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SHUTDOWN CHARACTERISTICS OF A SNAP-8 POWER CONVERSION SYSTEM

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16. Abstract

An experimental study of the shutdown of a SNAP-8 mercury Rankine power conversion system was conducted to determine the system response to both normal and emergency shutdown procedures. A failure of the condenser coolant flow was the simulated system condition for the emergency shutdown procedure. The results of both shutdown procedures show that the system can be repeatably shut down in such a way as to ensure its restart capability. Transient data for three typical shutdowns are presented.

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SUMMARY

An experimental study of the shutdown of a SNAP-8 mercury Rankine power conversion system was conducted to determine the system response to both normal and emergency shutdown procedures. The normal shutdown was conducted from the rated mercury flow of 12 300 pounds per hour (5600 kg/hr). A failure of the condenser coolant pump was simulated for the emergency shutdown test. This resulted in a rapid increase in the condenser mercury vapor pressure. The emergency shutdown procedures, however, held the pressure within the safe limit. Results of both the normal and emergency shutdowns show that the system can be repeatably shut down in such a way as to ensure its restart capability.

INTRODUCTION

SNAP-8 is a Rankine cycle power system for space using a nuclear heat source. It is capable of producing more than 35 kilowatts of usable electric power. Thermal energy is transferred from a nuclear reactor to a mercury boiler by pump-circulated NaK (a mixutre of sodium and potassium). Mercury is vaporized in the boiler and drives the turboalternator; it is then liquefied in the condenser and pumped back to the boiler. Waste heat is transferred from the condenser to a space radiator by the NaK heat-rejection loop. A more detailed description of the system may be found in reference 1.

For long term use in space, it is intended that the SNAP-8 system have shutdown and restart capability. Shutdowns must be accomplished in a manner that will safely restore the system to the proper prestart conditions. SNAP-8 startup is discussed in reference 2. Also, system shutdowns must not impair the operability of the components. A requirement for system restart is that the mercury inventory in the boiler and condenser be withdrawn from the power loop during system shutdown. In order to evaluate proposed system shutdown procedures, shutdown tests were included in the SNAP-8 test program conducted at the Lewis Research Center. These tests were performed on an experimental full-scale SNAP-8 power conversion system using a computer-controlled electric heater to simulate the reactor and a computer-controlled air-cooled heat exchanger to simulate the radiator. The transient data obtained from a normal shutdown and two simulated emergency shutdowns are presented and discussed.

APPARATUS

Test System

The SNAP-8 test system included all of the major SNAP-8 components with the exception of the reactor and the radiator. The primary NaK loop, the mercury power loop, and the heat-rejection NaK loop are shown schematically in figure 1. The primary loop contained a centrifugal pump motor assembly, an electric heater, a tantalum - stainless steel boiler, and an auxiliary (NaK-to-NaK) heat exchanger. The electric heater, ignitron power controller, and analog computer were used to simulate the operation of the nuclear reactor (ref. 3). The NaK flow was controlled by valve V-115 at the pump discharge. The auxiliary heat exchanger transferred heat from the primary to the heat-rejection loop prior to mercury loop startup and following shutdown. NaK flow was regulated by valve V-117.

The components in the mercury loop were a centrifugal pump motor assembly, a tantalum - stainless steel boiler, a four-stage axial flow turbine alternator, and a condenser. The mercury flow rate was controlled by a continuous feedback system using the electrohydraulic flow control valve V-230. A gas operated shutoff valve V-217 isolated a mercury reservoir (standpipe) from the system. The standpipe was used for mercury injection during startups and also to withdraw mercury inventory in the shutdown tests. The standpipe gas pressure was manually adjusted from 0 to 50 psia ($34\ N/cm^2$).

The heat-rejection NaK loop components were a centrifugal pump motor assembly, a condenser, and two finned NaK-to-air multitube heat exchangers. Butterfly valves controlled by the analog computer varied the air flow to the heat exchangers to simulate a space radiator (ref. 4). The NaK flow of the heat-rejection loop was controlled with valve V-314. The mercury condenser inlet pressure was maintained within preset limits by a deadband control (ref. 5). The control sensed condenser inlet pressure and manipulated the condenser NaK flow with the control valve V-314.

As the pressure exceeded the upper deadband limit, the NaK flow was linearly increased until the condensing pressure fell back into the deadband. Conversely, as the pressure decreased below the lower deadband limit, the NaK flow was linearly decreased until the mercury condensing pressure increased above the lower deadband limit. The NaK flow was held constant as long as the condenser pressure remained within the deadband limits.

A parasitic-load speed control was used with the turbine alternator. The control detects changes in alternator line frequency, which is directly proportional to turbine alternator speed, and varies the electric power to a parasitic-load resistor (ref. 6).

The reactor simulator outlet temperature was controlled in the deadband mode throughout the shutdown testing. The control was a simulation of the SNAP-8 reactor control (ref. 3). If the temperature exceeded the upper deadband limit, the reactor simulator power was decreased in steps until the temperature fell back into the deadband. Conversely, when the temperature decreased below the lower deadband limit, the power was increased in steps to allow the temperature to increase back into the deadband.

Both NaK loops contained an expansion tank which served as a reservoir to compensate for changes in volume of the NaK fluid due to temperature variations and to maintain pressure at the inlet of the pumps. An oxide control system (not shown in fig. 1) was used to precipitate out oxides from the NaK fluid to minimize the problem of plugging of system valves and piping. A lubricant and coolant (L/C) loop containing polyphenol ether, circulated by the L/C pump, was used to lubricate the turbine alternator and the mercury pump bearings. It was also used to cool the turbine alternator and the NaK and mercury pump motor assemblies. The test facility contained vacuum, argon, and nitrogen systems which were also used for the operation of the loops. A test facility motor-generator set (auxiliary power supply) was used to drive the system pumps when not operating on turbine alternator power. This power supply was rated at 200 kilowatts and had an adjustable frequency range of 200 to 2000 hertz.

Instrumentation

The instrumentation used consisted of flow, pressure, temperature, power, and speed sensors. The mercury weight flow was measured at the boiler inlet and outlet by calibrated venturi flowmeters utilizing differential pressure transducers of the slack-diaphragm type with capillary tubes. The NaK flow rates in the primary and heat-rejection loops were measured with electromagnetic flowmeters. A venturi was also used in the heat-rejection loop, and it was found to agree with the electromagnetic flowmeter measurements.

Oil temperatures were measured with Instrument Society of America (ISA) standard calibration J (iron-constantan) thermocouples. NaK and mercury temperatures were measured by ISA standard K (chromel-alumel) thermocouples. Temperatures presented are accurate to ±1 percent.

The turbine alternator speed was measured by an electromagnetic reluctance probe which sensed the movement of a multiple tooth gear on the rotating shaft. The output of the reluctance probe was conditioned with a frequency to dc converter and indicated on a panel meter.

The turbine alternator output power, vehicle load power, parasitic load power, and reactor simulator electrical power measurements were made with true rms thermoelement-type wattmeters.

A computerized digital data system (ref. 7) was used to record data along with an FM analog system and control room strip-chart recorders, digital counters, and panel meters. The digital data system had a capacity of 400 data channels and recorded a cycle of data every 11.43 seconds. The FM analog system recorded 60 data channels continuously for time periods up to 24 minutes.

A complete description of the instrumentation employed in the Lewis SNAP-8 test facility is given in reference 8.

PROCEDURE

Two types of shutdown procedures are discussed - normal and emergency. The normal shutdown procedures are used in a flight system when no emergency exits. The emergency shutdown procedures are intended to protect the system components and to allow for restart after the cause of failure or malfunction has been corrected.

