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EXPERIMENTAL EVALUATION OF SNAP-8 POWER CONVERSION SYSTEM STARTUP

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16. Abstract

The SNAP-8 electrical generating system for space uses a nuclear reactor as the heat source. The power conversion system is turboelectric and operates on the mercury Rankine cycle. A startup test program was conducted on the power conversion system using a reactor simulator and a radiator simulator. Data from this program are presented and discussed. The data show that the power conversion system startup is dependable and that the resultant reactor temperature transients are well within the specified constraints.

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SUMMARY

The SNAP-8 space power system uses a nuclear reactor as the heat source and a turboelectric power conversion system operating on the mercury Rankine cycle for converting this heat to electric power. An extensive startup program was conducted on a SNAP-8 test system consisting of a power conversion system, reactor simulator, and radiator simulator. Startup procedures were experimentally evaluated for the relatively fast transient that brings the system to self-sustained operation and for the more gradual transient that achieves rated power output.

From the test results, startup procedures were defined that provide for dependable startup of the power conversion system and substantial margin in regard to reactor limitations. For these procedures, the temperature transients imposed on the reactor simulator were well within the acceptable values for the reactor.

INTRODUCTION

Electrical generating systems using a nuclear reactor as the heat source are prime candidates for space flight missions requiring many kilowatts of electric power. A relatively efficient way to convert the thermal power of a nuclear reactor to electrical power is by means of a turboelectric power conversion system, such as the SNAP-8 mercury Rankine system (ref. 1). The successful development of a turboelectric system for space, however, requires that considerable attention be directed towards defining startup procedures that are dependable and, at the same time, compatible with the operational constraints of the reactor. In an efficient startup of the turboelectric system, that is, one that requires minimal auxiliary power and equipment, startup dependability requires a relatively fast transient to a self-sustained condition. Fast startups, however, may cause temperature gradients in the reactor that exceed the constraining values and overly stress the nuclear fuel elements.

Startup, therefore, has been the subject of much analytical and experimental work in the development of the SNAP-8 power conversion system. Throughout the system development program, computer simulations have been used to formulate promising startup procedures and to point out problem areas requiring experimental investigation (refs. 2 and 3). Experimental startup studies began in 1965 when a simplified two-phase mercury loop was coupled with a reactor simulator and a radiator simulator at the Lewis Research Center. This system was used to study reactor loop transients during startup of the mercury loop (ref. 4). In 1968, the contractor for the power conversion system conducted a series of startup tests on a power conversion system using a gas-fired heat source. In these tests, the feasibility of completely automatic startups was demonstrated. The culmination of the startup work came in 1969 at the Lewis Research Center when 135 startup tests were conducted on a power conversion system coupled with a reactor simulator and a radiator simulator. For the first time, startup procedures for a complete power conversion system were experimentally evaluated concurrently with the associated reactor loop transients. The objective was final definition of startup procedures providing ample margin in relation to the requirements of both the power conversion system and the reactor.

The results of the latter test program are presented and discussed in this report. The discussion is centered first on the critical phase of the startup that brings the system to self-sustained operation and second on the startup phase that raises the power output of the system to the rated value. For both phases, factors that must be considered in selecting the rate of increase of the mercury flow are discussed. In addition, the performance of the condenser pressure control is presented for both phases.

TEST SYSTEM

The test system was essentially a complete SNAP-8 power conversion system coupled with a reactor simulator and a radiator simulator. A simplified schematic diagram of the test system is shown in figure 1. The major components of the power conversion system were the boiler, turbine-alternator, condenser, auxiliary heat exchanger, and system pumps. These components were flight-type, but the system was not arranged in a flight configuration. The test system configuration was selected for easy accessibility of components and instrumentation; however, attention was given to preserving the first-order dynamic characteristics of a flight-configured system. In order to provide flexibility in conducting the test program, the startup controls used in the power conversion system were not flight-type but were, rather, test-support equipment.

The sodium-potassium (NaK) primary loop contained a centrifugal motor-driven pump, the reactor simulator, the boiler, and the auxiliary heat exchanger. An electric heater (ref. 5) together with an ignitron power controller and an analog computer comprised the reactor simulator. The electric heater was configured similar to the reactor, and reactor nucleonics and control logic were programmed on the computer. The power controller matched the heater electrical power with the time-varying computer signal representing reactor power. . Details of the reactor simulator are given in references 4 and 6. The purpose of the auxiliary heat exchanger was to provide a heat sink for the reactor, or reactor simulator, prior to startup of the mercury loop.

The major components in the mercury power loop included a centrifugal pump and motor, the counterflow boiler, the four-stage axial-flow turbine-alternator, and the condenser. The boiler was a seven-tube-in-shell heat exchanger utilizing tantalum as the mercury containment material for long-term corrosion resistance (refs. 7 and 8). The condenser was a counterflow tube-in-shell heat exchanger with 78 tapered tubes containing the mercury (ref. 9). The turbine-alternator and the pump are described in references 10 and 11, respectively.

The heat-rejection loop included a centrifugal motor-driven pump, the condenser, and the radiator simulator. This simulator used two finned NaK-to-air multitube heat exchangers. Two butterfly valves controlled by the analog computer varied the airflows to the heat exchangers in order to match the outlet NaK temperature to that computed for a space radiator. The heat exchangers were modified prior to startup testing by addition of metallic mass in order that the heat capacity of these exchangers would be equal to the anticipated heat capacity of a typical space radiator. A complete description of the radiator simulator is given in reference 12. The feed-forward control circuit reported in reference 12 was not used during this series of tests. Only feedback control was used. Because an accurate simulation of radiator outlet temperature was essential for realistic condenser conditions in startup, the outlet temperature transient of the radiator simulator during a typical startup was compared with the transient computed with a digital computer model of a flight radiator. The agreement was satisfactory.

A lubricant-coolant loop (not shown in fig. 1) containing polyphenyl ether (4P3E) was used to lubricate and cool the turbine-alternator and mercury pump. It was also used to cool oxide traps on the NaK pumps.

As mentioned previously, the controls necessary for startups used test support equipment rather than flight-type components. This provided flexibility in conducting the test program. The mercury reservoir shown in figure 1 was used to inject the mercury loop inventory during startup. The reservoir was a standpipe pressurized with gas. In the flight system, the mercury would be injected at the same location (pump inlet); however, the reservoir would be pressurized by the lubricant-coolant pump.

