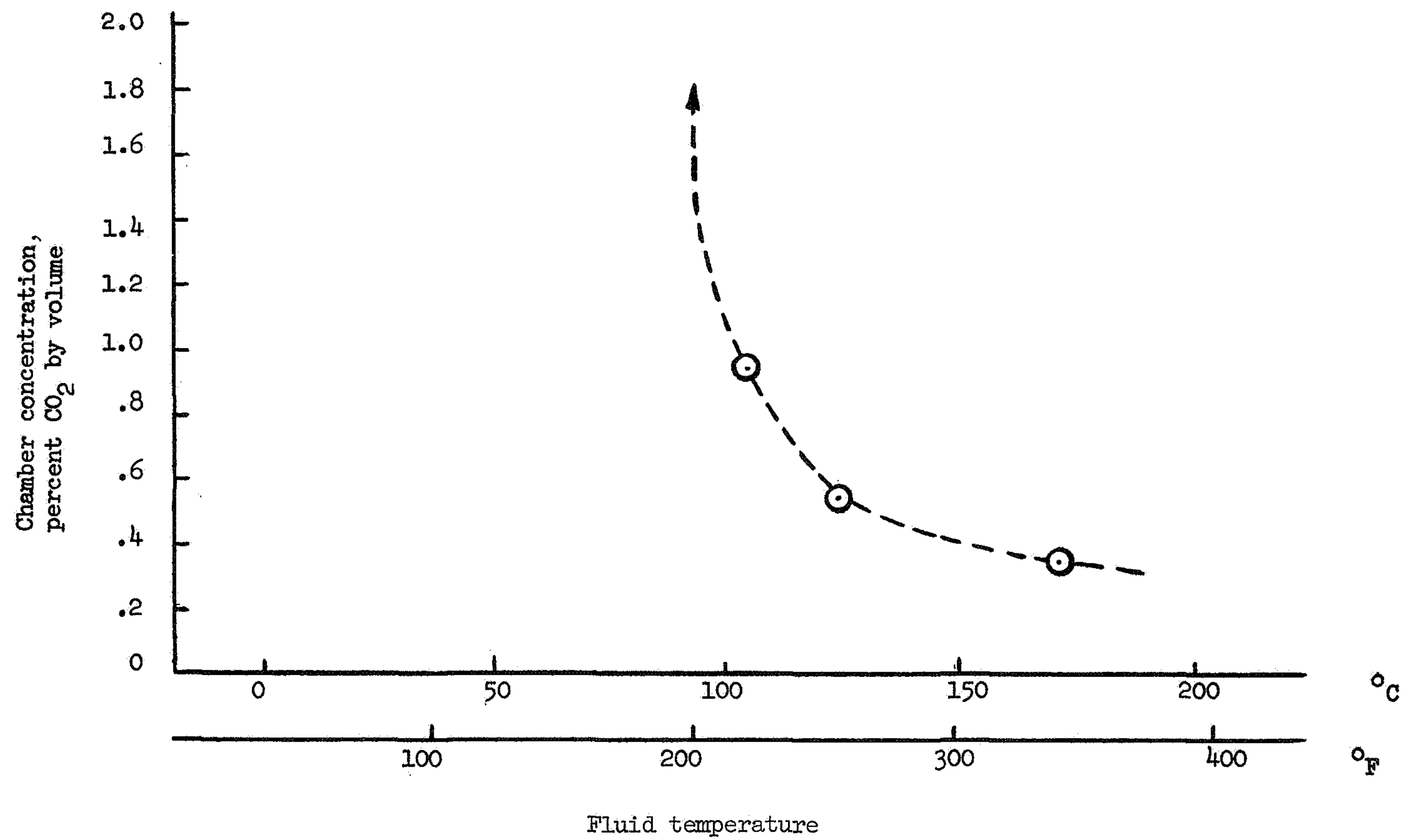

Figure 5.- ILSS chamber CO_2 concentration as a function of fluid temperature.