Normal Shutdown

In normal shutdown, the mercury flow rate was first ramped from the rated flow level of 12 300 pounds per hour (5600 kg/hr) to the self-sustaining level of 6600 pounds per hour (3000 kg/hr) in 600 seconds. (System self-sustaining flow condition is the minimum mercury flow that the turbine alternator requires to produce sufficient power to operate the system pumps and electrical controls.) During this 600-second time period, all four pumps were receiving power from the alternator and the condensing pressure was being maintained by the deadband controller. Also, as the alternator power decreased with mercury flow, vehicle load was removed in 15-kilowatt increments. When steady-state conditions were reached at the 6600 pound per hour (3000 kg/hr) mercury flow level, the flow was then ramped down to 400 pounds per hour (180 kg/hr) in approximately 150 seconds. The condenser NaK coolant flow rate was controlled throughout the shutdown to maintain mercury condensing pressure in the deadband of 11 to 14 psia (8 to 10 N/cm^2). As the turbine alternator frequency decayed to about 300 hertz, the turbine alternator and mercury pump motor assembly liftoff seals (ref. 6) automatically seated. The L/C flow to the bearings of both components was stopped while the coolant flow to both heat exchangers was maintained. When the turbine alternator frequency decayed to 220 hertz, the four system pumps were transferred to the auxiliary power supply. At a mercury flow rate of 400 pounds per hour (180 kg/hr), valve V-217 was opened so that the mercury inventories of the boiler and condenser could be transferred to the standpipe. During the removal of mercury inventory, the mercury flow to the turbine alternator was maintained at 400 pounds per hour (180 kg/hr) for 160 seconds with the mercury pump operating on 220-hertz auxiliary power. During the mercury transfer period, argon gas pressure in the standpipe was maintained equal to the hydrostatic head of the liquid mercury between the liquid levels in the condenser and standpipe. At the completion of transfer of the mercury boiler and condenser inventory to the standpipe, the mercury flow control valve was closed, NaK flow was reestablished in the auxiliary heat exchanger, and the mercury condenser outlet valve V-210 was closed. The heat-rejection loop flow control valve V-314 was reset to the position required for the next mercury loop startup. The reactor simulator control was maintained in the deadband mode of 1280° to 1320° F (967 to 989 K) during the entire shutdown.

Emergency Shutdown

A failure of the heat-rejection loop NaK pump was simulated for the emergency shutdowns. All system pumps were operating on the auxiliary power supply during both emergency shutdowns presented in this report. The first shutdown was executed from a mercury flow rate of 6600 pounds per hour (3000 kg/hr) with the only alternator load being the parasitic load. The primary loop NaK flow rate was 45 000 pounds per hour (20 400 kg/hr). The second shutdown was executed from a mercury flow rate of 12 300 pounds per hour (5600 kg/hr). To simulate the power requirement of the four pumps, 15 kilowatts of alternator power were applied to the vehicle load. The shutdowns were initiated by closing valve V-314, which stopped the heat-rejection loop NaK coolant flow to the condenser. When the condenser coolant flow was zero, the mercury flow control valve V-230 was closed in approximately 1 second. Also, mercury inventory withdrawal to the standpipe through valve V-217 was initiated at the same time. The standpipe gas pressure was regulated as in the normal shutdown.

In the shutdown from rated mercury flow conditions of 12 300 pounds per hour (5600 kg/hr), the primary NaK flow was decreased from 46 500 to 23 000 pounds per hour (21 100 to 10 500 kg/hr) by throttling the primary NaK loop flow control valve V-115. The NaK flow was reduced after the mercury flow was stopped to simulate the transfer of the primary NaK pump from a 400-hertz alternator power to an auxiliary 220-hertz power supply. As in the normal shutdown, the reactor-simulator control was in the deadband mode. For both emergency shutdowns the auxiliary heat exchanger NaK flow reestablished about $4\frac{1}{2}$ minutes after the mercury flow was stopped.

RESULTS AND DISCUSSION

Normal Shutdown

Power reduction ramp. - The pertinent variables for the reduction in power from the rated mercury flow of 12 300 pounds per hour (5600 kg/hr) to the self-sustaining mercury flow of 6600 pounds per hour (3000 kg/hr) are shown in figure 2. The mercury was decreased linearly as shown in figure 2(a). The disturbance in flow at 590 seconds was caused by the switching of the mercury flow control valve V-230 from computer to manual control. The boiler inlet pressure (fig. 2(b)) decreased with the decreasing mercury flow. It also reflected the small change in flow at 590 seconds. The boiler outlet pressure (fig. 2(c)) decreased faster than the inlet pressure. As expected from reference 9, the boiler pressure drop increased with the decreasing mercury flow. The alternator power (fig. 2(e)) decreased from 56 kilowatts at the rated mercury flow to 22 kilowatts at the self-sustaining mercury flow rate. The variations in the alternator power which occurred at 210 and 580 seconds were caused by the removal of 15 kilowatts of vehicle load. The power was removed from the vehicle load to avoid overloading the turbine alternator as the mercury flow decreased. The trace of the parasitic load power is shown in figure 2(f). It shows that approximately 15 kilowatts were applied by the speed control at 210 and 580 seconds.

The reactor simulator power trace is shown in figure 2(g). It decreases from 550 kilowatts (at rated mercury flow) to 305 kilowatts at the self-sustaining level. The primary loop NaK flow rate (fig. 2(h)) was approximately 46 500 pounds per hour (21 100 kg/hr). The reactor simulator control was in the deadband mode of 1280° to 1320° F (967 to 989 K) on the reactor simulator outlet temperature throughout the shutdown. The reactor simulator power was reduced smoothly by the simulation of the reactor's inherent temperature feedback effect. The reactor simulator inlet temperature, shown in figure 2(i) increased from 1130° to 1180° F (884 to 911 K) due to the reduction in mercury flow. The reactor simulator outlet temperature (fig. 2(j)) remained at about 1300° F (978 K) throughout the power reduction mercury flow ramp.

The heat-rejection loop NaK flow (fig. 2(k)) was decreasing with the decrease in mercury flow rate. It was controlled by the deadband control to maintain the condenser inlet pressure between 11 and 14 psia (8 to 10 N/cm^2) throughout this phase of the shutdown. The peak pressure at 60 seconds was because the deadband control was not in operation until that time. The condenser outlet pressure (fig. 2(m)) was approximately equal to the condenser inlet pressure plus the liquid mercury head in the condenser.

Final shutdown phase. - The variables for the final phase of the normal shutdown sequence are shown in figure 3. This phase of the shutdown was the mercury flow reduction from the self-sustaining level of 6600 pounds per hour (3000 kg/hr) to a zero mrecruy flow rate. The liquid mercury flow rate is shown in figure 3(a). The mercury ramp started at 5 seconds. At 117 seconds, all pump power was transferred from the alternator to the auxiliary power supply. The mercury flow ramp was smooth during this transfer of the pump power. The mercury flow ramp was stopped at 400 pounds per hour (180 kg/hr) which was at 155 seconds. This gave a mercury ramp duration of 150 seconds. The mercury flow was held at 400 pounds per hour (180 kg/hr) until 327 seconds. This provided a 172-second duration of the 400 pound per hour (180 kg/hr) flow, during which time the boiler and condenser mercury inventories were being removed. The large spike in the flow recording which occurred at 327 seconds was caused by the closure of the boiler isolation valve V-260. This resulted in a pressure pulse applied to the flow sensing instrumentation which caused the appearance of a high instantaneous flow.

The boiler inlet pressure (fig. 3(b)) decayed more rapidly for this phase of the shutdown than during the power reduction phase. The drop in the boiler inlet pressure after 327 seconds was caused by the closure of the boiler isolation valve. The boiler outlet pressure (fig. 3(c)) decayed less rapidly than the inlet pressure. There was a lower boiler pressure drop as the flow was reduced from the self-sustaining level of 6600 pounds per hour (3000 kg/hr).