The flow control valve in the mercury loop (fig. 1) was actuated electrohydraulically and was used to generate mercury flow ramps for the startups. A combination open-loop and feedback control of mercury flow was used with this valve. Figure 2 shows a block diagram of the control. The open-loop path provided the main control, while the feedback loop served merely as a trimming control to eliminate any error. The gain of the feedback loop, therefore, could be kept low to ensure stability. In a flight system, the mercury flow control valve would be actuated by an electric motor with only open-loop (programmed) control. The valve area variation would be specifically contoured for the selected flow ramps.

The flow control valve in the NaK heat-rejection loop (fig. 1) was electropneumatically actuated. A feedback control of NaK flow was used with this valve. This control received its input, or demand, signal from the condenser pressure control (fig. 3), which was flight-type in regard to its control logic. This logic will be discussed in the section Condenser pressure control. For a flight system, the electropneumatic valve with flow feedback would be replaced by an electric-motor-operated valve with a specially contoured area variation.

The other valves shown in figure 1 were used in the open-closed mode. Valve sequencing and other procedures were automated in 27 startups by use of a breadboard programmer.

For some of the tests, the original SNAP-8 inverter (a dc motor and a three-phase four-pole permanent-magnet alternator) supplied the necessary power to drive the system pumps prior to startup of the turbine-alternator. This inverter provided a frequency range from 95 to 260 hertz. When the test program called for frequencies and powers beyond the capabilities of this inverter, a test-facility inverter was used.

INSTRUMENTATION

System pressures including those at the mercury pump outlet, mercury boiler inlet and outlet, and the mercury condenser inlet were measured with slack-diaphragm-capillary-tube pressure transducers.

The mercury liquid flow rate was obtained by means of a calibrated Venturi meter located upstream of the boiler inlet. The differential pressure of the Venturi was measured by a transducer of the slack-diaphragm-capillary-tube type. This differential pressure measurement was used in conjunction with the analog computer to provide an on-line flow signal. Flows of NaK were measured by electromagnetic flowmeters.

The reactor simulator inlet and outlet NaK temperatures were measured by Chromel-Alumel thermocouples mounted on the outside surface of the piping.

The pump input powers were measured by thermal-element watt transducers, and the input electrical power of the reactor simulator was measured by a Hall-effect watt transducer. The output power of the alternator was measured by an electrodynamometer watt transducer. Power measurement transducers were calibrated over their expected operating range by a voltmeter and a precision current shunt.

Pump speeds were measured with electromagnetic speed pickups. Turbine-alternator speed was obtained from the alternator output frequency. A detailed description of system instrumentation is given in references 13 and 14.

Strip-chart analog recorders in the control room were used to record transient data. Conditioned voltage signals for the variables of interest were sent to these recorders. Before the recorders were used, each channel was calibrated at zero span, full span, and midspan by a voltage source to create expected recorder input voltage values. A computerized digital data recording system was also used to record transient data, as well as steady-state data. The recording system scanned and recorded a cycle of data, containing 400 different instrument outputs, in 11.43 seconds. A computer program, which calculated test-system parameters, processed each cycle of transient data separately. The results were stored on tape, and output was obtained in tabulated form and in computer plots.

STARTUP PROCEDURE

The startup plan for a flight SNAP-8 system calls for startup of the reactor followed by a slow increase of the reactor and boiler temperatures to rated values. The primary-loop NaK is circulated by running the pump at reduced speed on battery-inverter power. While the primary loop is being heated, the mercury remains in the injection reservoir, the mercury loop being at vacuum conditions. During this heating period, the reactor power is brought to a value of about 100 kilowatts (one-fifth of the required power for rated SNAP-8 conditions) by dissipating heat to space through the auxiliary heat exchanger and the radiator. The heat-rejection-loop pump, running at reduced speed on the inverter, circulates NaK through both the radiator and the auxiliary heat exchanger. Reactor operation at this power level of about 100 kilowatts is necessary to ensure satisfactory reactor response during the transient introduced by power conversion system startup. At the end of the primary-loop heatup, the inverter frequency is increased linearly up to the value required by the mercury pump during mercury injection. Associated with this increase in inverter frequency is an increase in primary-loop and in heat-rejection-loop flow. When the resultant temperature transients in the primary loop have settled out, startup of the power conversion system may begin.

In the test program, the initial condition for startups of the power conversion system corresponded to the end of the primary-loop heating period with the primary-loop temperatures steady at the values associated with the final inverter frequency. The reactor simulator outlet temperature was within the range of 967 to 989 K (1280° to 1320° F), which was the dead band of the simulated reactor control. Reactor simulator power was usually close to 100 kilowatts, although some variations about this value were used. Primary-loop flow ranged from 12 000 to 17 000 kilograms per hour (26 500 to 37 500 lb/hr), depending upon the inverter frequency, which was a test variable in the mercury injection study. The heat-rejection-loop flow was throttled to values of 2300 to 3200 kilograms per hour (5000 to 7000 lb/hr) by the initial setting of the heat-rejection flow control valve. Radiator simulator outlet temperature was generally about 310 K (100° F). Just prior to mercury injection, the heat transfer through the auxiliary heat exchanger was stopped by closing the open-closed valve in the auxiliary loop.

Power conversion system startup has two different phases. In the first phase, the system is brought rather rapidly to a minimum self-sustaining power level at which all of the rotating components are at rated speed. The second phase consists of slowly raising the power output to the rated value.

The first phase is called the bootstrap operation. In the test program, the mercury loop lines between the boiler and the pump and between the condenser and the pump were prefilled with liquid mercury (fig. 1). Then the mercury pump was started and operated at reduced speed on the inverter. Speeds of 55 to 75 percent of rated were used. Next, the pump was filled with liquid mercury by opening the valve at the pump inlet and the injection valve. When the pump inlet pressure indicated that the pump was filled, the open-closed valve at the pump outlet was opened. (For a flight system, the valves at the pump inlet and outlet would be eliminated and the lines and pump would be filled in one operation.) After pump filling, the open-closed valve at the boiler inlet was opened and the mercury flow control valve started a ramp upward in mercury flow, drawing inventory from the mercury reservoir (standpipe). When the frequency of the accelerating turbine-alternator reached that of the inverter, the mercury pump and the other system pumps were transferred from inverter power to alternator power. The turbine-alternator-pump combination then accelerated to rated speed. The ramp in mercury flow was stopped at the level required to sustain the system in steady state safely. This self-sustaining flow was 3000 kilograms per hour (6600 lb/hr). At the end of the ramp, the condenser outlet valve was opened. The mercury reservoir valve was closed when the desired inventory had been injected. The mercury loop was then a closed system with the pump inlet pressurized by the condenser. Condensing pressure was controlled by the dead-band condenser control manipulating the flow control valve in the heat-rejection loop.

