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Lewis Research Center
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ABSTRACT

A SNAP-8 experimental power system was operated for 1445 hours at the Lewis Research Center over a time span of 1463 hours. Approximately 1100 hours of continuous system operation were achieved. Steady-state system performance did not degrade with time. All SNAP-8 prototype components performed satisfactorily throughout the test with the exception of the parasitic load resistor. Three automatic shutdowns occurred during the course of the test. The automatic protective system employed functioned properly. There was no oil contamination of the mercury loop as a result of the shutdowns.

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SUMMARY

A SNAP-8 experimental power system was operated for 1445 hours at the Lewis Research Center over a time span of 1463 hours. Approximately 1100 hours of continuous system operation were achieved.

During the test, the system was started three times. The third start was erratic, causing severe perturbations in the mercury loop. Large pressure, flow, and turbine-alternator speed excursions occurred and resulted in a flooded mercury boiler. The system's steady-state performance, however, was not affected.

Steady-state system operation for 1445 hours demonstrated that system performance did not degrade with time. A parasitic load resistor failure occurred after 336 hours of testing. All other SNAP-8 components performed satisfactorily throughout the test.

Three automatic shutdowns occurred during the course of the test. The automatic protective system designed for the Lewis SNAP-8 facility functioned properly and the system was shutdown without incident. In all cases, the turbine-alternator did not overspeed and slowly coasted down in speed. The shutdowns produced no oil contamination of the mercury loop.

INTRODUCTION

SNAP-8 is a Rankine-cycle system presently being developed to produce electric power for space applications. The system is designed to produce 35 kilowatts of usable electricity and incorporates a nuclear reactor as the energy source. Three liquid-metal loops are used for power generation, and an organic-fluid loop is employed for cooling and lubricating various system components.

In order to investigate the system's endurance and to obtain startup information, a SNAP-8 test facility was constructed at NASA's Lewis Research Center, Cleveland, Ohio. This facility for ground testing incorporated the principal SNAP-8 prototype components with the exception of the nuclear reactor heat source, the space radiator, mercury injection system, and start programmer. An electric heater simulated the nuclear reactor, and waste heat was removed by air-cooled heat exchangers rather than by a space radiator. The system was operated for a total of 1445 hours (1100 hr continuously). Additional time was acquired on certain SNAP-8 components as they were operated in subsystems prior to the total-system test.

Since the majority of the system testing was of an endurance nature at near-rated power, information was acquired on system degradation with time. Key system parameters are presented for the startup to illustrate system interactions during this phase of operation. During the course of the 1445-hour test, the system was subjected to several automatic shutdowns. Selected parameters are presented to illustrate system interactions as determined by the automatic shutdown sequence designed for this test facility.

Prior to this test, the Lewis SNAP-8 facility was operated with breadboard components in place of the actual SNAP-8 components (ref. 1). The purpose of this breadboard test was to work out system design problems associated with liquid metals and to acquire preliminary performance information on the reactor simulator (NaK heater) and the radiator simulator (air-cooled heat exchangers).

DESCRIPTION OF SNAP-8 TEST FACILITY

The Lewis SNAP-8 test facility consisted of prototype components, test support equipment required for ground simulation of flight conditions and system control, and various forms of instrumentation for system control and evaluation. Figure 1 is a photograph of the system showing some of the major system components. No attempt was made to assemble the components into a flight configuration since component accessibility was more desirable for a test loop of this nature.

The primary NaK (sodium-potassium eutectic) loop, mercury loop, and heat-rejection loop are presented schematically in figure 2. The organic lubricant/coolant loop is presented in figure 3. For clarity, the vacuum systems, gas systems for valve control, dumping and filling systems, and the NaK-purification system are not shown on the schematics. An automatic protective system was developed for this facility and is discussed in the appendix.

In the following description of the four loops that comprise SNAP-8, only the major components are discussed. A description of the SNAP-8 system and the function of all components may be found in reference 2.

Primary NaK Loop

The primary NaK loop consisted basically of a heater, NaK pump, and boiler. The function of this loop was to supply the energy required to vaporize the mercury flowing through the boiler. An electric heater (reactor simulator) was used as the energy source for this test in place of the SNAP-8 reactor. The heater consisted of electrical elements immersed in the NaK stream. Power to the heater (500 kW max.) was controlled by an analog computer programmed to simulate the dynamic response of the reactor (ref. 3). The NaK centrifugal pump was motor driven and utilized NaK for cooling the motor and lubricating the tilting-pad journal and thrust bearings (refs. 4 and 5). The SNAP-8 mercury boiler investigated was a tube-in-shell counterflow heat exchanger that utilized tantalum as the mercury containment material for long-term corrosion resistance (refs. 6 and 7).

Mercury Loop

Electrical power was generated by expanding mercury vapor at 1233° F (941 K) and 220 psia (1.52×10^{6} N/m^{2}) through a four-stage axial-flow turbine which was coupled to an alternator (refs. 8 and 9). A speed control which sensed alternator frequency varied the electrical load on the alternator and thus maintained the turbine-alternator at a constant speed of 12 000 rpm (ref. 10). Electrical loading that was needed for speed-control purposes was dissipated in the form of heat by the parasitic load resistor located in the primary NaK loop.

Mercury vapor leaving the turbine was returned to the liquid state in the condenser. The SNAP-8 condenser was a counterflow tube-in-tube heat exchanger that incorporated tapered mercury tubes. The mercury containment tubes were constructed of 9 chromium-1 percent molybdenum (9M) steel for corrosion resistance (ref. 11). Liquid mercury was supplied to the boiler by a centrifugal mercury pump that was motor driven (refs. 12 and 13). This pump operated on conventional oil-lubricated ball bearings and incorporated a unique shaft seal to prevent intermixing of the mercury and oil.

Heat-Rejection NaK Loop

The purpose of the heat-rejection NaK loop was to transfer waste heat from the mercury condenser to the space radiator. This was accomplished by flowing the NaK through two air-cooled heat exchangers designated radiators 1 and 2 on the schematic (fig. 2). The motor-driven NaK pump in this loop was identical to the one used in the primary NaK loop. The temperature-control valve at the condenser outlet sensed the loop temperature at this point. If the temperature was below 600° F (590 K), the valve bypassed a portion of the total NaK flow through the NaK/NaK heat exchanger shown in the primary loop schematic. Bypass flow was continued until the condenser NaK outlet temperature reached 600° F (590 K).

Lubricant/Coolant Loop

The lube/coolant loop (fig. 3) had the primary function of supplying lubricant to bearings in the turbine-alternator and mercury pump. Another function was to cool the NaK pumps and various sections of the turbine-alternator and mercury pump. The cooling and lubricating fluid selected for SNAP-8 is polyphenyl ether (4P3E). This fluid (for brevity it will be called "oil") was selected largely for its radiation resistance. The oil was passed through a heater and cooler combination to maintain a preset temperature. It was then filtered and entered a manifold from which it was distributed to the various SNAP-8 pumps and turbine-alternator. Since the affinity of 4P3E for entrapping gas greatly affects its lubricating properties, the fluid flow from all components was circulated through a degassing tank before being returned to the oil pump. From a system's standpoint, the major concern with the oil loop is the possibility of oil contamination of the mercury loop via the shaft seals in the mercury pump and turbine-alternator. Double isolation valves to and from these components were provided to minimize the possibility of oil contamination of the mercury loop (ref. 14). The performance evaluation of this subsystem is covered in detail in reference 15.

INSTRUMENTATION

Static pressures in the mercury and NaK loops were measured by inductive slack-diaphragm Bourdon-tube pressure transducers. The transducers were calibrated against a Bourdon-tube reference gage (1/4 percent accuracy). All pressure measurements were accurate to ±1 percent.

NaK flows in the primary and heat-rejection loops were measured with electromagnetic flowmeters. A venturi was used in the heat-rejection loop only. The venturi and electromagnetic flowmeter in the heat-rejection loop agreed within 1 percent. Mercury flow was measured at the boiler inlet, boiler outlet, and pump inlet by means of calibrated venturi flowmeters. Pressure drop from the venturi inlet to throat was measured with slack-diaphragm differential-pressure transducers in all cases.

Temperatures were measured by Instrument Society of America (ISA) type K (Chromel-Alumel) thermocouples. Temperatures presented in this report are accurate to ±1 percent.

Turbine and pump speeds were measured by electromagnetic reluctance probes that sensed gear teeth on the rotating shafts. The frequency signals from the probes were converted to dc voltages and read on instruments accurate to 1 percent.

Startup and endurance data presented in this report were recorded on a computerized digital data system (ref. 16) that scanned all instrumentation in less than 20 seconds per test point. This system had a capacity of 400 parameters, and recording was initiated upon command from the control room. Additional system performance data were acquired from control room recordings on strip charts and from visual display at the control panel.

Data shown for the automatic shutdown were recorded on a tape-recording system that was installed for the purpose of failure analysis. Since the amount of information that could be recorded on tape was limited to 46 channels, the majority of the data related to components rather than the overall system. Electrical data presented in this report are accurate to ±1/2 percent. A complete description of the majority of the instrumentation employed in the SNAP-8 test facility is reported in references 1 and 17.