The turbine alternator frequency is shown in figure 3(d). The turbine speed began to decrease at 40 seconds. All of the parasitic resistor load power on the alternator was removed by the speed control before 52 seconds (fig. 3(f)). After 117 seconds, the turbine alternator frequency reached 220 hertz. At this time the four system pumps were transferred from the alternator to the auxiliary power supply. Beyond this time, there was zero load applied to the alternator, as evidenced by the alternator power trace (fig. 3(e)). The turbine alternator frequency increased from 220 to 295 hertz after the removal of the electrical load. No action of the speed control was required to bring the turbine alternator frequency back down. The reason the turbine alternator frequency began to rise again at 190 seconds was due to the low condenser inlet pressure. The turbine alternator frequency decayed to zero about 20 seconds after the final time shown on the figure.

The reactor simulator power (fig. 3(g)) decreased from 312 to 65 kilowatts during this phase of the shutdown due to the simulated negative feedback effect of temperature on reactor power. There was no simulated control drum step to decrease the reactor simulator power. Figure 3(h) shows the primary NaK loop flow decay rate as the primary NaK pump-motor frequency decelerated along with the turbine alternator frequency. At 117 seconds, the primary flow stabilized as the pump was transferred to the auxiliary power. The reactor simulator inlet temperature, shown in figure 3(i), increased from 1190° to 1290° F (917 to 972 K) during this phase of the shutdown. The maximum rate of change of the inlet temperature was 0.6° F per second (0.33 K/sec) for this shutdown. The reactor simulator outlet temperature (fig. 3(j)) varied only slightly during this shutdown. The reactor simulator outlet temperature remained within the deadband limits of 1280° to 1320° F (967 to 989 K) throughout the shutdown.

The heat-rejection loop NaK flow shown in figure 3(k), as in the first phase of the shutdown, was regulated by the deadband control of the condenser inlet pressure of 11 to 14 psia (8 to 10 N/cm^2). The condenser inlet and outlet pressures are shown in figures 3(l) and (m). The drop in condenser pressure at 167 seconds was caused by the removal of inventory.

The beginning of the inventory removal at 167 seconds is illustrated in figure 3(n). The amount of mercury removed from the system into the standpipe was 52 pounds (24 kg). This was 100 percent of the condenser and boiler mercury inventories for this shutdown. During the removal of inventory, an argon gas pressure was maintained on the standpipe and varied in such a manner as to eliminate the difference in head of the liquid mercury which of course would not exist in zero gravity. The pressure in the standpipe was set equal to the liquid head difference between the standpipe and the condenser. The difference between the standpipe pressure and liquid head pressure is termed the "unbalanced pressure." A positive unbalanced pressure resulted when the pressure in the standpipe was greater than the pressure due to the difference in head between the condenser and standpipe. The variation of the unbalanced pressure with time during this shutdown is shown in figure 3(o). After the shutdown, the valves were returned to the initial position for the next startup and the system was subsequently restarted.

Emergency Shutdown

From self-sustaining mercury flow level. - The traces of the pertinent variables for an emergency shutdown from the system's self-sustaining mercury flow of 6600 pounds per hour (3000 kg/hr) are shown in figure 4. The heat-rejection loop NaK flow control valve was shut at 20 seconds. At 21 seconds, the mercury loop flow control valve was closed and mercury flow dropped to zero in about 2 seconds (fig. 4(a)). The boiler inlet pressure decayed very rapidly as seen in figure 4(b). The boiler inlet pressure reached 100 psia (69 N/cm^2) in about 2 seconds and then dropped to 25 psia (17 N/cm^2) in about 8 seconds. The boiler outlet pressure (fig. 4(c)) also dropped quickly. The turbine alternator frequency (fig. 4(d)) decayed rapidly due to the quick stoppage of mercury flow and the high condenser inlet pressure. The turbine alternator frequency began to fall when the mercury flow reached zero. After 45 seconds the turbine alternator frequency decay rate was less because the condenser inlet pressure had decayed. The alternator power output curve (fig. 4(e)) is a reflection of the parasitic load being removed by the speed control (fig. 4(f)).

The reactor simulator power reduction (fig. 4(g)) was more rapid for this shutdown than for the normal shutdowns. It decreased from 312 to 33 kilowatts in about 330 seconds, while the primary loop NaK flow was held at 45 000 pounds per hour (20 400 kg/hr) (fig. 4(h)). The reactor simulator inlet temperature (fig. 4(i)) increased from 1180° to 1300° F (911 to 978 K). The maximum rate of change of the reactor simulator inlet temperature was 6° F (3.3 K) per second over a period of 6 seconds which was well within the safe operating envelope for the reactor inlet temperature derivative (ref. 2). The reactor simulator outlet temperature (fig. 4(j)) increased slightly, but it did not go out of the deadband of 1280° to 1320° F (967 to 989 K).

Figure 4(k) is a trace of the heat-rejection loop NaK flow. The flow control valve in the heat-rejection loop was closed at 20 seconds. The flow decayed to zero in less than 1 second. The condenser inlet pressure (fig. 4(l)) began to rise rapidly as soon as the heat-rejection loop NaK flow was stopped. The immediate stoppage of the mercury flow limited the condenser pressure to 25 psia (17 N/cm^2) at 23 seconds. The condenser outlet pressure (fig. 4(m)) is approximately equal to the inlet pressure plus the liquid head of mercury in the condenser. Removal of the mercury inventory into the standpipe (fig. 4(n)) was begun when the mercury flow reached zero. The unbalanced pressure, shown in figure 4(o), varied from 2.4 to -3 psi (1.6 to -2.1 N/cm^2) during the withdrawal period. Due to an inadvertent early closure of the standpipe isolation valve, only 66 percent of the boiler and condenser mercury inventories was removed during this shutdown. During another shutdown from 6600 pounds per hour (3000 kg/hr) using emergency procedures, 97 percent of the boiler and condenser mercury inventories was removed. After the shutdown, the valves were returned to the initial position for the next startup and the system was subsequently restarted.

From rated power level. - Traces of the pertinent variables for the emergency shutdown from the rated mercury flow of 12 300 pounds per hour (5600 kg/hr) are shown in figure 5. This shutdown also simulated loss of the heat-rejection loop NaK flow. This occurred at 6 seconds. The heat-rejection loop NaK flow decayed to zero in about 1 second (fig. 5(k)). The mercury flow control valve was shut at 7 seconds. The signal to close the mercury flow control valve occurred when the heat-rejection loop NaK flow reached zero. The mercury flow decayed to zero in about 2 seconds as shown in figure 5(a) at 9 seconds.

The boiler inlet pressure decay rate can be seen in figure 5(b). It is believed that the slower rate of pressure decay at 7 seconds was due to a high instantaneous vapor flow at that time. This was caused by the quick decline in boiler pressure which lowered the saturation temperature and hence permitted instantaneous boiling of a large amount of the residual liquid mercury in the boiler. Hower, this condition was not noted during the emergency shutdown from 6600 pounds per hour (3000 kg/hr) mercury flow. It is theorized that the lesser boiler inventory at the mercury flow rate of 6600 pounds per hour (3000 kg/hr) held the instantaneous boiling rate below detectable levels.

The increase in mercury vapor flow during the instantaneous boiling can be seen as a slight rise in boiler outlet pressure at 7 seconds in figure 5(c). The turbine alternator frequency decay rate, shown in figure 5(d), was much faster for this shutdown than for the emergency shutdown from 6600 pounds per hour (3000 kg/hr) mercury flow, because vehicle load was left on to simulate pump power and because there was a higher condenser inlet pressure. The alternator power output is shown in figure 5(e). Since vehicle load was applied, power was dissipated into it by the alternator after the speed control had removed the parasitic load. As seen in figure 5(f), the parasitic load was removed at about 10 seconds.