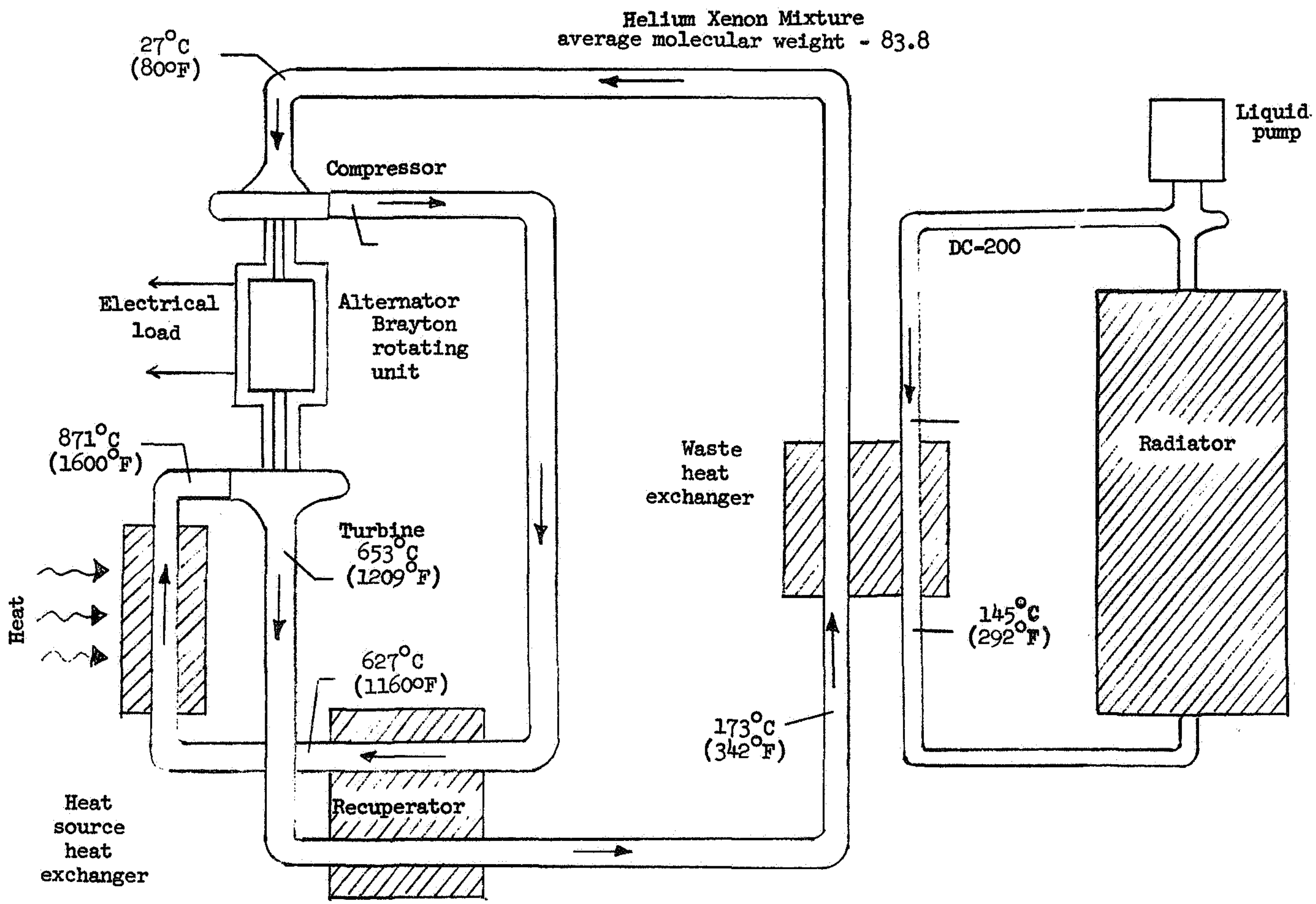

Figure 6.- Brayton power system.