OPERATING PROCEDURE

After completing the total system assembly, the lube/coolant loop was charged with 4P3E and the pump was started on facility (400 Hz) power. All oil-loop piping was hot flushed at 300° F (425 K) with the exception of the turbine-alternator and mercury pump bearing lines. During the hot flush, the oil was degassed by flowing it through the expansion tank which was operating at less than 5 torr (665 N/m^2) absolute pressure. This was continued until observation of the expansion tank pressure indicated that the oil had been sufficiently degassed (pressure <1 torr (135 N/m^2)). Rated oil flow was established to all components with the exception of the turbine-alternator and mercury pump bearing lines. Flow was not established in these lines until the turbine-alternator and mercury pump were started.

Prior to mercury-loop startup, the NaK loops were filled with clean NaK from the dump tank (not shown in fig. 2). After degassing the NaK pumps in both loops by a series of consecutive deadhead startups on facility power, the control valves were opened and NaK flow was established at approximately 25 000 pounds per hour (11 350 kg/hr) in each loop. The primary-loop temperature was raised to 1300° F (980 K) at a rate of 100 F degrees (55 K deg) per hour by means of the NaK heater. Line heaters on the heat-rejection loop piping were used to raise this loop temperature to 600° F (590 K) at a rate of 100 F degrees (55 K deg) per hour. The NaK loops were maintained at the above temperatures for a minimum of 4 hours and then hot dumped into the NaK dump tank. The NaK was allowed to cool to approximately 100° F (310 K) and was then recharged into the system and brought up to temperature again. The liquid metal was then checked for oxide content by flowing it through an oxide control loop (ref. 1). This completed one hot-flush cycle.

After completing three hot flushes and verifying that the oxide level in the NaK was less than 20 ppm, preparations were made for mercury loop startup and mercury injection into the boiler. At this time the primary loop was at 1300° F (980 K), the heat-rejection loop at 600° F (590 K), and flow was set at 25 000 pounds per hour (11 350 kg/hr) in both loops. A mercury pump bypass loop was established as follows:

(1) Boiler inlet control valve closed
(2) Condenser outlet valve closed
(3) Mercury pump inlet valve closed
(4) Mercury pump bypass line control valve 5 percent open
(5) Mercury flow control valve (pump outlet) driven to the full open position
(6) Mercury standpipe valve open

Liquid mercury was then injected into the system upstream of the mercury pump inlet valve. Enough mercury was injected to fill the mercury standpipe and the piping between the boiler inlet and condenser outlet valves. The mercury pump was started dry on 400-hertz facility power. This was done to prevent mercury leakage across the dynamic shaft seals into the lubricant-coolant loop. Once the pump was at rated speed (approx. 7800 rpm), the following steps were taken:

(1) Adjusted gas pressure on the mercury standpipe to achieve the required pump net positive suction head
(2) Opened pump inlet valve to establish flow through the mercury loop bypass
(3) Adjusted bypass line control valve to achieve 11 000-pound per hour (5000-kg/hr) mercury flow
(4) Mercury required to fill the pump void added as needed from the standpipe

After verifying that the mercury pump was functioning properly, the primary and heat-rejection loop NaK flows were raised to 48 000 pounds per hour (21 800 kg/hr) and 40 000 pounds per hour (18 150 kg/hr), respectively.

Mercury injection into the boiler was then accomplished by cracking the boiler inlet control valve and fully opening the condenser outlet valve. The low mercury flow (<500 lb/hr (230 kg/hr)) into the boiler was maintained until the vapor temperature at the turbine inlet reached 1000° F (810 K). The boiler inlet control valve was then adjusted for a mercury flow of 6000 pounds per hour (2700 kg/hr), and the mercury pump bypass valve was fully closed. The 6000-pound per hour (2700-kg/hr) mercury flow rate resulted in turbine rotation and sufficient alternator power output to the speed control for safe operation (approx. 8 kW).

During mercury injection and turbine-alternator start, the heat input into the primary loop was adjusted to maintain the NaK inlet temperature to the boiler at 1300° F (980 K). The mercury condensing pressure was maintained at 17 psia (1.17×10^5 N/m^2) or less by adjusting the cooling airflow to the heat exchangers in the heat-rejection loop.

After verifying that all system loops were operating properly, the system power level was increased in step-wise manner until maximum conditions were achieved (alternator power out $\approx$ 45 kW). At each power step the boiler temperature profile and mercury vapor quality were checked for proper performance before proceeding to the next step (ref. 7). After reaching maximum alternator power output, the SNAP-8 system pumps were transferred from facility power to alternator power.

The system was maintained at steady-state operating conditions for the majority of the test. Periodic manual adjustments of the various loops were required to maintain steady conditions.

In the event of a planned system shutdown the following chronological order of loop shutdown was established:

(1) Mercury loop

(2) Both NaK loops (any order)

(3) Lube/coolant loop

The NaK and lube/coolant loops presented no shutdown problems since only interruption of electric power to the heater and pumps was required. The mercury loop shutdown, however, was of major concern since improper procedures could result in turbine-alternator overspeed and/or oil contamination of the mercury loop. General operating procedure called for a reduction in loop flow prior to an automatic shutdown of the mercury loop via the automatic protective system (see appendix). This was followed by manual shutdown of the remaining system loops.

RESULTS AND DISCUSSION

The SNAP-8 experimental system was operated for 1445 hours over a total time span of 1463 hours. A total of 1100 hours of continuous operation were achieved on the system. Table I is a listing of all SNAP-8 components used during the test. The table presents total operating time on the components up to the completion of the test and the number of startups on the components where applicable. Total operating times differ since some components were operated as parts of subsystems prior to the start of the overall system test.

During the course of testing, three automatic shutdowns occurred. A shutdown of the mercury loop was initiated 11 hours after startup due to a false alternator trip signal. The second shutdown occurred after approximately 363 hours of testing. This shutdown was due to an accidental manual tripping of a circuit breaker that interrupted all power to the control room. The power interruption initiated an automatic shutdown of all the systems (mercury loop, NaK loops, oil loop, vacuum pumps, etc.). The third automatic shutdown (mercury loop only) occurred at the 1445-hour point as system flow was being reduced in preparation for a manual shutdown. This shutdown was again due to a false trip signal. In all cases the turbine-alternator did not overspeed and slowly coasted down in speed. Mercury samples taken after each shutdown at various points in the mercury loop showed no evidence of oil contamination either from vacuum pumps or from the lube/coolant system.

The SNAP-8 system is designed for a gross output of 60 kilowatts. This output is obtained at a design mercury flow rate through the turbine of 11 800 pounds per hour (5350 kg/hr). Due to a voltage limitation on the NaK heater control in the primary loop, the heat input to the boiler was limited to approximately 475 kilowatts. As a result the mercury flow was limited to approximately 10 500 pounds per hour (4760 kg/hr). The alternator output at this flow rate was about 45 kilowatts, a value approximately 8 kilowatts less than expected for this mercury flow rate as the result of oversize first-stage turbine inlet nozzles.

After 336 hours of testing, an electrical short developed in one phase of the parasitic-load resistor. This was caused by a NaK leak in one of the electrical elements. From this time, a backup parasitic load (load bank) was used in the speed control circuit. These loads were switched without interruption in system operation. Since the SNAP-8 parasitic load resistor added heat to the primary NaK loop, the available energy to the boiler was further limited.

The system test was terminated because of a mercury leak that developed at a weld in facility piping between the boiler and turbine. Because the leak was not in SNAP-8 equipment, the system was operated for a considerable length of time with the leak. At the 1440-hour point, the leak rate had become excessive and system flows were reduced in preparation for shutdown. An automatic shutdown of the mercury loop occurred at the 1445-hour point.

System Startup

Approximately 3 hours after the accidental system shutdown at the 363-hour point, the third system startup was performed. This startup is presented since data were not taken continuously on the first two startups. The startup was accomplished manually. Both NaK loops and the lube/coolant loop were restarted. A mercury loop prestart checkout was performed, and the mercury pump was started. When the mercury pump bypass loop flow reached 6700 pounds per hour (3040 kg/hr) the boiler inlet valve started to pass mercury at a rate that supported turbine-alternator rotation. As a result, a premature startup was initiated. The boiler inlet valve was then opened, but 30 to 40 seconds elapsed before data acquisition began. The time history of the startup is presented in figures 4 and 5. The unplanned nature of the startup resulted in illogical operation of the system and the imposition of widely varying and severe conditions on the power system. The startup is described, not to present how the system should be started, but rather to show the tolerance of the power system to large perturbations in flow, pressure, and temperature.

The data show that during the first 60 seconds, the NaK heater power was gradually increased from approximately 57 to 150 kilowatts. An increase in boiler mercury outlet temperature, accompanied by a decrease in boiler NaK outlet temperature was indicative of some mercury flow. This flow is evident from the steep rise in turbine inlet temperature.