The reactor simulator power trace is shown in figure 5(g). The reactor simulator temperature control was in the deadband mode of 1280° to 1320° F (967 to 989 K) during the shutdown. A step in the reactor simulator power occurred at 37 seconds as the reactor outlet temperature rose above 1320° F (989 K). The primary loop NaK flow (fig. 5(h)) was reduced from 46 500 to 21 000 pounds per hour (21 100 to 9500 kg/hr) by throttling the flow control valve. This throttling of the primary loop NaK flow was done to simulate the flow capacity of the pump had it been switched to the 220-hertz auxiliary power supply when the turbine alternator frequency decayed to this level.

The reactor simulator inlet temperature (fig. 5(i)) increased from 1120° to 1310° F (878 to 984 K) during the shutdown. The maximum rate of change of the reactor simulator inlet temperature was 7.5° F per second (4.2 K/sec) and lasted for 8 seconds. The rate of increase in inlet temperature decreased after 30 seconds, and was well within the safe operating limit for the reactor temperature derivative. The reactor simulator NaK outlet temperature variation (shown in fig. 5(j)) increased slowly from 1300° to 1325° F (978 to 992 K). At 37 seconds, the outlet temperature reached 1320° F (989 K). This caused the previously mentioned step of the reactor simulator power control.

Although not shown, the outlet temperature decreased below 1320° F (989 K) at 350 seconds.

The abrupt stoppage of the heat-rejection loop NaK flow, which occurred in about 1 second, is shown in figure 5(k). Figure 5(l) shows that the condenser inlet pressure rose immediately upon stoppage of the heat-rejection loop NaK flow. The stoppage of the mercury flow and the withdrawl of inventory held the condenser inlet pressure below 43 psia (30 N/cm^2) during the shutdown. The condenser outlet pressure (fig. 5(m)) was about equal to the condenser inlet pressure plus the liquid head of mercury in the condenser.

The standpipe isolation valve was opened at 6 seconds to allow for mercury withdrawal. The inventory removal can be seen in figure 5(n). The amount of inventory removed was 73 pounds (33 kg). This represented 95 percent of the boiler and condenser mercury inventory prior to the shutdown. During the inventory withdrawal period, a zero-gravity withdrawal condition was again simulated (fig. 5(o)). The simulation was very close, with the unbalanced pressure reaching 3 psi (2 N/cm^2) for only a short time.

Again, the valves were returned to the initial position for the next startup and the system was subsequently restarted.

CONCLUDING REMARKS

Both normal and emergency shutdowns were successfully completed with no system parameters exceeding safe operating limits. The emergency shutdowns were performed from the self-sustaining mercury flow rate of 6600 pounds per hour (3000 kg/hr) and from the rated mercury flow of 12 300 pounds per hour (6600 kg/hr). All shutdowns were accomplished with the simulated reactor control in the normal deadband mode. During the normal shutdowns, the transfer of the system pumps from the turbine alternator to the auxiliary power supply was successfully completed.

At the conclusion of each normal and emergency shutdown the valves were returned to the initial position for the next startup and the system was successfully restarted. The mercury inventory that was withdrawn to the standpipe during the shutdown was sufficient for the subsequent injection.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 25, 1970,
120-27.

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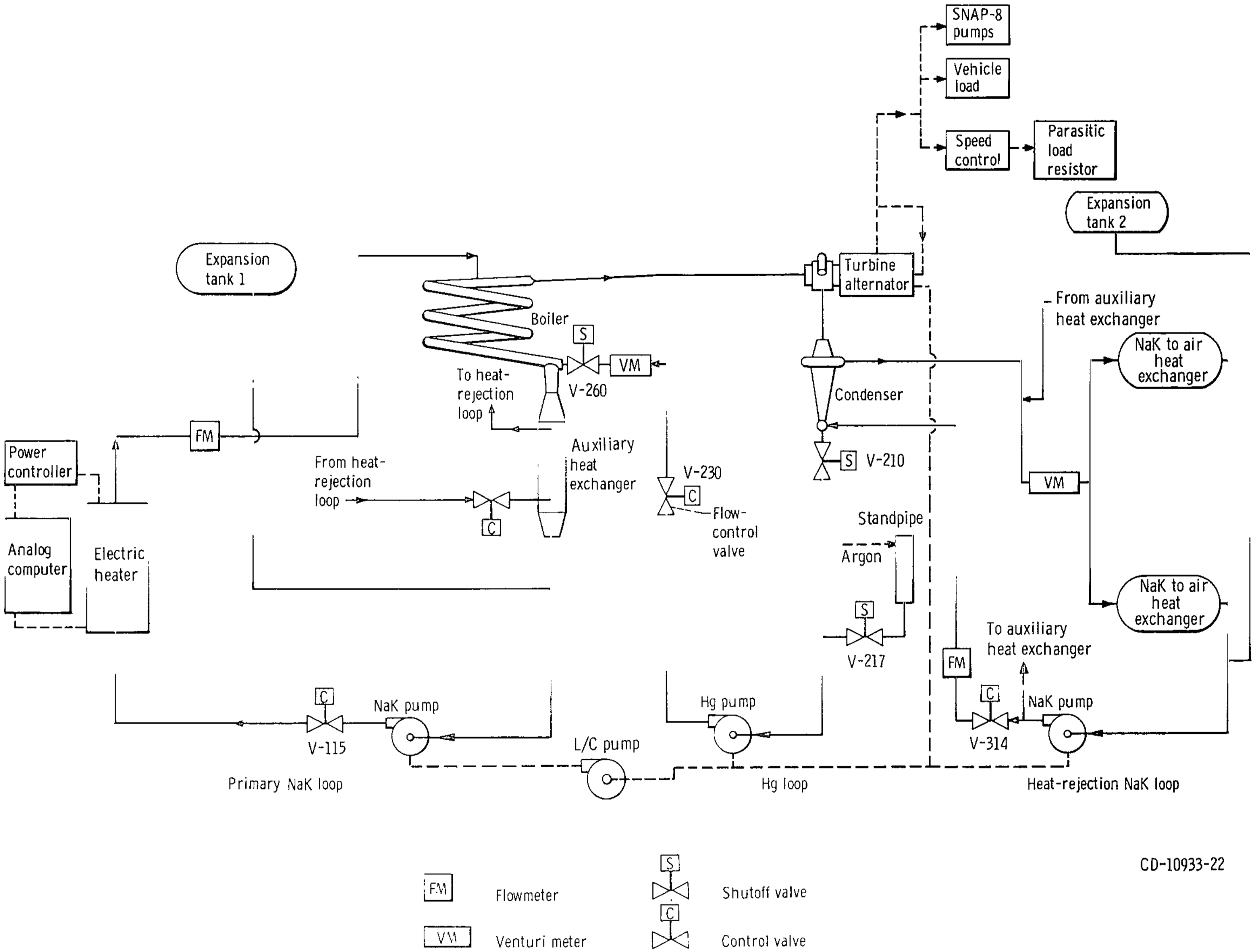

Figure 1. - SNAP-8 test system schematic.