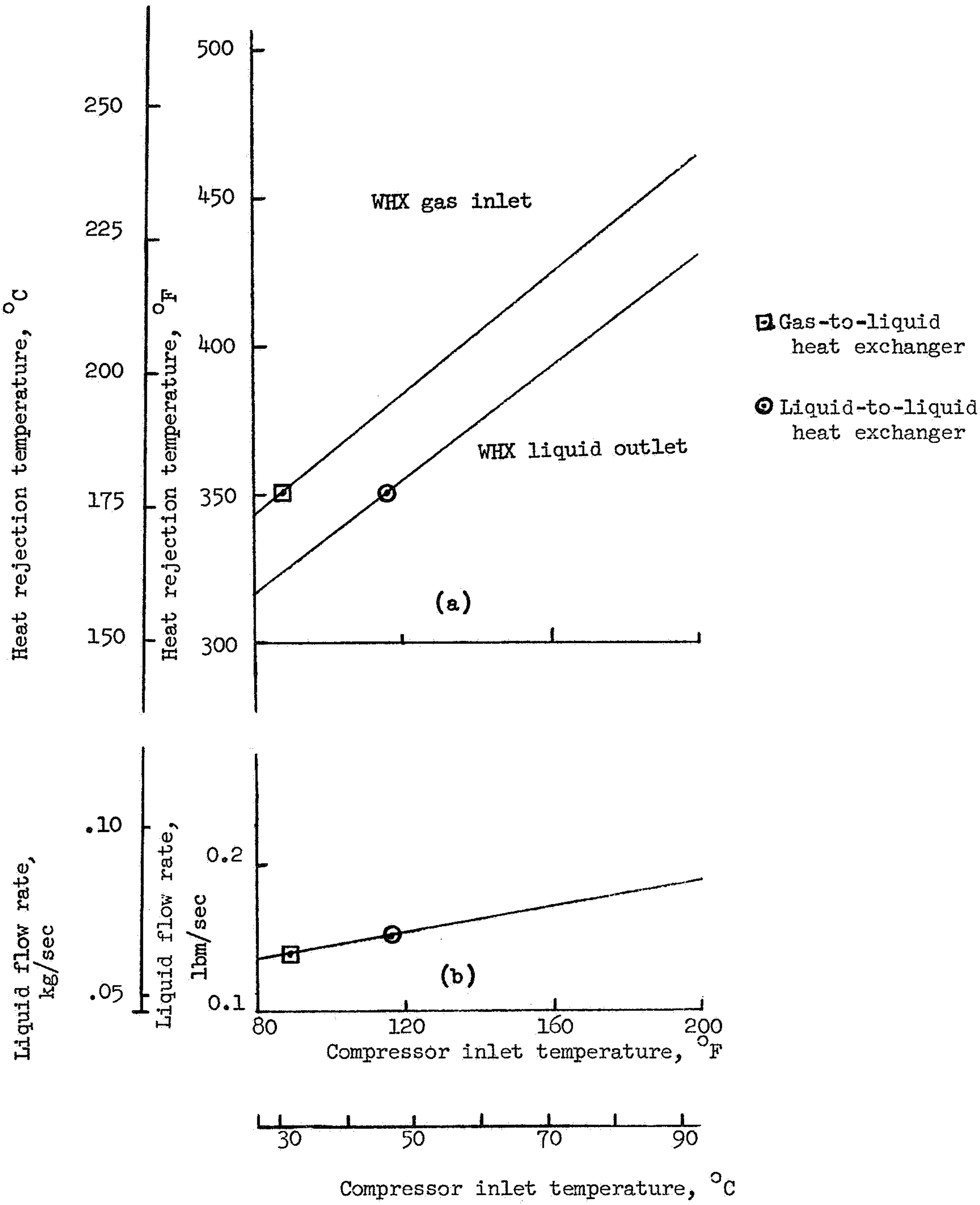

Figure 7.- Parametric Brayton power system performance. Liquid flow rate and heat rejection temperature. Constants: 9.4 kWe alternator output; 870° C (1600° F) turbine inlet temperature.