The startup sequence provides for a time delay between the conclusion of the bootstrap operation and the remainder of the startup which brings the power output of the system to its rated value. This delay allows the reactor loop transients to subside. The second phase is accomplished by gradually ramping the mercury flow up to its rated value of 5580 kilograms per hour (12 300 lb/hr). This ramp is called the power ramp.

Figure 4 shows the transients in mercury flow, rotating speeds, and net alternator power output for both phases of the power conversion system startup.

RESULTS AND DISCUSSION

Bootstrap Operation

The most critical part of the power conversion system startup is the bootstrap operation. Consequently, a large percentage of the startup runs was devoted to examining this operation. Ninety-one runs were made in which some, or all, of the pumps were brought to rated speed by the accelerating turbine-alternator. These runs were used primarily to study two important factors in the bootstrap operation: the mercury flow ramp duration and condenser pressure control. The ramp-duration study will be discussed first. The objective was to determine the ramp duration that would give dependable bootstrapping and, at the same time, cause minimum disturbances in the reactor loop.

Maximum limit for duration of mercury flow ramp. - A startup showing the maximum limit for duration of the bootstrap ramp is shown in figure 5. In this figure, the mercury flow and turbine-alternator speed are shown as functions of time. The mercury flow was started up on a ramp with an intended duration of 145 seconds, as shown by the dashed lines. At 70 seconds the alternator frequency was equal to the inverter frequency and the pumps were transferred to alternator power. After this transfer, the acceleration of the turbine-alternator and pumps became very slow. In fact, the acceleration of the mercury pump was so slow that the mercury flow dropped below the intended ramp. As rated speed was approached, a small additional load was added because of the automatic activation of the turbine speed control. With this addition, the load exceeded the available power and caused the turbine-alternator to decelerate rapidly. Because the pumps were being supplied with alternator power, the mercury flow also fell rapidly because of the deceleration of the pump. At this point (105 sec) the pumps were transferred manually to an auxiliary power supply. This allowed the turbine-alternator to recover its acceleration to rated speed. Otherwise, the startup would have been unsuccessful.

An understanding of the problem experienced in this run can be gained from figure 6, which indicates the speed and power characteristics of the turbine-alternator and pumps during a typical bootstrap ramp. In the speed plot, the initial pump speeds are shown by a horizontal dashed line. Pump transfer from auxiliary power to alternator power occurs at the intersection of the dashed line and the turbine-alternator speed curve. The remainder of the speed curve, up to rated speed, applies to both the pumps and turbine-alternator and represents the bootstrapping. The turbine output power provided by the mercury vapor flow and the total pump power load on the turbine are also shown in figure 6. The difference between the turbine output power and the pump power at any time represents the instantaneous turbine power margin. The turbine-alternator accelerates at a rate proportional to this margin. If the power margin is too small, any perturbation in turbine power or load can cause deceleration of the turbine-alternator. An example of this was the load added by the speed control, as shown in figure 5. As can be seen in figure 6, the minimum power margin occurs when the turbine-alternator approaches rated speed. This results from the fact that the power requirement of the pumps increases with the cube of the speed.

Figure 7 shows the minimum turbine power margin as a function of mercury flow ramp duration. The dashed line in the figure represents the steady-state margin associated with the final flow of the bootstrap ramp. This steady-state margin in turbine output power was calculated from the electrical power measurements for the alternator and pumps by using prior information on alternator efficiency. The data points in the figure, which represent the minimum power margins in the transients, were determined by adjusting the steady-state value by the fraction of the steady-state flow that had been reached when the turbine achieved rated speed. This procedure was considered more accurate for the transient data than the use of the electrical power measurements. Figure 7 shows that the power margin became small for the longer mercury flow ramps. For the shorter ramps, the minimum power margin was equal to the steady-state margin. However, as the ramp duration became longer than approximately 70 seconds, the minimum power margin decreased. The margin was essentially zero for a ramp duration of 145 seconds.

Minimum limit for duration of mercury flow ramp. - Shorter mercury flow ramps, therefore, make the bootstrapping more dependable. However, consideration must be given to two factors that tend to impose a minimum limit on the ramp duration. One of these was a problem encountered in the mercury loop involving the transient pressure-drop characteristics of the boiler. The second was the concern for reactor-simulator transients which, if too severe, could be detrimental to an actual reactor.

The variation with time of parameters pertinent to the mercury loop problem, including pump and turbine speeds, pump discharge pressure, boiler inlet and exit pressures, and mercury flow, is shown in figure 8. For this startup, the intended mercury flow ramp duration was 30 seconds, as shown by the dashed lines. With the mercury pump still at its initial speed, however, the mercury flow began to deviate from the intended ramp. This was caused by the boiler pressure-drop transient. At approximately 28 seconds into the ramp, boiling began abruptly, as indicated by the boiler inlet pressure. At this time, the boiler inlet pressure rose rapidly and approached the level of pump discharge pressure. Consequently, the pressure drop available for the mercury flow control valve was too small, and the flow ramp could not be maintained. This problem could be eliminated with a higher initial speed of the mercury pump.

Startup test data showed that the initial pump speed, or power supply frequency, required to maintain the intended mercury flow ramp was related to the ramp duration (fig. 9). For a given ramp duration, initial pump speeds above the curve shown in figure 9 provided sufficient pump discharge pressure to maintain the flow ramp, despite the surge in boiler inlet pressure. However, initial pump speeds below the curve did not produce enough pressure to maintain the intended flow ramp. As shown in the figure, the mercury pump initial speed requirement increased by a factor of approximately 2 in going from a 145-second ramp to a 30-second ramp. This means the inverter power required to drive the pump at the higher speed would increase by a factor of 8. For the mercury pump alone, the factor of 8 would not be significant, since the power involved is small. For simplicity, however, all pumps of the system should use a common frequency from the auxiliary power supply. Since the pump speeds are directly proportional to power supply frequency, a higher speed for the mercury pump would entail a higher speed for all pumps. Thus, the factor of 8 becomes important.