From 80 to 140 seconds, the mercury flow rate into the boiler was increased to approximately 4500 pounds per hour (2040 kg/hr). The effectiveness of the mercury boiler is evident from the sharp increase in mercury outlet quality and the continued increase in boiler-outlet mercury temperature. At 100 seconds the boiler began transferring heat from the NaK into the mercury faster than the established mercury flow rate could remove it. The result was a decrease in the boiler mercury inventory. At 120 seconds the mercury pump suction pressure had fallen from 15 psia (1.03×10^5 N/m^2) to approximately 2 psia (1.38×10^4 N/m^2). The pump inlet pressure remained at this level until 200 seconds.

The alternator reached 400 hertz at 140 seconds, but when the mercury flow dropped at 160 seconds, the alternator frequency decreased to 150 hertz. The indicated mercury flow of approximately 2000 pounds per hour (910 kg/hr) is believed to be high because of inaccuracies in the mercury venturi calibration at very low flows. The boiler inventory dropped to a calculated minimum value of approximately 4 pounds (1.8 kg).

The low mercury pump suction pressure and the increasing condenser outlet pressure led to the discovery that the condenser outlet valve had been left closed. This valve was immediately opened (at 200 sec) as seen in the condenser inventory curve, resulting in a sudden transfer of mercury from the condenser to the boiler. The indicated 11 800-pound per hour (5350-kg/hr) mercury flow rate may be several thousand pounds per hour below actual maximum due to the large surge. Pressures were similarly affected. The high effectiveness of the mercury boiler is again demonstrated, since the sharp increase in mercury flow rate resulted in only a 1-percent decrease in quality. At 220 seconds the alternator frequency reached 400 hertz.

From 200 to 400 seconds the mercury flow was set at 5000 to 5500 pounds per hour (2270 to 2500 kg/hr), and the NaK heater power was stepped up to 250 kilowatts. The boiler mercury quality remained above 90 percent. The condenser inventory decreased to its minimum of 15 to 20 pounds (6.8 to 9.1 kg), and the condenser inlet quality stabilized at approximately 90 percent. System pressures reached equilibrium for this flow condition but the temperature was still attempting to reach equilibrium. The turbine inlet temperature was increasing although the boiler mercury outlet temperature had stabilized. The effectiveness of the condenser is demonstrated by the proximity of the curves for condenser mercury outlet temperature and condenser NaK inlet temperature. The condenser NaK outlet temperature and turbine discharge temperature (also the condenser mercury inlet temperature) are similarly close. The condenser mercury outlet temperature is slightly lower than the NaK inlet temperature because the area where the mercury temperature was measured had been left uninsulated.

From 420 to 660 seconds the mercury liquid flow rate was slowly raised to 6200 pounds per hour (2820 kg/hr) with an associated increase in NaK heater power and decrease in boiler NaK outlet temperature. The turbine inlet temperature reached 1110° F (870 K) by 660 seconds. During the entire startup the primary NaK flow rate was approximately 47 000 pounds per hour (21 300 kg/hr) and the heat-rejection loop flow rate was approximately 32 000 pounds per hour (14 500 kg/hr). A constant boiler NaK inlet temperature of 1300° F (980 K) was maintained by controlling the power to the NaK heater.

The curves show the high effectiveness of both the boiler and condenser. The boiler was able to produce high quality vapor with superheat almost immediately and the condenser performed as a highly effective counterflow heat exchanger. The condenser temperatures never stabilized over the time interval of the startup, because the airflow through the radiators was continually being adjusted.

Steady-State Operation

Figure 6 presents plots of selected loop pressures, and mercury flow rates as a function of time. All data shown were recorded at approximately the same time of the day so that there is a 23- to 25-hour time interval between consecutive data points.

The general trend of the curves illustrates that mercury loop operation was steady from the 18th day through the 60th day of testing. During the first 17 days loop conditions were being adjusted, and this is reflected in the data for this period. On the 17th day an accidental shutdown of the entire system occurred. The system was restarted within 4 hours with no apparent change in performance with the exception of the boiler. On the 61st day, the mercury flow rate was cut back in preparation for shutdown, and the data reflect this cutback.

The pressure drop across the mercury flow control valve for a constant mercury flow is a direct indication of mercury loop degradation over the 1445-hour test. Factors affecting the flow control valve pressure drop are boiler and turbine pressure drop, changes in system fixed valve characteristics, piping erosion, etc. It is presented in the form of inlet and outlet pressure rather than ΔP since the absolute pressures give a better indication of how steadily the loop was operating. Inlet pressure to the valve is essentially pump outlet pressure and the valve outlet pressure is essentially boiler inlet pressure. On the 20th day the valve ΔP was 153.6 psi (1.06×10^{6} N/m^2) for 10 473-

pounds per hour (4750-kg/hr) mercury liquid flow. On the 58th day the valve ΔP was 139.7 psi (0.963×10^{6} N/m^{2}) for a flow of 10 115 pounds per hour (4590 kg/hr). Since the pressure drop should change as the square of the flow change, it can be concluded that the valve pressure drop was consistent with the flow variation and the loop performance was unchanged over this time span.

Since the flow control valve inlet pressure was constant for a constant mercury flow, the head characteristic of the mercury pump can be concluded to have been unaffected by the endurance run. Minor variations in pump outlet pressure are attributed to fluctuations of mercury pump inlet pressure.

A mercury leak in the piping between the boiler and turbine occurred early in the test due to a weld flaw. This mercury loss reduced the condenser inventory and lowered the mercury pump inlet pressure. The leak became progressively worse during the course of the test and mercury additions at the pump inlet became frequent in order to maintain proper mercury inventory in the condenser. Pump inlet pressure became erratic from the 31st day on due to mercury additions. The mercury leak was the reason for shutdown at the 1445-hour point.

During the first 17 days of testing the boiler pressure drop for 10 000-pound per hour (4550-kg/hr) mercury flow was higher than it was for the balance of the test. An accidental shutdown and dump of the mercury loop occurred on the 17th day. Prior to the shutdown the boiler was operating with proper mercury inventory. The mercury loop startup that followed the shutdown was erratic and as a result too much mercury was injected into the boiler. This caused the boiler to operate in a flooded condition which resulted in less pressure drop. Attempts to reduce boiler mercury inventory by reducing flow conditions were unsuccessful (ref. 7), and it was decided to continue operation rather than risk the consequences of complete mercury loop shutdown and dump (i.e., possible oil contamination of the mercury loop).

Temperatures plotted in figure 7 illustrate the thermal stability of the system. A comparison of these temperatures to the pressures presented in figure 6 demonstrate the fact that the system performance remained unchanged throughout the run.

The boiler NaK inlet and boiler mercury outlet temperature plots demonstrate the constant and extremely good heat-transfer performance of the boiler. The difference between these two temperatures for a given data point (Terminal Temperature Difference) varied from 8 to 17 F degrees (4 to 9 K deg) throughout the run. It should also be noted that the operation of the boiler in a flooded condition following the accidental shutdown had no effect on either the boiler mercury outlet temperature or the Terminal Temperature Difference.

The condenser mercury inlet and NaK outlet temperature plots demonstrate the good heat-transfer characteristic of this component. Differences between these temperatures ranged from 30 F degrees (17 K deg) to less than 10 F degrees (5 K deg) from the 11th day on. Before this, larger differences can be attributed in part to slightly larger mercury and heat-rejection loop NaK flows. Also the higher condenser mercury inlet pressure would have an effect on the mercury side heat-transfer coefficient of the condenser due to the higher vapor density.

Large dips in the temperature plots were due to manual changes of system operating conditions such as those occurring on the 30th day due to boiler mapping and on the 60th, 61st, and 62nd days just prior to shutdown.

Data plotted in figure 8 demonstrate system power and efficiency. The electric heater (system input) power and alternator output power were constant for the majority of the endurance test. The ratio of alternator power to heater power has been plotted as an overall system efficiency. This efficiency ranged from 9 to 10 percent and did not degrade with time. A problem existed with the alternator power instrumentation prior to the 9th day of testing, and as a result no data points are shown for the first 8 days of operation.

CONCLUDING REMARKS

The operation of a SNAP-8 experimental power conversion system yielded the following results:

1. The SNAP-8 system was operated successfully for 1445 hours. Throughout the test, only minor system control adjustments were required. With the exception of the parasitic load failure, the SNAP-8 components performed without incident. The automatic shutdowns and mercury leak encountered during operation were due to problems with test support equipment.

2. Overall system performance did not degrade with time. During the 1445 hours of testing the overall system gross efficiency ranged from 9 to 10 percent.

3. Three system startups were made. The third start, which resulted in severe pressure and flow perturbations in the mercury loop, demonstrated the self-stabilizing characteristics of the system.