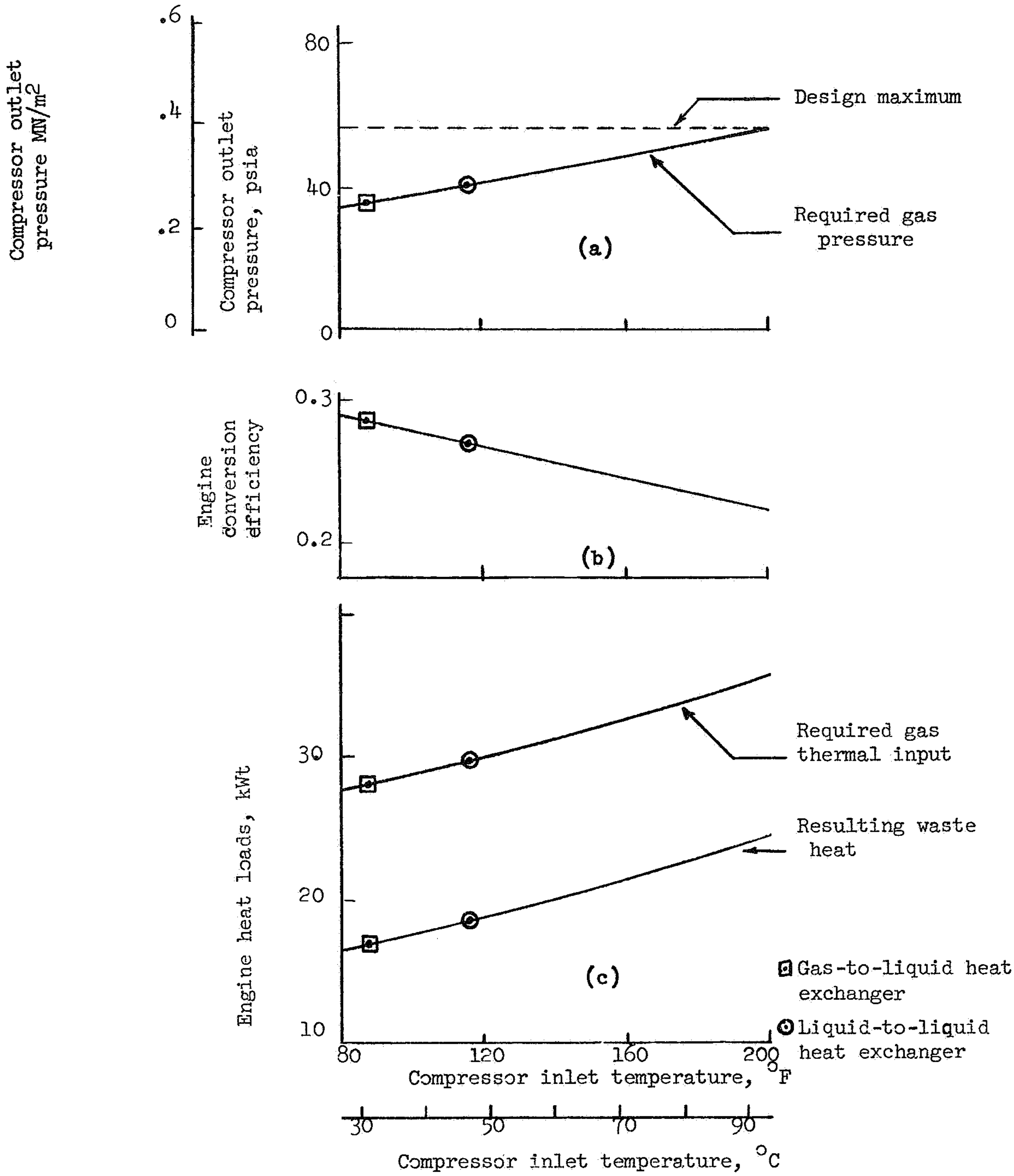

Figure 8.- Parametric Brayton power system performance. Heat loads, engine conversion efficiency and compressor outlet pressure. Constants: 9.4 kWe alternator output; 870° C (1600° F) turbine inlet temperature.