The second factor which tends to dictate a minimum limit for the ramp duration is the constraint imposed on reactor temperature transients. If the mercury flow were ramped up to the self-sustaining level in a short time, heat would be extracted rapidly from the boiler, and the temperature of the NaK entering the reactor would drop quickly. An excessively fast temperature change in the reactor could impose undesirable thermal stress gradients in the reactor fuel elements. Therefore, in selecting a mercury flow ramp duration, consideration has to be given to the rate of change of reactor-simulator inlet temperature. The maximum allowable rate of change of reactor inlet temperature is dependent on the time duration of the particular rate of change. The constraint varies from 1.4 K (2.5° R) per second for rates of change that exist for 60 seconds or more to 5.6 K (10° R) per second for instantaneous rates of change.

Figure 10 shows how the rate of change of reactor-simulator inlet temperature compared with the reactor constraint for various values of the mercury flow ramp duration. The comparison is made for average rates of change over 10-second intervals. The data symbols represent the maximum 10-second rate of change for a given startup, and the dashed line designates the appropriate value of the reactor constraint. Comparison of the solid curve through the data symbols with the dashed line shows that the 10-second rate of temperature change at the reactor simulator inlet was below the reactor constraint by a significant factor for all of the ramp durations. There was a definite decrease in the safety factor, however, with decreasing ramp duration. The safety factor was 4 for a 140-second ramp duration but decreased to 2 for a ramp duration of 30 seconds. Examination of data other than those shown in figure 10 indicated that similar safety factors in the rate of temperature change existed for time intervals either longer or shorter than 10 seconds.

Selection of ramp. - In selecting the mercury flow ramp duration for the bootstrap operation, consideration must be given to the maximum limit associated with the turbine minimum power margin and the consequences of backing off too far from this limit. As discussed in the previous section, inverter power required for the pumps increases as the ramp duration decreases, as does the rate of change of reactor-simulator inlet temperature. For convenience, the tradeoffs involved in selecting the ramp duration are shown in figure 11. The turbine power margin, initial pump power requirement, and the maximum rate of change of reactor-simulator inlet temperature for a 10-second interval are shown as functions of mercury flow ramp duration. Based on the curves shown in figure 11, a ramp duration in the range of 80 to 100 seconds is a good selection. Ramps in this range provide almost the steady-state turbine power margin, a relatively low initial pump power requirement, and a safety factor of 3 from the constraining value of inlet temperature rate of change for the reactor.

Figure 12 illustrates the transients of several variables during a bootstrap operation with a 100-second mercury flow ramp. An initial speed of 72.5 percent of rated speed was used for all the pumps. For the mercury pump, this initial speed satisfied the criterion of figure 9. As shown in figure 12, the mercury flow transient adhered rather closely to the intended ramp (dashed lines) and the turbine-alternator accelerated smoothly to rated speed with the pump load transfer occurring at about 55 seconds. The largest reactor-simulator inlet temperature rate of change for a 10-second interval was approximately 1.4 K (2.5° R) per second. This occurred during the time interval from 60 to 70 seconds.

Condenser pressure control. - As mentioned previously, another important aspect of the bootstrap operation is condenser pressure control. There is an upper limit of condenser pressure associated with the self-sustaining value of mercury flow, since this pressure is the turbine back pressure. During the flow ramp, the pressure must not build up toward this limit too quickly. If it does, the turbine-alternator acceleration will be impeded. There is also a lower limit for condenser pressure after the injection process ends. Then, in a zero-gravity environment, the pump suction pressure is essentially equal to the condenser pressure. Consequently, the condenser pressure at the end of mercury injection has to be large enough to prevent pump cavitation. Because of these limits, a condenser pressure control is used in the startup.

The control is a dead-band control. The concept is shown in figure 13. The bottom plot shows the mercury flow ramp to the self-sustaining level. The plot at the top shows the acceptable corridor for the condenser pressure as prescribed by the turbine back pressure and pump suction pressure requirements. Corrective action is taken whenever the condenser pressure goes outside the prescribed dead band, represented by the dashed lines within the acceptable corridor. The corrective action is shown in the middle plot and consists of ramping the condenser NaK flow upward when the pressure goes above the dead band and downward when the pressure goes below the dead band. The control does not operate when the pressure is within the dead band. In addition, the control does not operate during the initial buildup of condenser pressure into the dead band. This pressure buildup is controlled by an initial condenser NaK flow.

The performance of the condenser pressure control was thoroughly investigated. Many of the tests involved the use of off-design startup conditions. This subjected the control to extreme condenser transients. The testing showed that dead bands as small as 1.4 newtons per square centimeter (2 psia) resulted in stable control provided the ramp rate of the condenser NaK coolant flow was low (about 15 percent of rated NaK flow per minute). With this ramp rate low, however, initial overshoot of the dead band and, hence, high turbine back pressure were a problem for some startups. The overshoot problem was corrected by doubling the rate of the coolant flow ramp to a value of about 30 percent of rated NaK flow per minute. With this higher rate, dead bands of 2.1 or 2.8 newtons per square centimeter (3 or 4 psia) were required for adequate stability margin. The zero-gravity requirement for pump suction pressure was satisfied by using initial NaK flows below about 15 percent of the rated value.

The performance of the pressure control during extreme condenser transients is illustrated in figures 14 and 15. In the startup shown in figure 14, the mercury flow was ramped up to the self-sustaining level in 30 seconds rather than in the preferred time of 80 to 100 seconds. In the startup shown in figure 15, more than twice the design value of liquid mercury inventory was allowed to accumulate in the condenser before injection was stopped. For both startups, the pressure response was satisfactory in regard to initial overshoot. Although the initial overshoot of the pressure above the dead band was noticeable, it was small enough to avoid an appreciable loss in turbine power. Both pressure responses were also good in regard to the number of oscillations and the amplitude of the oscillations. Finally, the pressures at the end of injection for both startups were well above the value required for pump suction in zero gravity. Many other tests of this nature showed that the control could cope with a wide range of conditions in the bootstrap operation. A detailed discussion of the condenser pressure control test results can be found in reference 15.