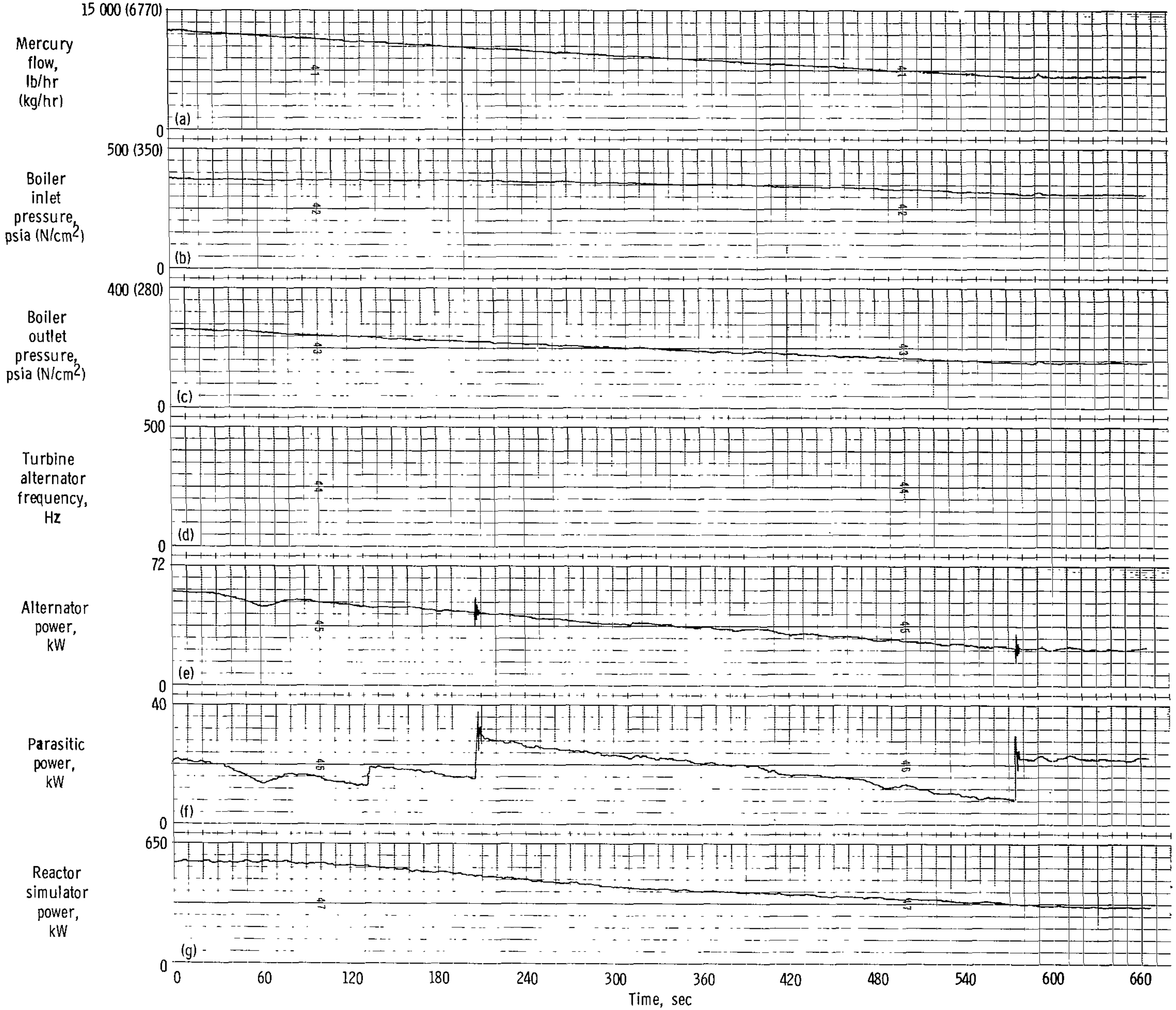

Figure 2. - Normal shutdown (power reduction ramp).

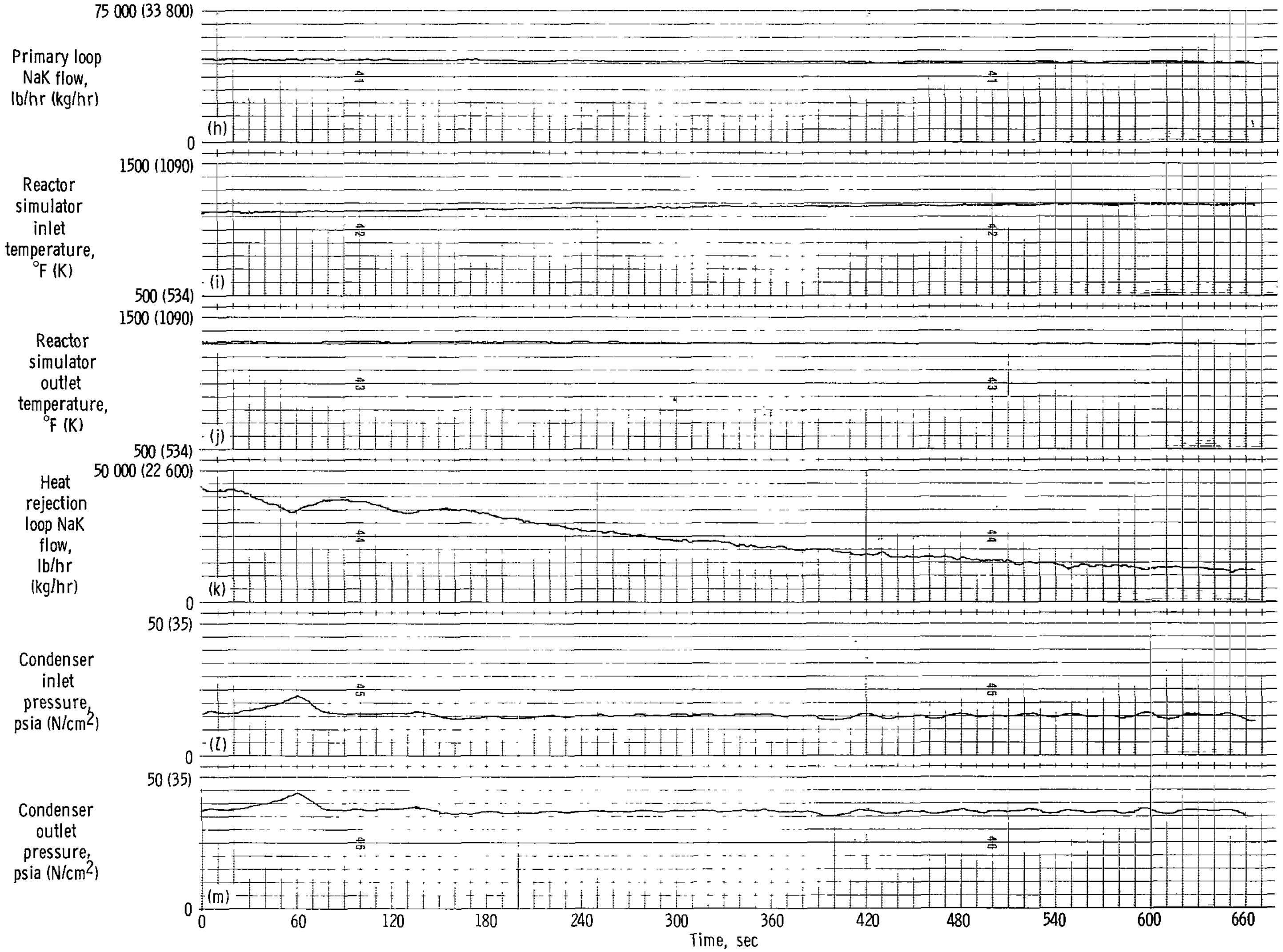

Figure 2. - Concluded.