4. The third startup resulted in a flooded boiler but overall boiler performance was unaffected.

5. The three automatic shutdowns demonstrated that proper operation of the lube/coolant isolation valves, and lift-off seals on the turbine-alternator and mercury pump can prevent oil contamination of the mercury loop.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 31, 1968,
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APPENDIX -.AUTOMATIC PROTECTIVE SYSTEM

Since the SNAP-8 system is extremely complex, single component failures could result in a chain reaction of failures if not properly detected. The need for test support equipment (additional valves, vacuum pumps, etc.) adds greatly to the problem. For this reason an automatic protective system was incorporated. Examination of the lube/coolant loop and both NaK loops showed that they were self-protecting. A component failure in these loops would not cause damage to the loops themselves. However, the loss of any one of these subsystems would seriously affect the operation of the mercury loop and its components if proper corrective actions were not taken in time. For example, the loss of primary NaK loop flow or the loss of the NaK heater would result in the loss of heat input to the mercury boiler. This, in turn, would cause a turbine-alternator shutdown and injection of liquid mercury into the turbine, resulting in severe thermal shock. Loss of lube/coolant loop flow will result in the loss of cooling and bearing lubrication in the turbine alternator and system pumps. This could lead to overheated turbine alternator and pump windings and bearing seizure if not detected in time. Loss of heat-rejection loop NaK flow will result in loss of condenser cooling and subsequent rise in condenser pressure. Rupture of the condenser could occur.

The parameters selected for the automatic protective system appear on the automatic shutdown function chart (fig. 9). These parameters are referred to as "fault signals." The majority of the fault signals result in an automatic shutdown of the mercury loop.

The mercury loop shutdown is sequenced by timers and relays operating on control panel power (28 V dc). In the event that control panel power is lost, all valves, relays, etc., go to "fail safe" positions and a complete system shutdown results. The shutdown is instantaneous, however, since all timers are lost.

The mercury loop shutdown and dump is started by the opening of the mercury pump contactor which disconnects power to the pump. The opened contactor, in turn, activates a number of relays simultaneously. These relays close valves at the pump and boiler inlets and open four mercury dump valves. These valve actions accomplish the following:

(1) Prevent mercury flow into the boiler

(2) Isolate the mercury pump from the mercury loop static pressure head

(3) Start a mercury dump which rapidly depletes the boiler and condenser inventories

In addition to the above, the mercury pump "lift-off seal" is vented (engaging the seal); the lube/coolant inlet valves to the pump bearings are closed; any system pumps not shut down are switched from turbine-alternator to facility 400-hertz power; and the space seal vacuum system transfers from the "running" to the "shutdown" mode which increases its capability of handling large quantities of lube/coolant fluid and mercury leakage.

Two events occur in the final phase of the mercury loop shutdown and each is dependent upon the success of actions just discussed.

(1) After all four dump valves have successfully opened, the alternator field voltage is removed allowing the alternator to slowly coast down in speed. The slow operating times of the dump valves allow sufficient time to deplete the boiler energy before removing the alternator field.

(2) The lube/coolant outlet valves from the mercury pump bearings close 3 seconds after the inlet valves to allow the slingers in the mercury pump to purge the bearings of as much oil as possible. The timers are activated by the closing of the inlet valves.

As noted on the shutdown function chart (fig. 9), alternator field voltage removal results in loss of a voltage and frequency monitor which senses all parameters designated on the schematic by an asterisk. As a result all fault signals designated by the asterisk will trip and all corrective actions listed will occur (turbine-alternator oil valves closed, turbine-alternator lift-off seal vented, etc.).

The remaining fault signals listed in figure 9 are self-explanatory. Those signals that do not lead to mercury loop shutdown all result in alarm panel indications so that appropriate action can be taken by operating personnel.

To assist in evaluating component and system performance just prior to and following an automatic shutdown, a 14-track magnetic tape recorder and a FM multiplexing system were employed. A total of 46 key system parameters were recorded in analog form. The data may be played back at a later date and displayed on a recording oscillograph or pen recorder.

Traces of selected parameters for the automatic shutdown at the 1445-hour point are presented in figure 10. This shutdown affected the mercury loop only. The NaK loops and lube/coolant loop functioned normally during and after the mercury loop shutdown and dump. All traces in figure 10 begin 8 seconds before shutdown. The four traces in figure 10(a) end 112 seconds after the mercury pump shutdown, which is the first step in the mercury loop trip sequence. The two traces in figure 10(b) end approximately 57 minutes after the mercury pump shutdown.

As shown in figure 10(a), the mercury pump speed drops from 7900 rpm to zero in about 6 seconds. Although not shown on a trace, the lube/coolant flow to the mercury pump bearings was shut off immediately following mercury pump cutoff. The oil flow dropped from 830 pounds per hour (372 kg/hr) to zero within 1 second. The trace of the boiler mercury outlet pressure starts to fall off about 1 second after shutdown, indicating that the mercury dump valves functioned properly. The turbine-alternator lube/coolant flow trace indicates shutoff at 1 second after the start of the automatic trip. This verifies that all dump valves went full open and that alternator field removal was successful.

The turbine-alternator speed trace is obtained from a speed pickup sensing shaft rotation. The turbine-alternator speed dropped slowly over a time span of approximately 110 seconds.

The boiler mercury outlet temperature trace presented in figure 10(b) illustrates that mercury loop cool down was gradual. One hour following the shutdown the boiler outlet temperature had dropped to only 750° F (670 K).

The data traces presented demonstrate that the mercury loop was protected sufficiently in that boiler overpressure and turbine-alternator overspeed did not occur. The oil flow to the turbine-alternator bearings was cut off before the turbine-alternator decelerated, preventing oil contamination of the mercury loop through the dynamic seals. Similarly, other data show that lube/coolant flow to the mercury pump bearings was shut off before mercury loop contamination could occur via the mercury pump dynamic seals.

Both NaK loops and the lube/coolant loop were manually shut down approximately 1 hour after the automatic mercury loop shutdown. Examination of tape recorder data and the system gave no evidence of SNAP-8 component or system malfunction. It is assumed that the mercury loop shutdown was due to a false signal that originated in the frequency monitor.

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TABLE I. - OPERATING TIMES ON SNAP-8 COMPONENTS

TESTED IN LEWIS FACILITY

Component	SNAP-8 unit	Total running time, hr	Number of startups
Turbine-alternator	6/2	1445	4
Hg pump	5/1	1456	20
NaK pump (primary loop)	7/2	1484	43
NaK pump (heat-rejection loop)	10/2	1483	49
Lube/coolant (L/C) pump	5/1	1584	47
Bare refractory double-containment boiler	1	1445	4
Auxiliary start heat exchanger	4	1484	--
Hg flow control valve	1	1456	--
Temperature control valve	2	1483	--
Hg injection check valve	3	1456	--
L/C solenoid valves (low temperature)	6 and 13	1445 (each)	--
L/C solenoid valves (high temperature)	1 and 2	1456 (each)	--
Speed control:			
Parasitic load resistor (PLR)	1	[a]336/1484	--
Saturable reactor	3	1445	--
Static exciter	1	1445	--
Voltage-regulator	1	1445	--

[a]Although PLR failed electrically after 336 hr, it saw NaK service for total test duration.