Power Ramp

Stabilization time. - The final phase of startup is the power ramp. It begins after a stabilization period for the reactor loop transients caused by the bootstrap operation. These transients are illustrated in figure 16. The bottom plot shows the bootstrap ramp of mercury flow to the self-sustaining flow. The middle plot shows the power response of the reactor simulator. The top plot shows the inlet and outlet NaK temperatures of the reactor simulator. It can be seen that the power and temperature transients were considerably diminished after 2 cycles, or 1200 seconds. A stabilization time of 1200 seconds, therefore, was selected.

The period of stabilization for a flight system may be different from that experienced during these tests. Differences could result from changes in reactor-loop heat capacity or changes in reactor temperature coefficients of reactivity. The coefficients used during these tests were those of the SNAP-8 development reactor. The coefficients expected for a flight-type reactor would provide closer control of temperature and therefore tend to reduce the stabilization time.

Effect of ramp duration. - After the stabilization period, the system is ramped to full power operation. During the test program, the duration of the power ramp was varied from 500 to 1000 seconds. Figure 17 shows reactor-simulator inlet and outlet temperature, reactor-simulator power, and mercury flow as a function of time for a 500-second power ramp. The curves indicate a smooth transition from self-sustaining to rated power operation. The minor irregularities in reactor simulator outlet temperature and power are due to the stepping action of the simulated reactor control. The reactor could easily tolerate a ramp of this duration. Power ramps even less than 500 seconds in duration may be compatible with the load-following capabilities of the reactor.

Problems in condenser pressure control, however, occurred during the 500-second power ramp. It is observed from the condenser pressure curve in figure 18 that these problems began at approximately 360 seconds into the ramp. Until this time, the condenser control had forced the condenser pressure back into the dead band, 6.9 to 9.7 newtons per square centimeter (10 to 14 psia), whenever it exceeded the upper limit. An indication that the control was operating properly is the stepwise increase in coolant flow (fig. 18). After 360 seconds, however, the condensing pressure remained above the upper dead-band limit even though the control ramped the coolant flow upward in a continuous manner. This mode of operation indicates that the ramp rate of the control was too small for a 500-second power ramp, even though it was close to the optimum value for the bootstrap operation previously discussed. Another problem occurred at about 450 seconds into the ramp. At this time the control was unable to increase coolant flow since the maximum flow capability of the heat-rejection loop had been obtained. The result was a further increase in condensing pressure above the upper dead-band limit.

These two problems could be corrected to allow use of a 500-second power ramp. First, a variable ramp rate in coolant flow could be built into the condenser pressure control for compatability with both the bootstrap operation and a fast power ramp. In addition, the flow capability of the heat-rejection loop could be increased beyond that required for steady-state rated power operation. This could be done by enlarging the loop piping or modifying the pump. However, when the disadvantages of control complexity and either larger piping or increased pumping power are considered, the more attractive solution is to slow down the mercury flow power ramp.

A 900-second power ramp is shown in figure 19. For this power ramp, the control had the same coolant flow ramp rate as for the 500-second power ramp. It also had the same maximum flow limitation. Both were sufficient for the 900-second power ramp. The condenser pressure was held within the dead band throughout the transient.

SUMMARY OF RESULTS

One hundred thirty-five startup tests were conducted on a SNAP-8 power conversion system coupled with a reactor simulator and radiator simulator. Both the relatively fast transient to a self-sustained condition and the gradual transient that achieves rated power were investigated. The investigations showed that dependable startup of the power conversion system can be ensured with procedures that will treat the reactor very gently. The more specific results of the testing are as follows:

1. Startup to the self-sustained level was successfully accomplished with mercury flow ramps up to a maximum limit of 145 seconds in duration. The turbine power margin, however, for acceleration of the turbine-alternator and pumps to rated speed was larger for shorter ramps.

2. For all durations used for the ramp in mercury flow to the self-sustaining level (30 to 145 sec), the maximum rates of temperature change at the inlet of the reactor simulator were always well within the specified acceptable values for the reactor. The safety factor, however, increased with increasing ramp duration.

3. Considering both the turbine power margin and the safety factor in rate of change of reactor inlet temperature, a duration in the range of 80 to 100 seconds was selected as optimum for the ramp to self-sustaining mercury flow. Ramps in this range had substantial turbine power margin and a safety factor of 3 from the constraining value of rate of change of reactor inlet temperature.

4. A simple dead-band control of condenser pressure effectively coped with a wide range of condenser conditions during the transient to self-sustained operation. The control is required to limit turbine back pressure and to maintain adequate mercury pump suction pressure.

5. A 500-second mercury flow ramp from the self-sustaining level to the rated-

power level was very compatible with reactor-simulator load-following capabilities. Slowing the power ramp down to 900 seconds enabled the condenser control to perform satisfactorily with a single ramp rate of condenser coolant flow for both phases of start-up.

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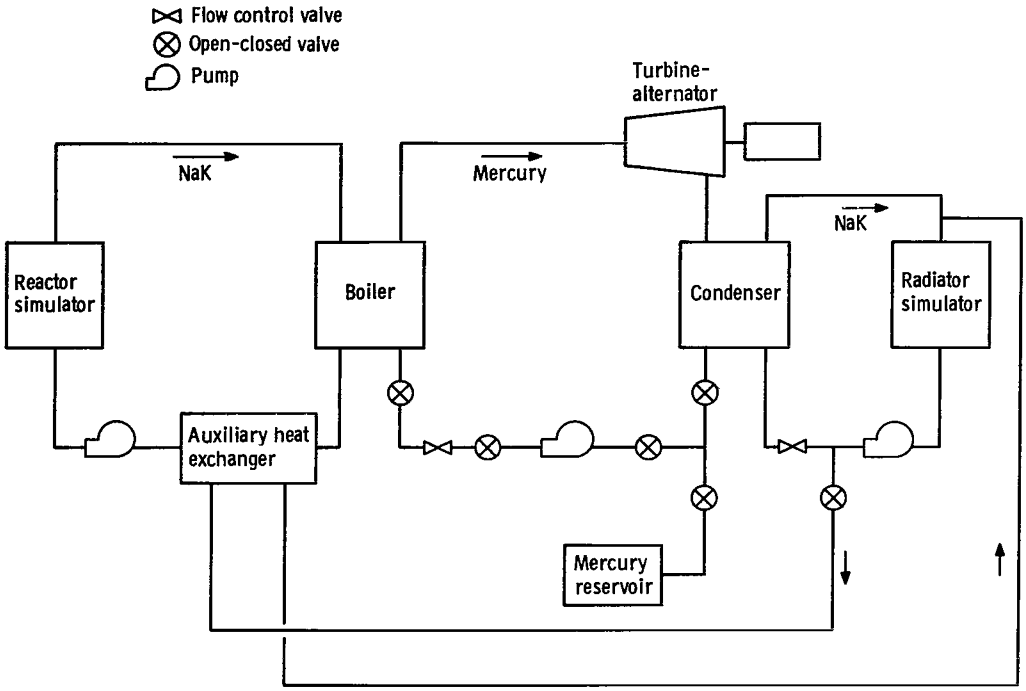

Figure 1. - Simplified diagram of SNAP-8 test system.