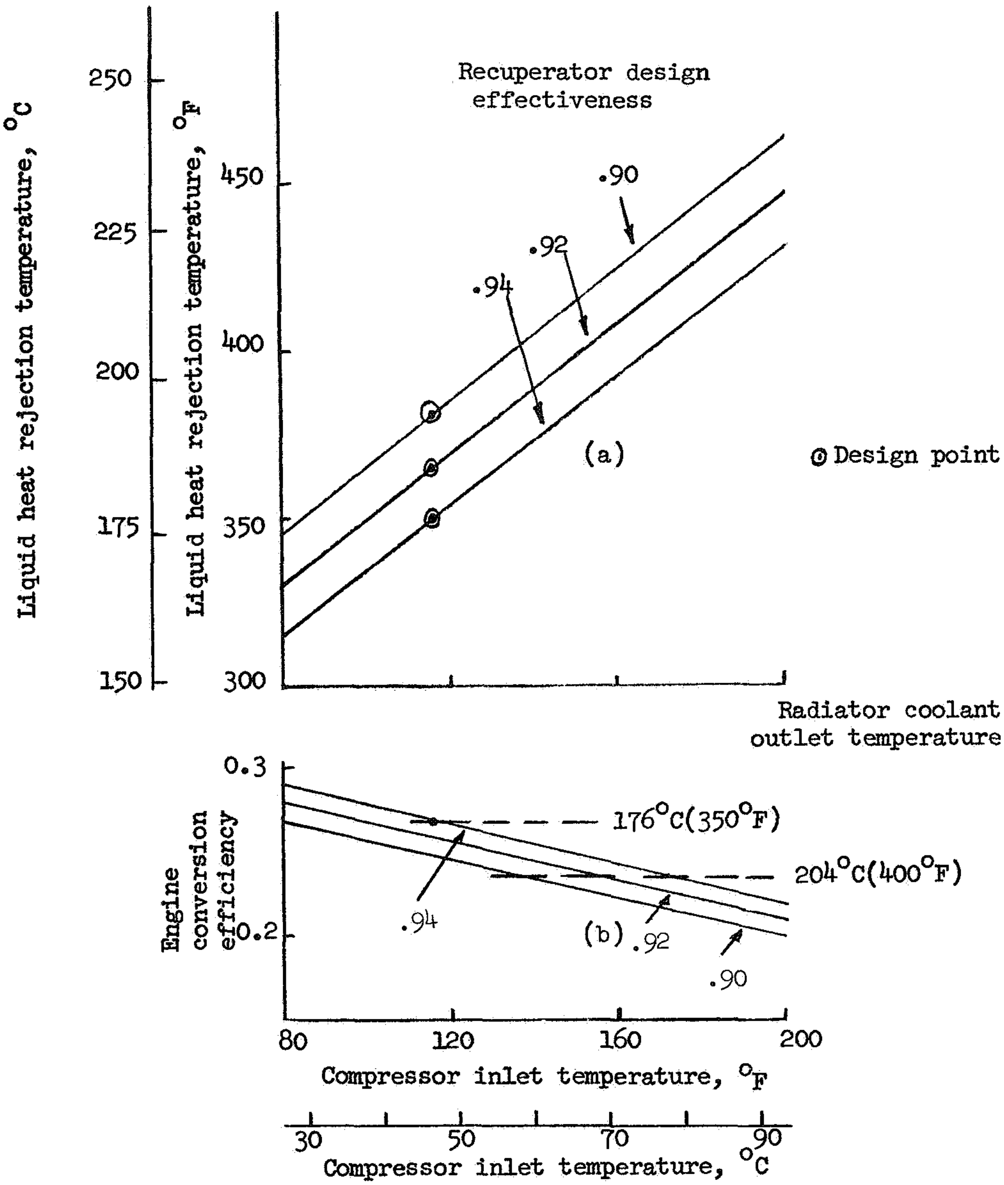

Figure 9.- Parametric Brayton power system performance. Liquid heat rejection temperature and engine conversion efficiency. Constants: 9.4 kWe alternator output; 870° C (1600° F) turbine inlet temperature.