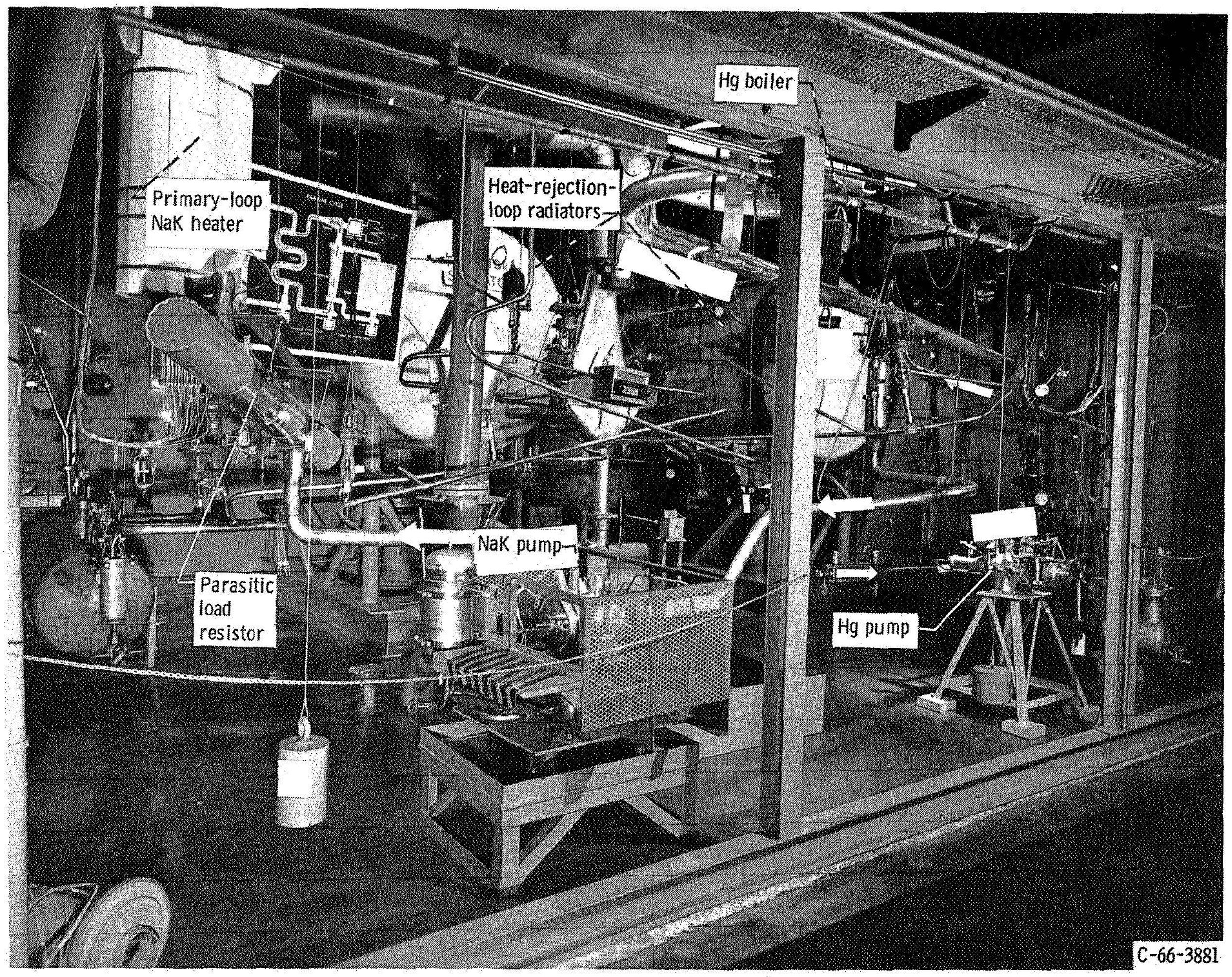

Figure 1. - Lewis SNAP-8 facility.

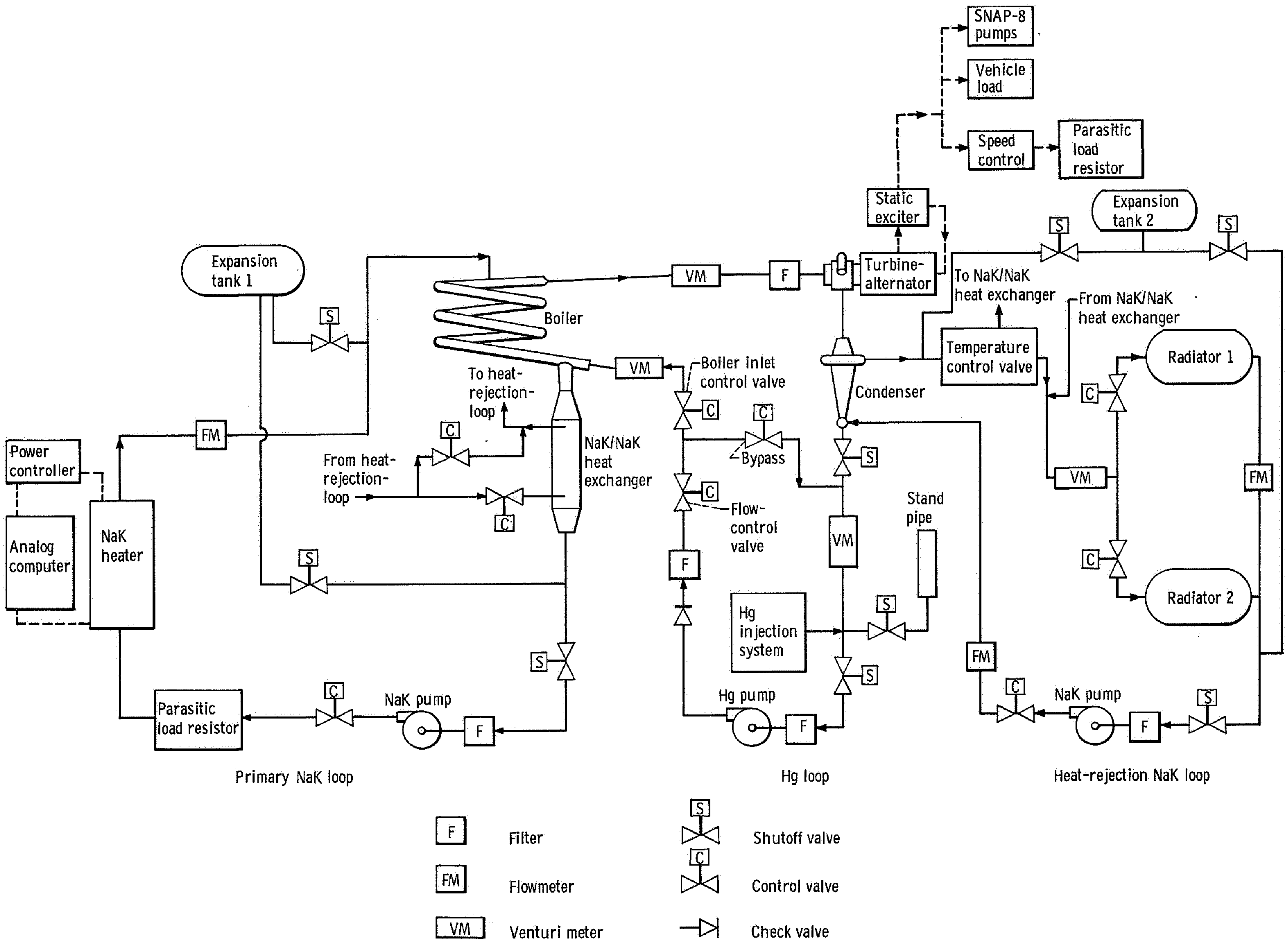

Figure 2. - SNAP-8 system schematic: three liquid-metal loops.

CD-10153-22

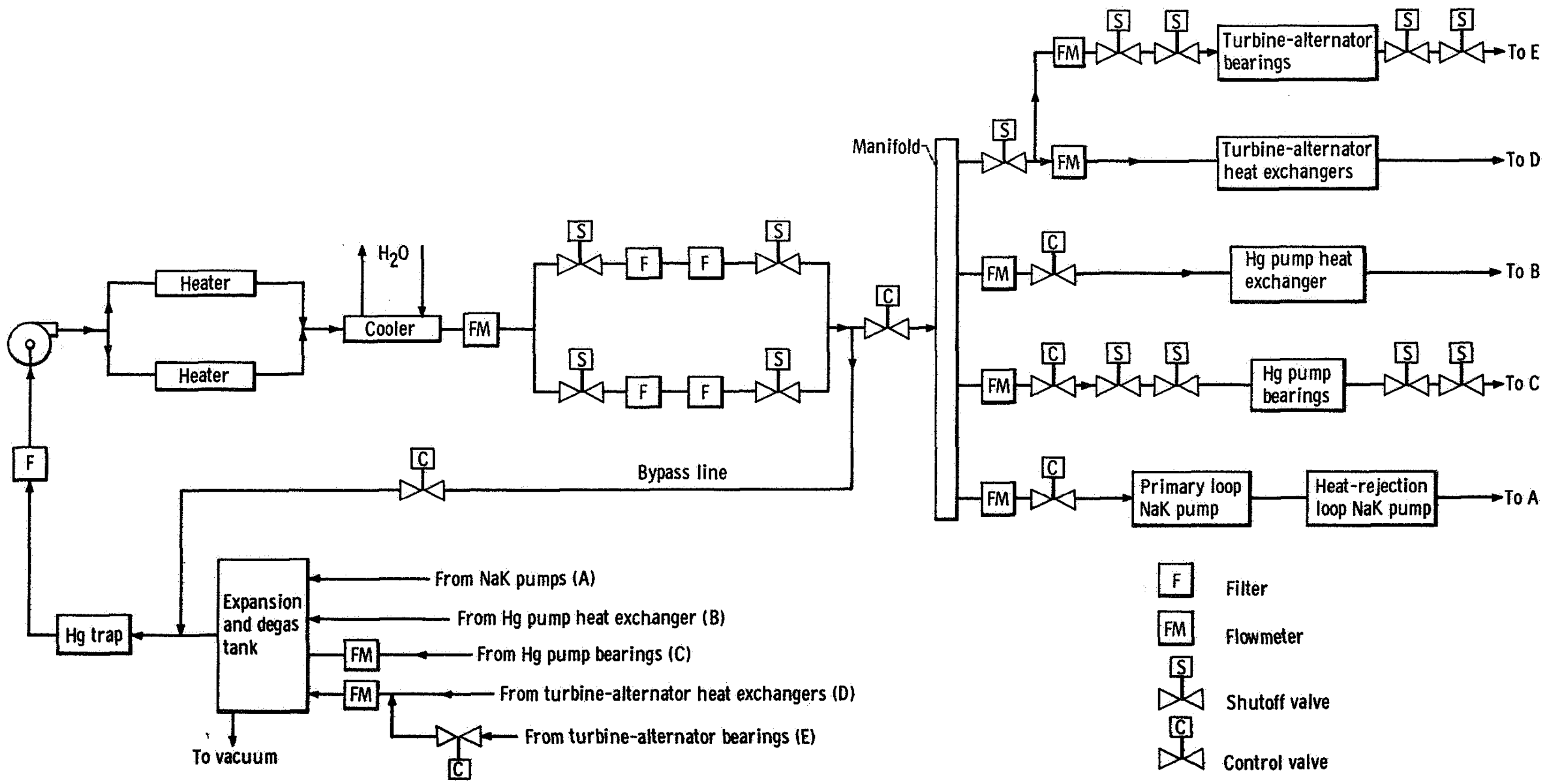

Figure 3. - SNAP-8 system schematic: lubricant coolant loop.