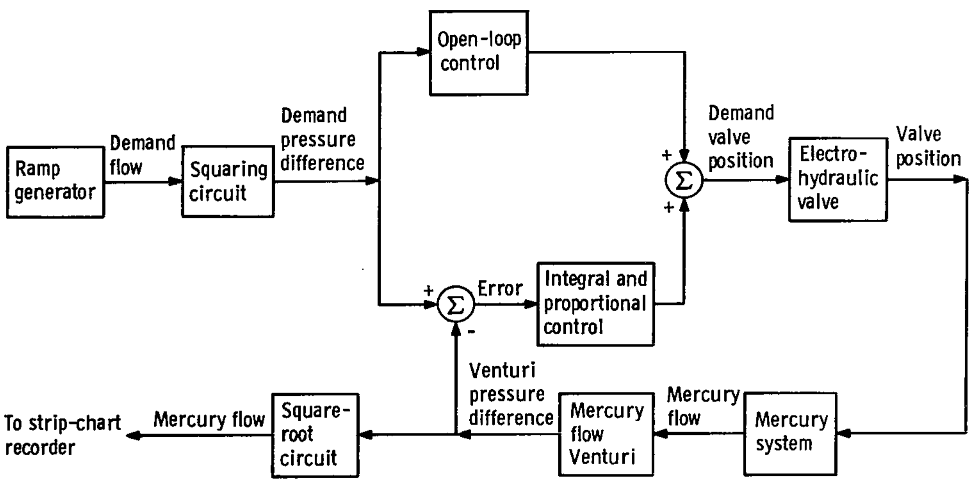

Figure 2. - Block diagram of mercury flow control.

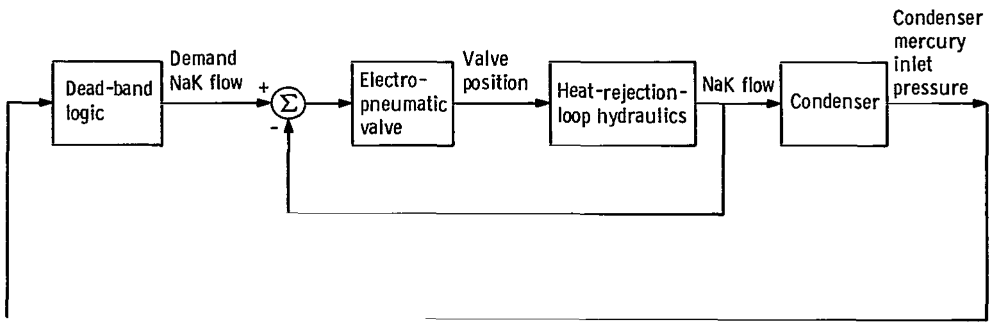

Figure 3. - Block diagram of condenser pressure control.

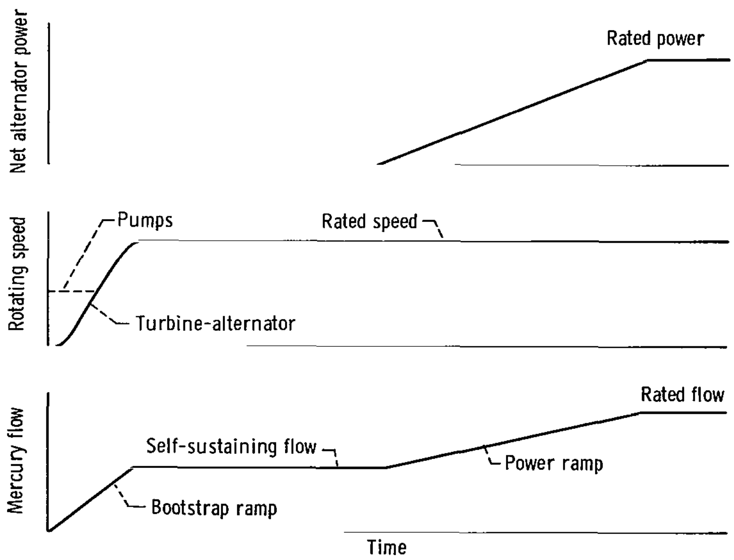

Figure 4. - Startup profiles of mercury flow, rotating speeds, and net alternator power.

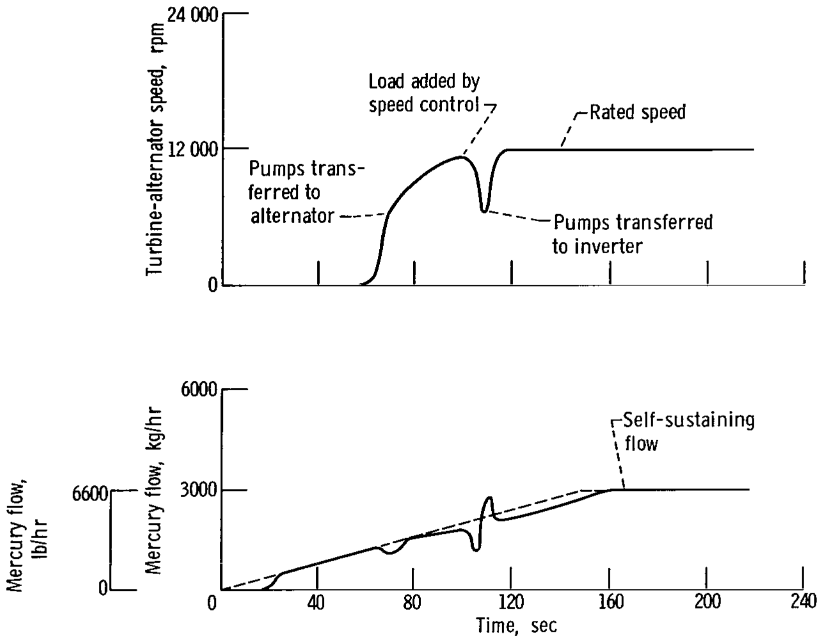

Figure 5. - Maximum limit for duration of bootstrap ramp.