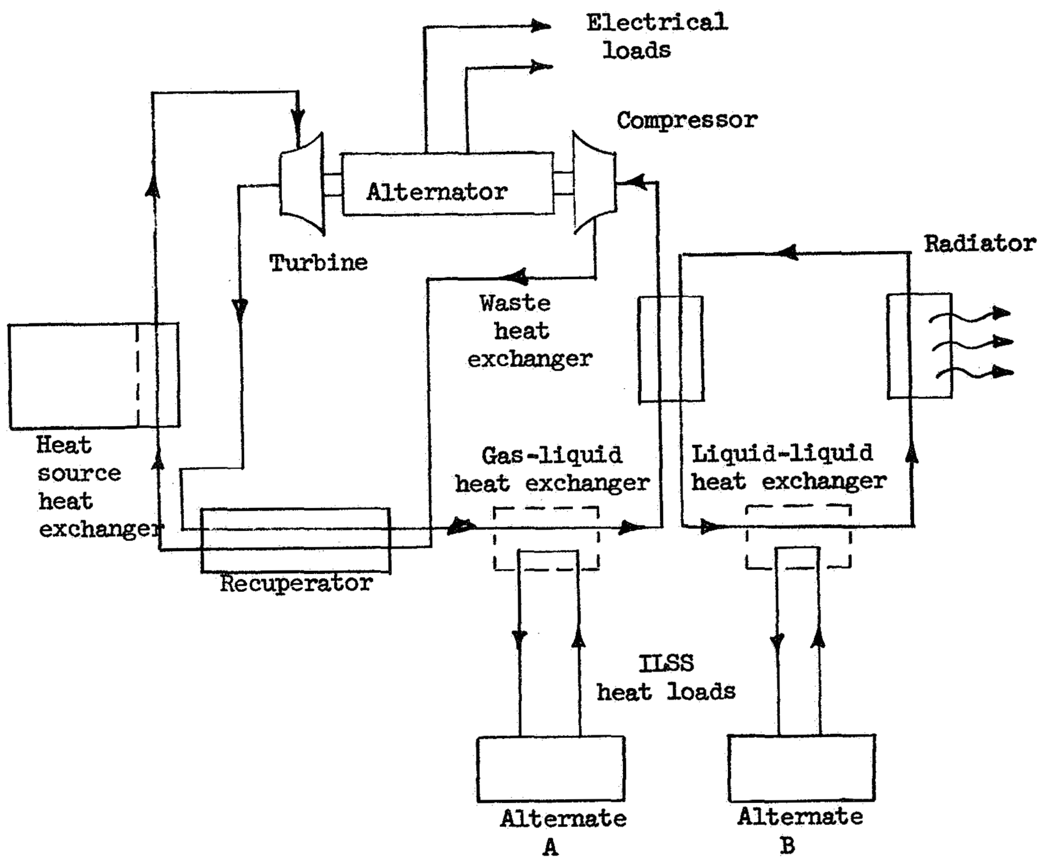

Figure 10.- System configuration for integration study.