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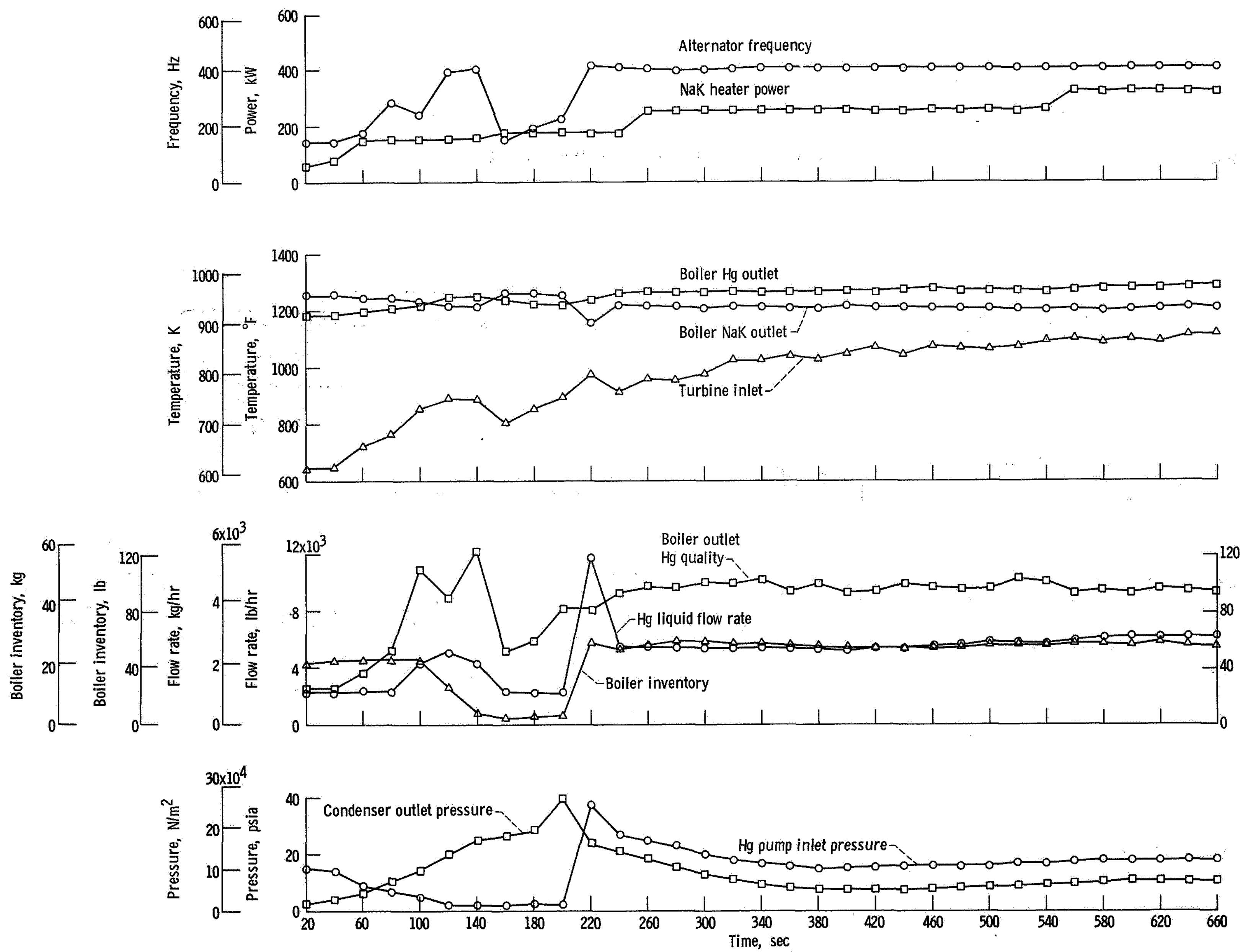

Figure 4. - Time history of SNAP-8 startup.

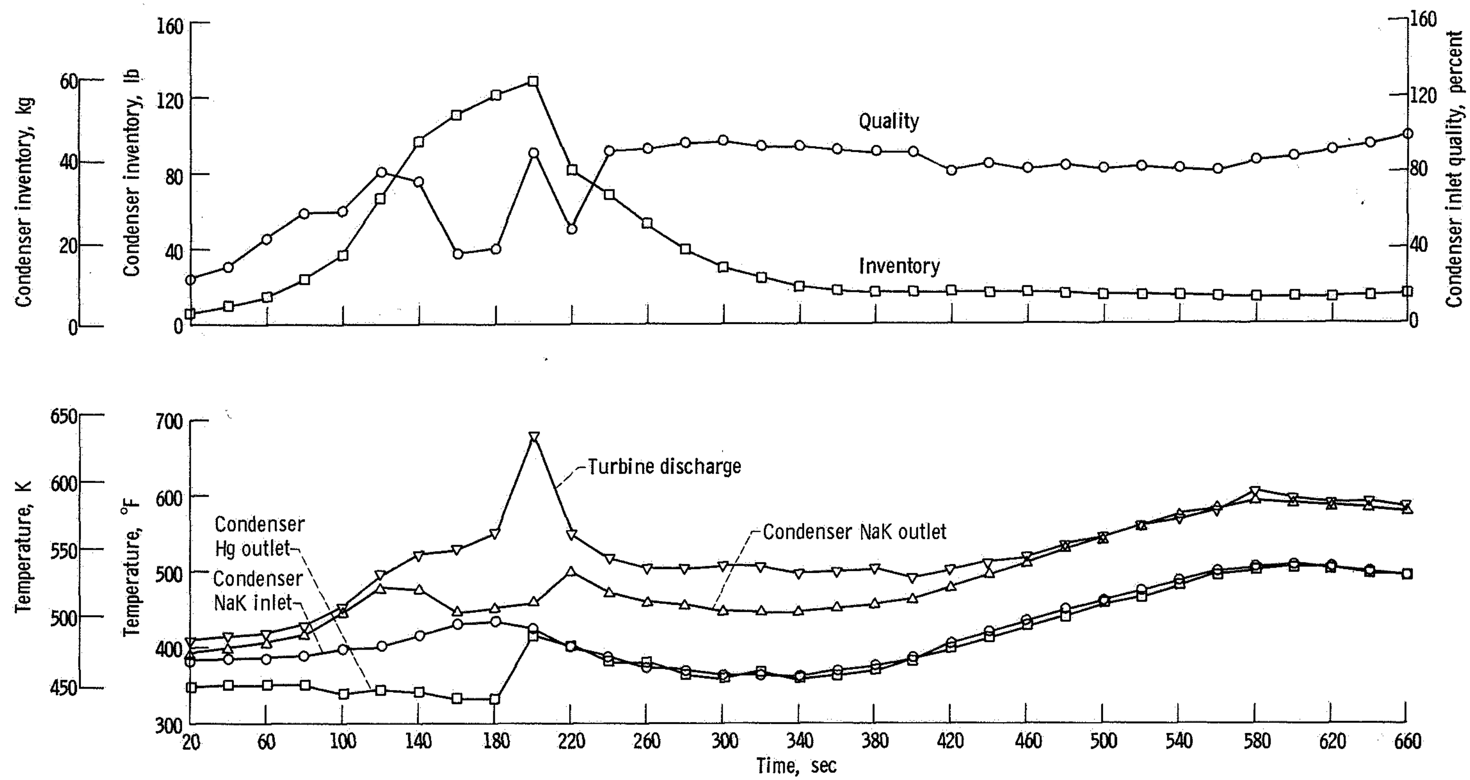

Figure 5. - Time history of SNAP-8 startup 3.