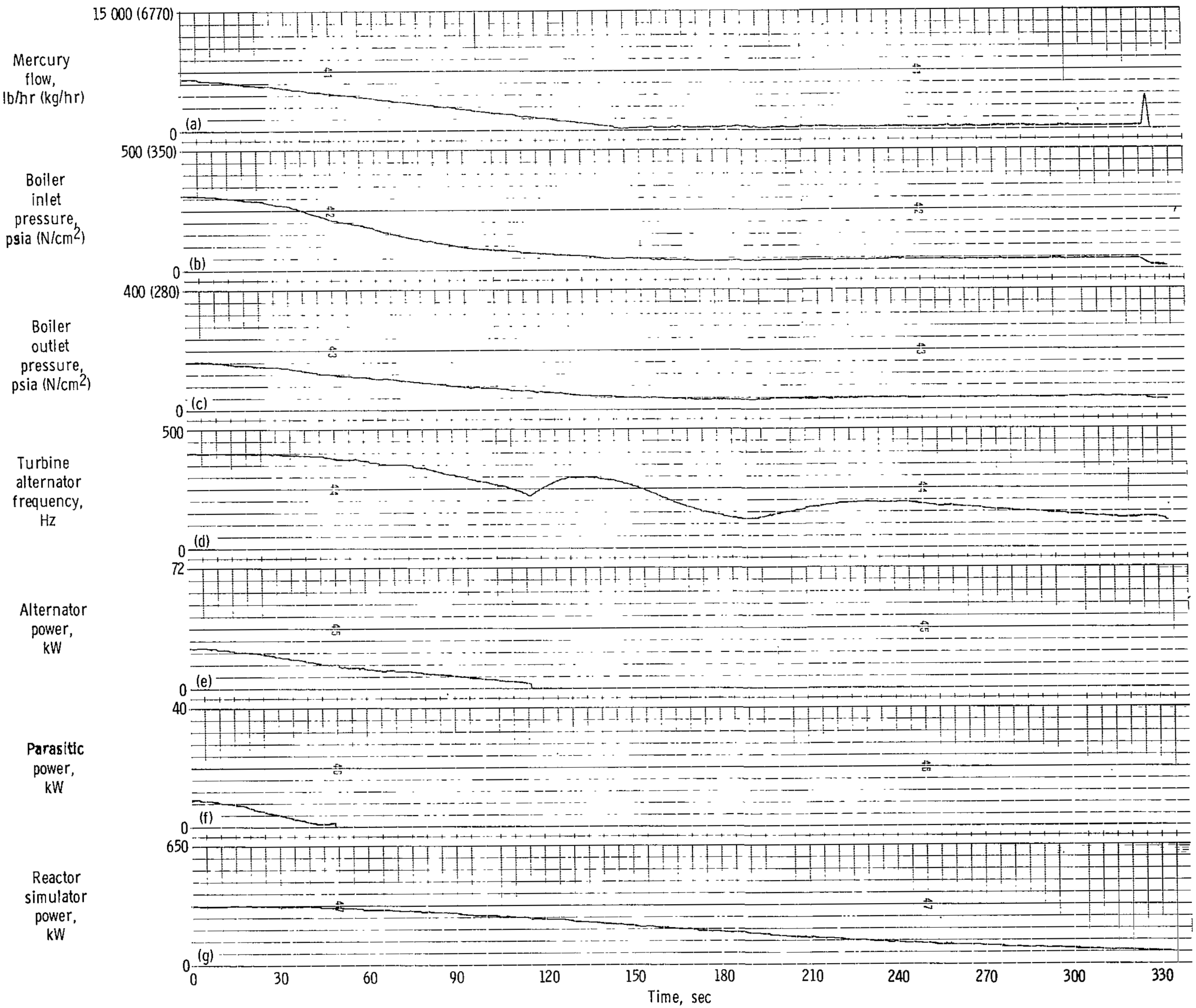

Figure 3. - Normal shutdown (final phase).

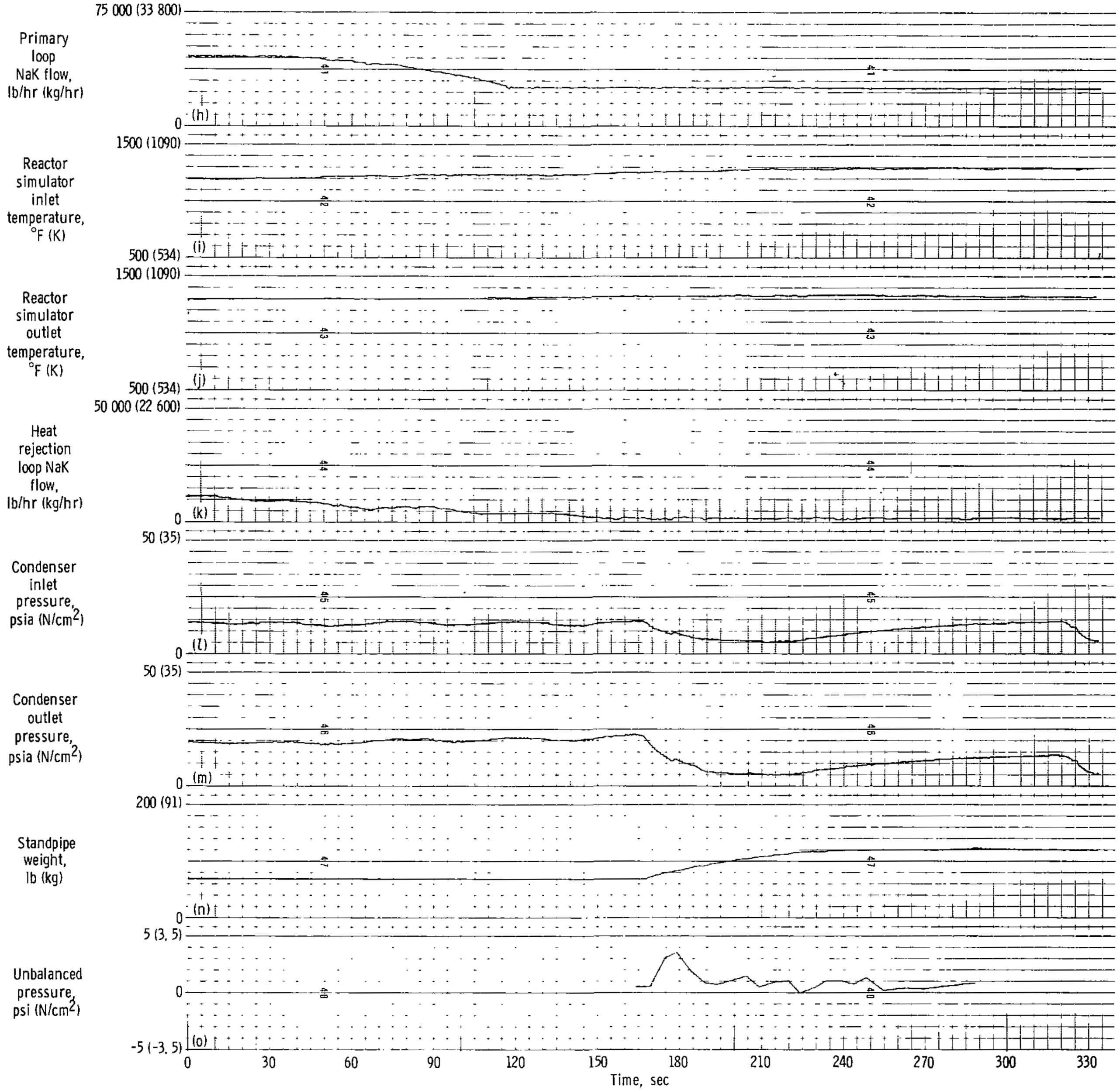

Figure 3. - Concluded.