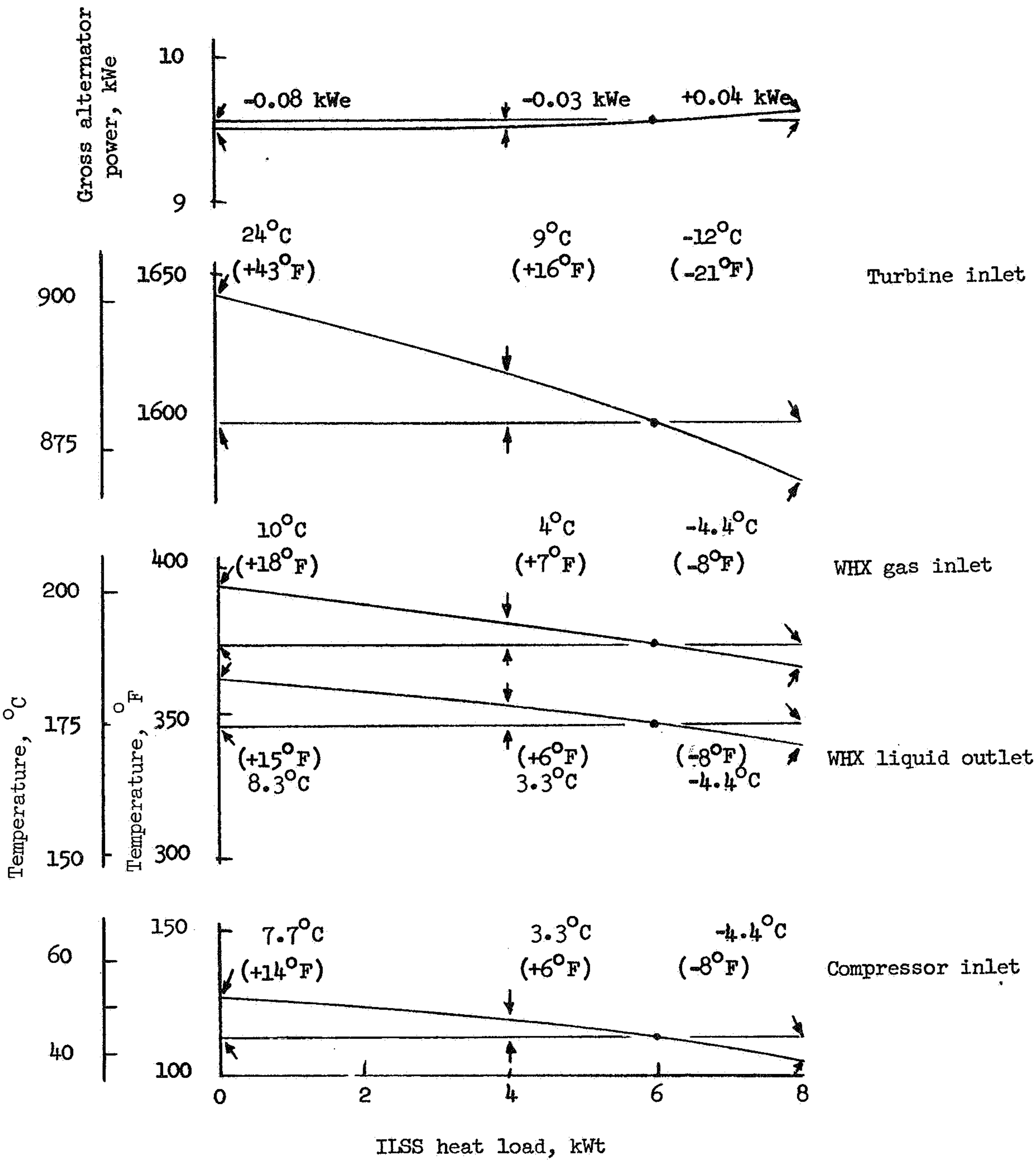

Figure 11.- Fixed Brayton power system performance. Liquid-liquid heat exchanger.

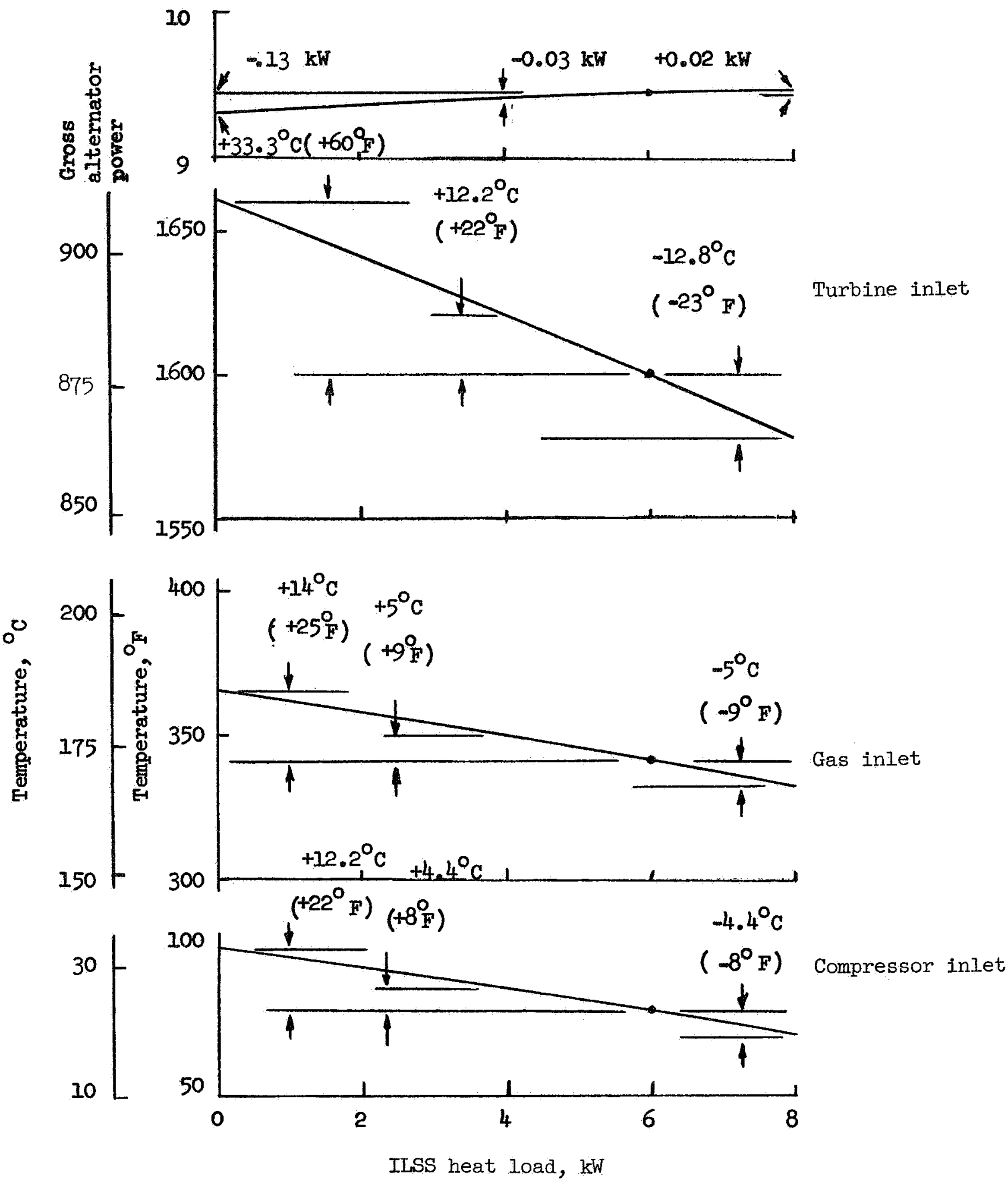

Figure 12.- Fixed Brayton power system performance. Gas-liquid heat exchanger.