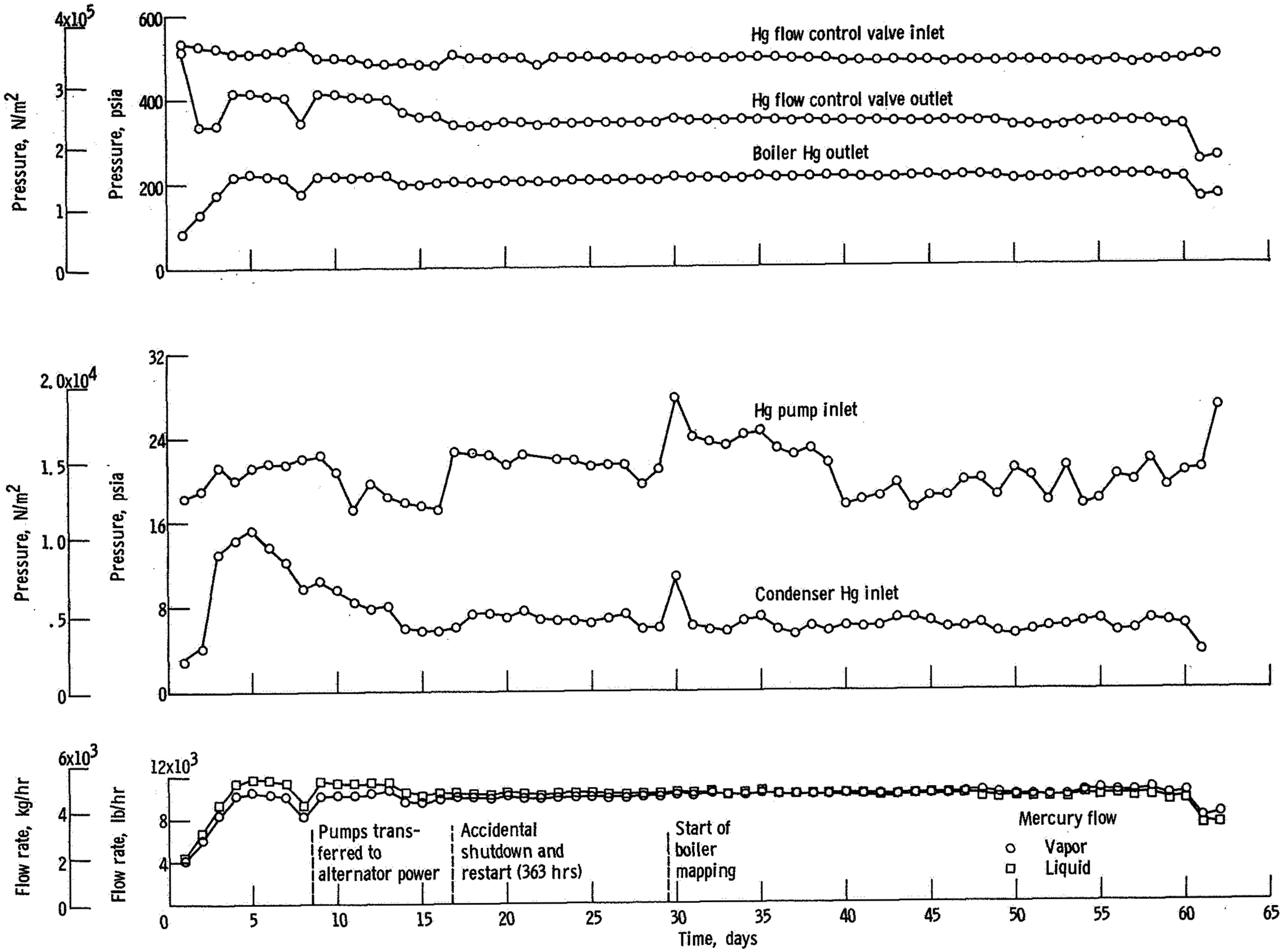

Figure 6. - Mercury loop pressures.

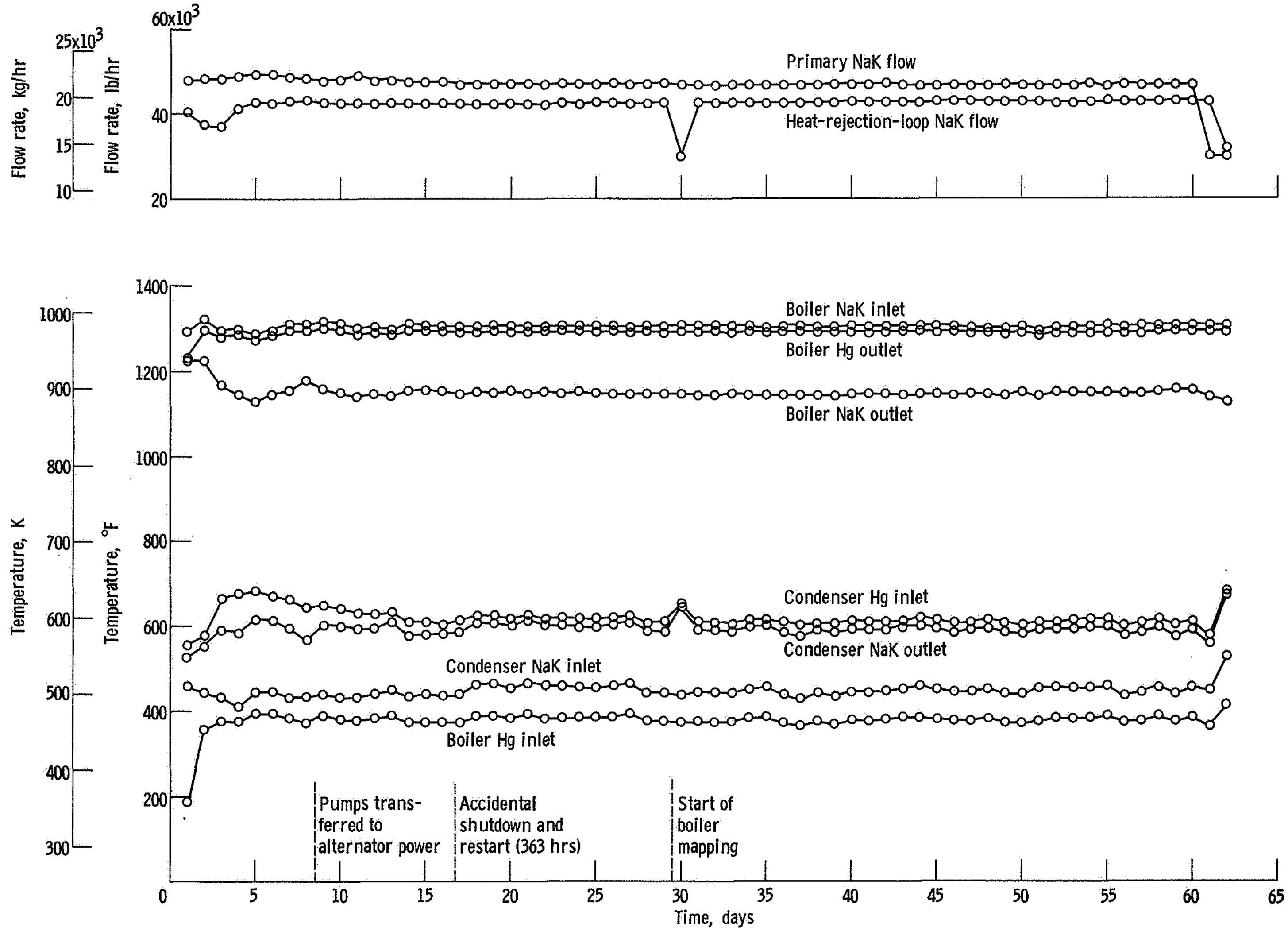

Figure 7. - System temperatures and NaK loop flow rates.

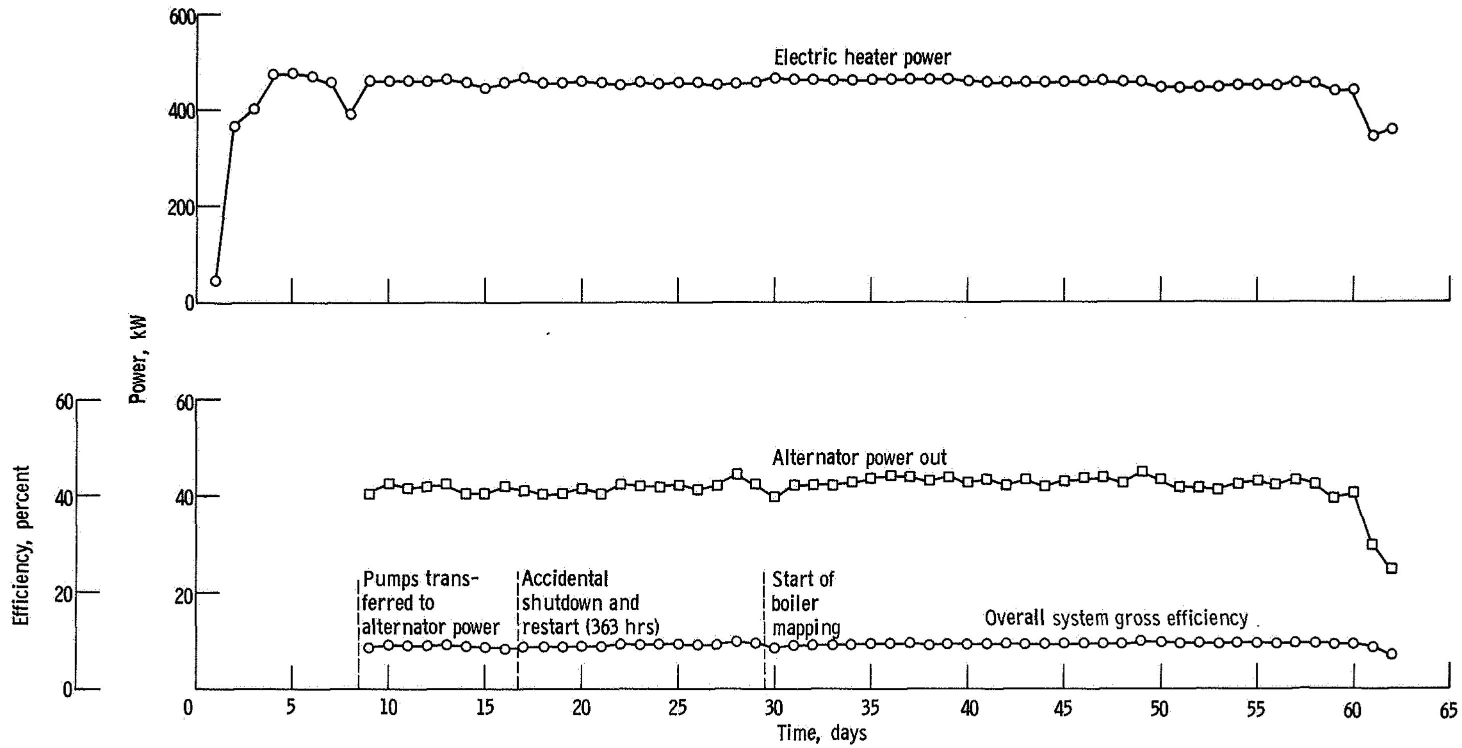

Figure 8. - Power and efficiency data.