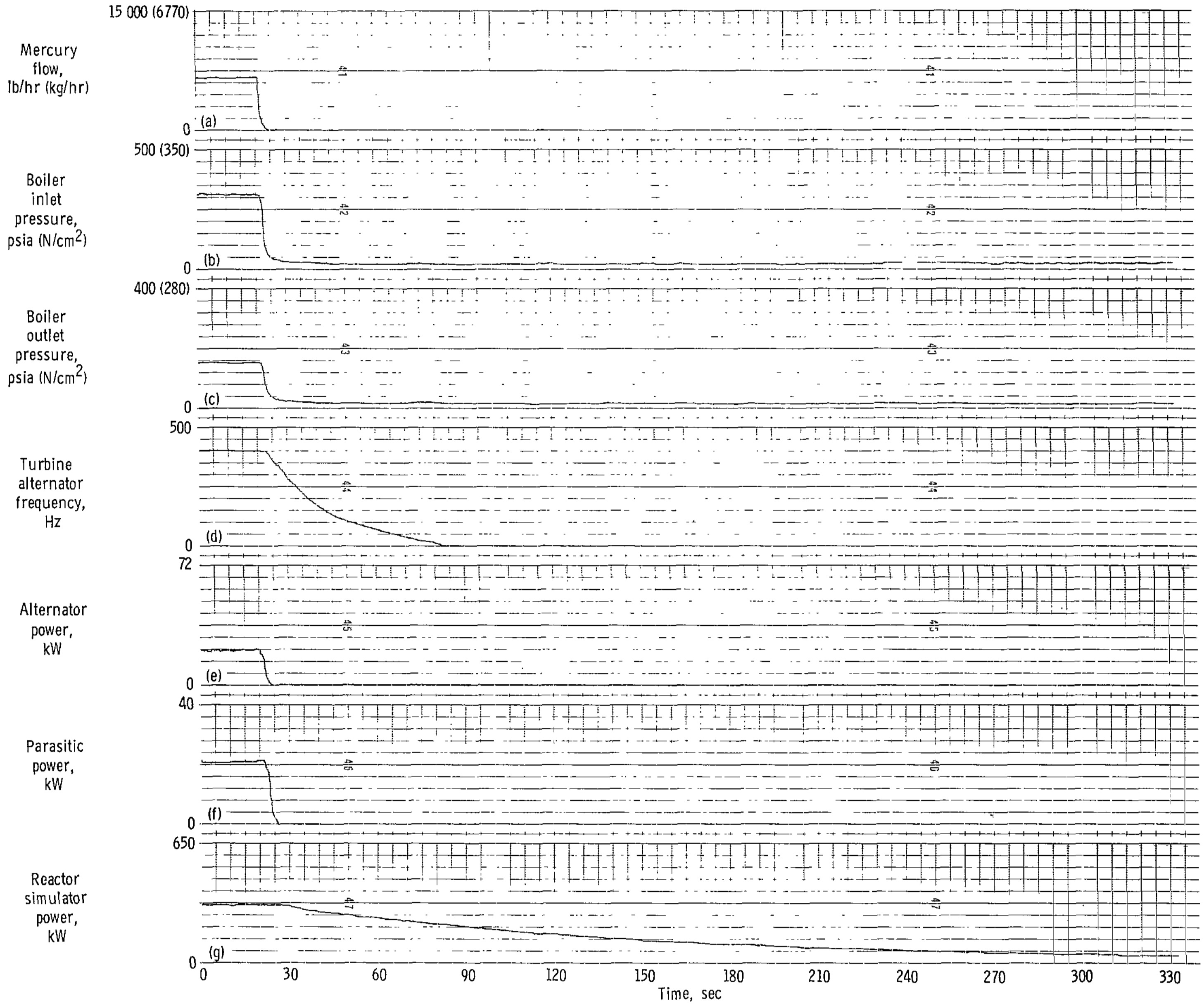

Figure 4. - Emergency shutdown from self-sustaining level.

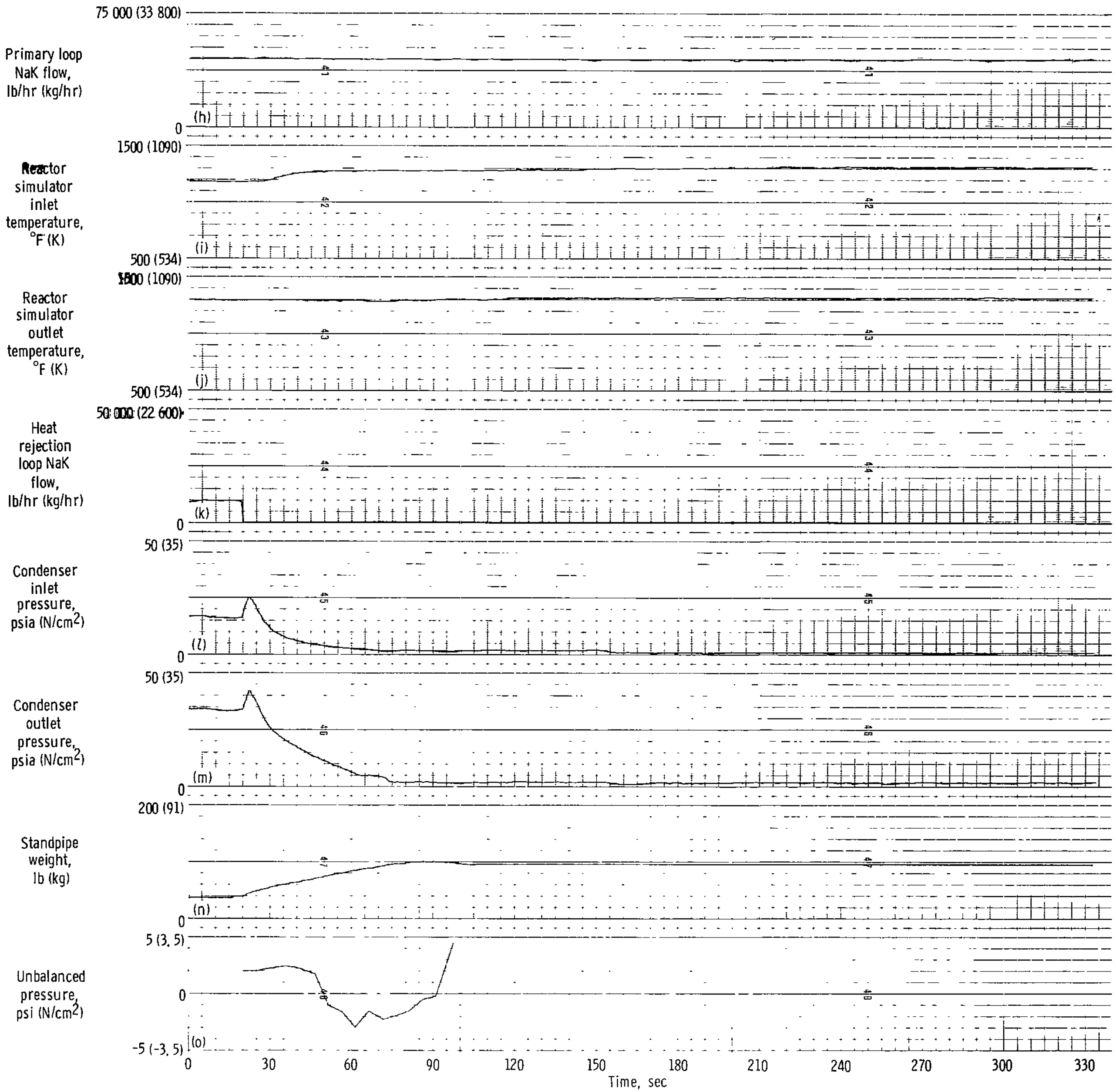

Figure 4. - Concluded.