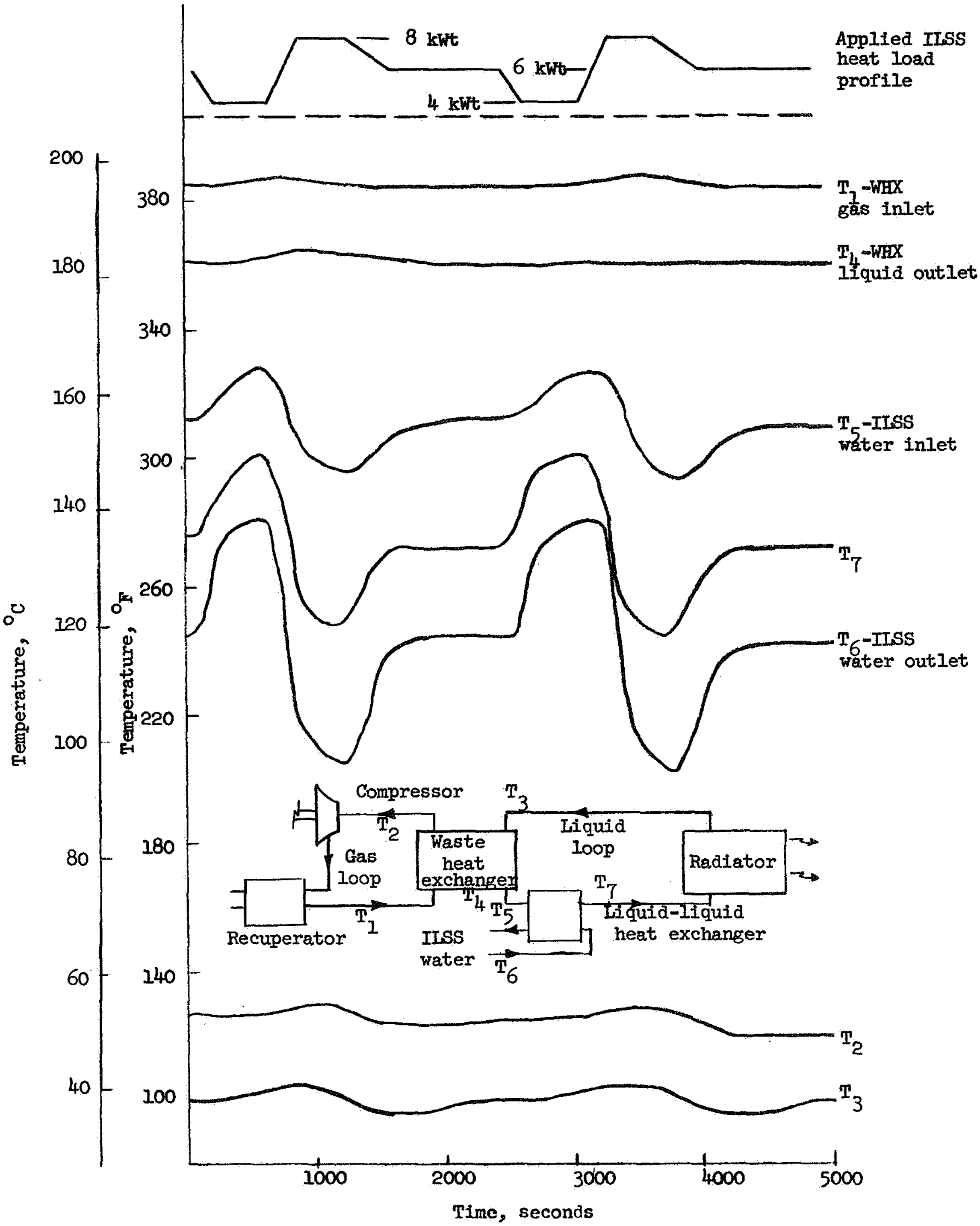

Figure 13.- Dynamic integrated system performance.

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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