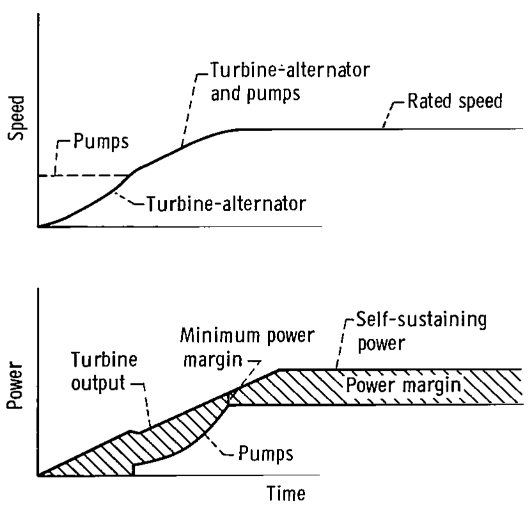

Figure 6. - Speed and power characteristics during bootstrap ramp.

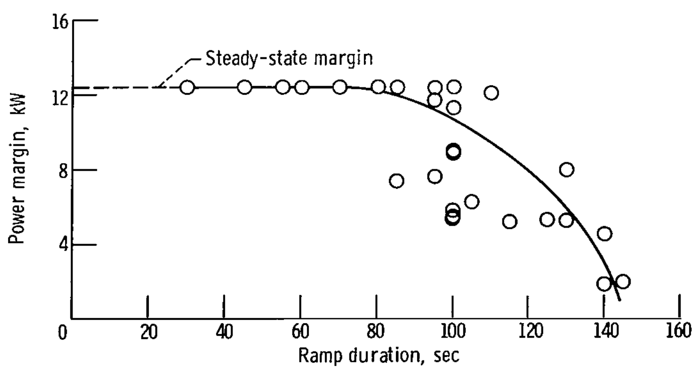

Figure 7. - Effect of mercury flow ramp duration on minimum turbine power margin.

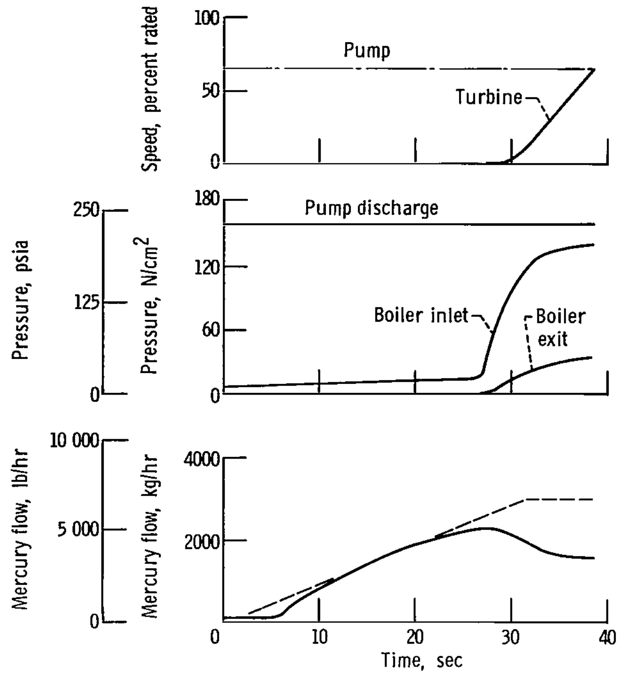

Figure 8. - Initial mercury loop characteristics for 30-second mercury flow ramp.

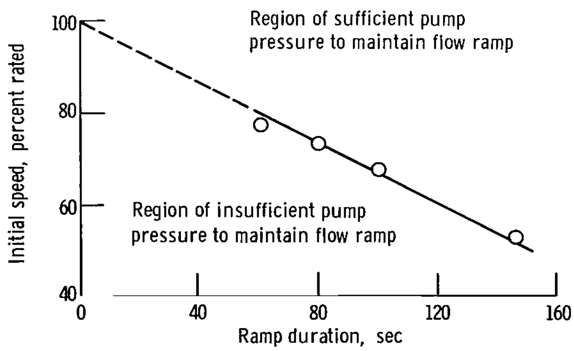

Figure 9. - Effect of mercury-flow ramp duration on minimum initial speed required for mercury pump.

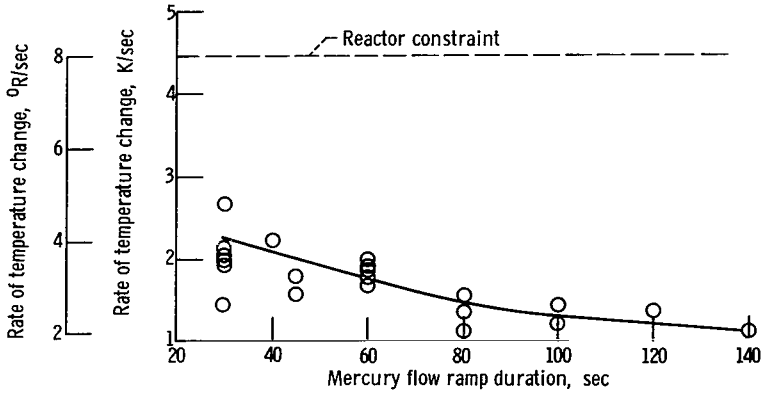

Figure 10. - Effect of ramp duration on maximum rate of temperature change with 10-second duration at reactor simulator inlet.