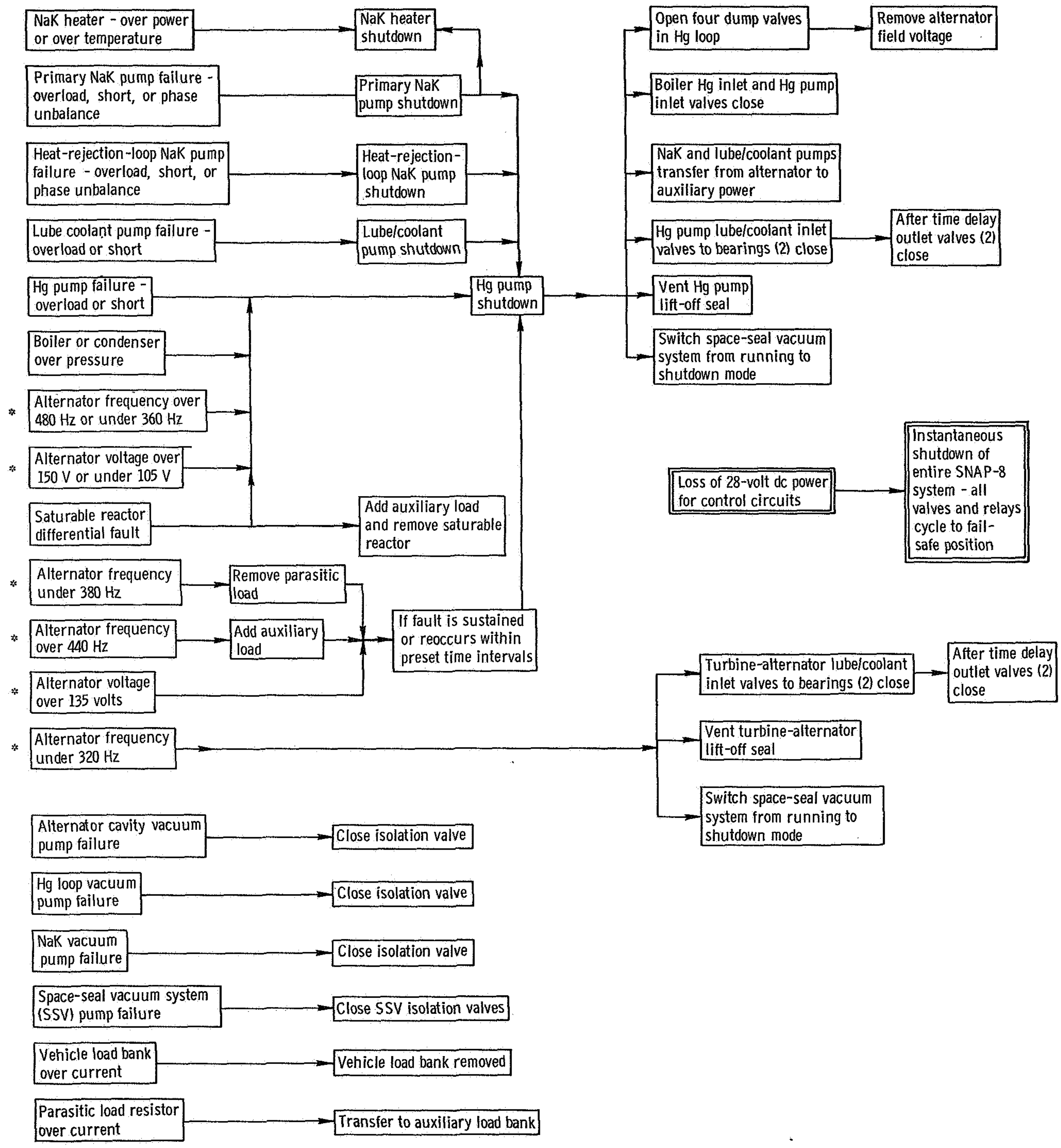

Figure 9. - Automatic shutdown function chart. (Parameters denoted by asterisk trip when alternator field voltage is removed.)

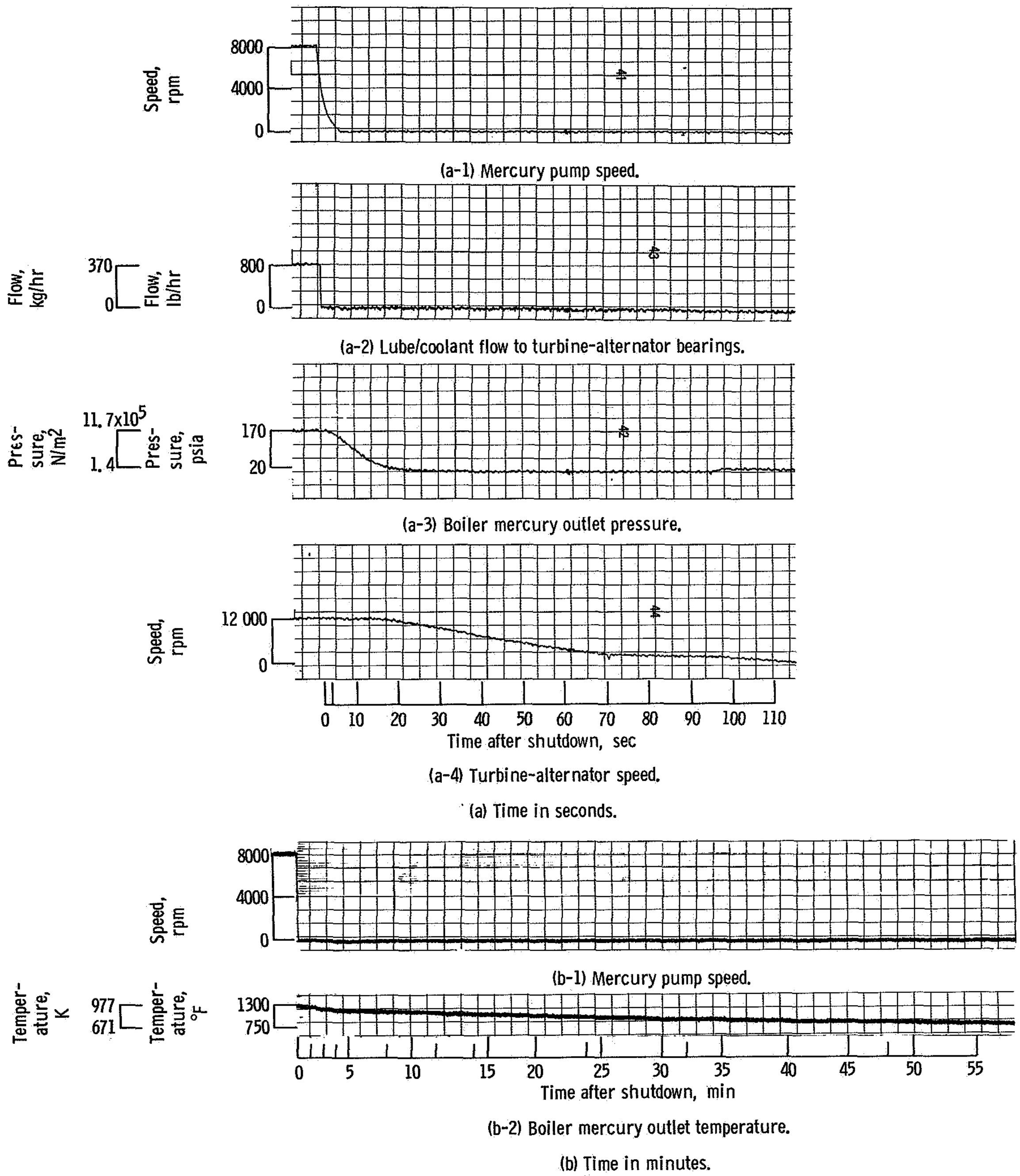

Figure 10. - Tape recorder data of mercury loop automatic shutdown after 1445 test hours.

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