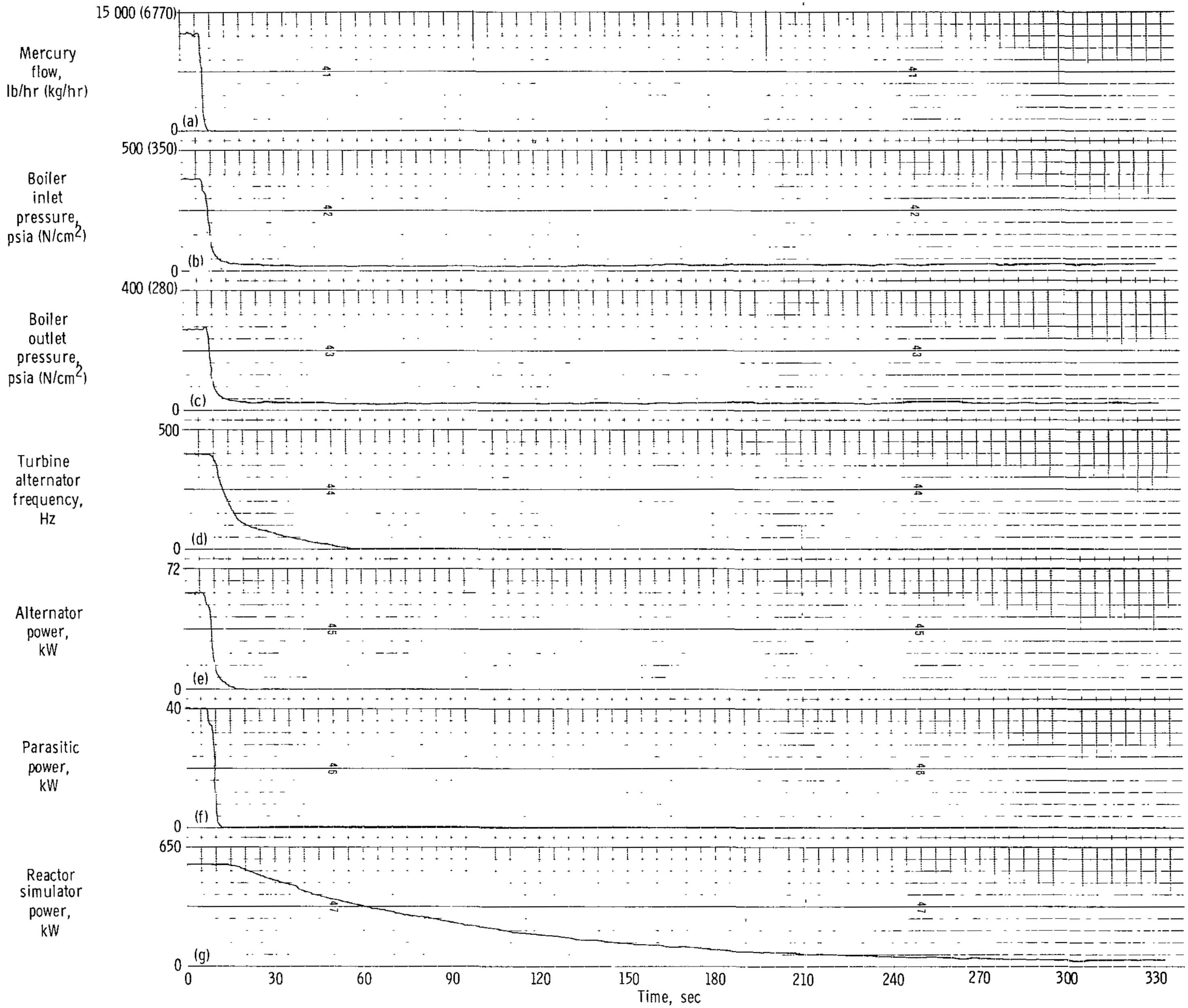

Figure 5. - Emergency shutdown from rated power level.

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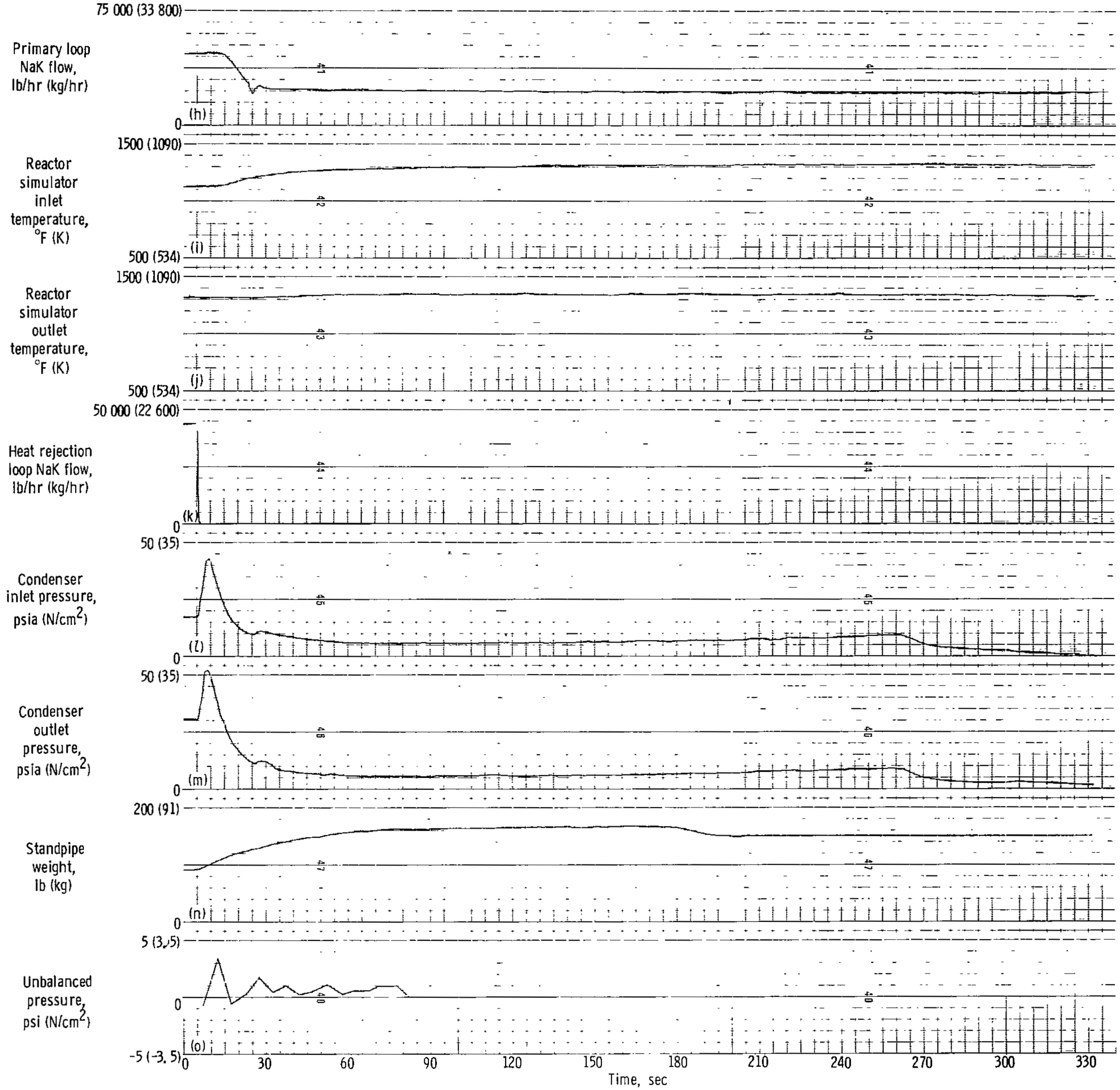

Figure 5. - Concluded.

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