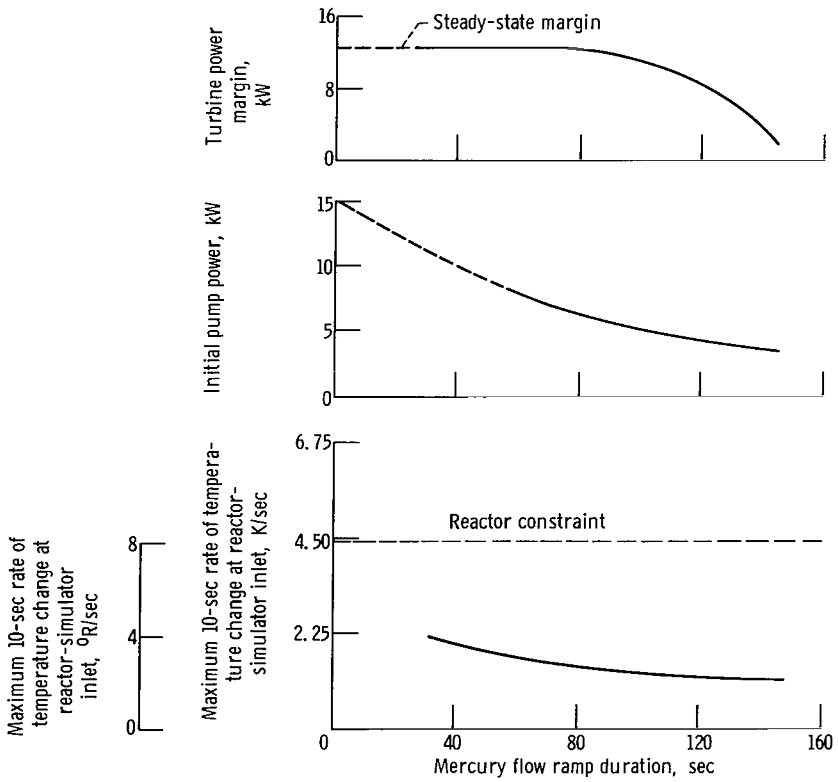

Figure 11. - Tradeoffs involved in selection of mercury flow ramp for bootstrap operation.

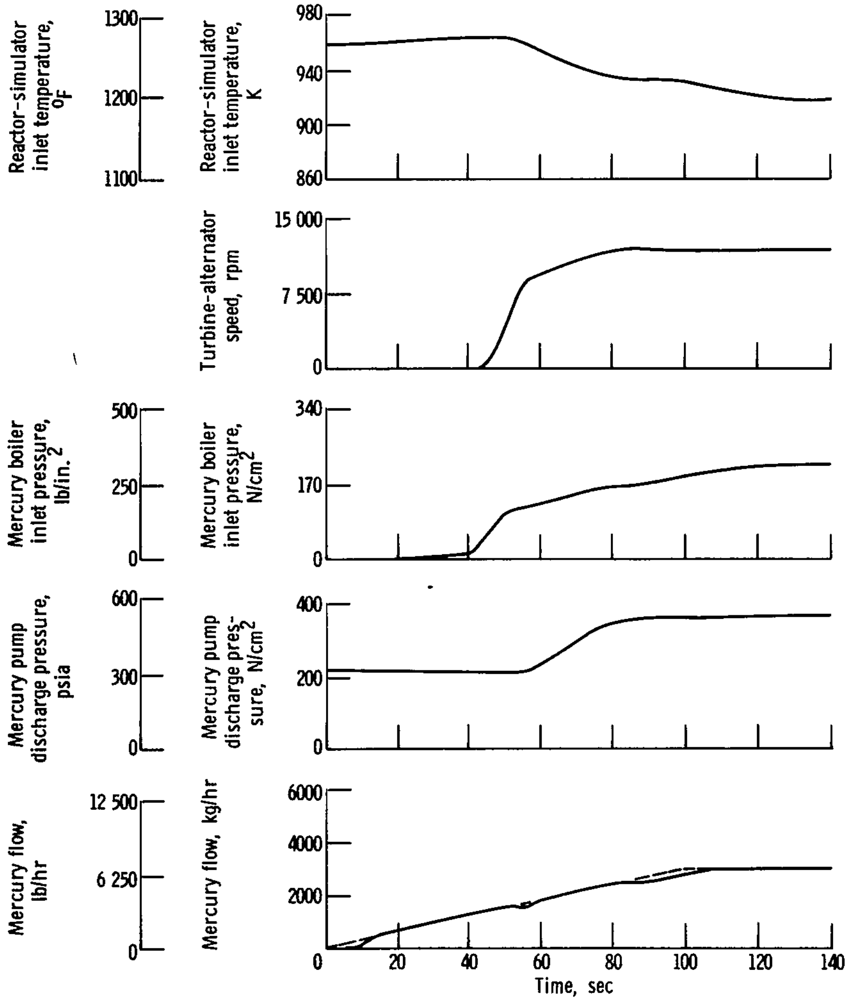

Figure 12. - Startup transients for 100-second mercury flow ramp. Pumps initially at 72.5 percent of rated speeds.

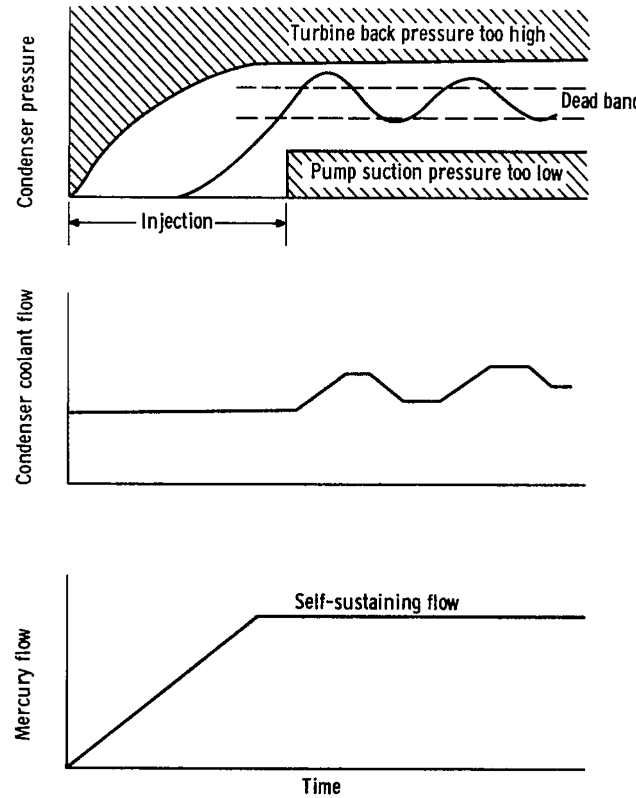

Figure 13. - Condenser pressure control concept.

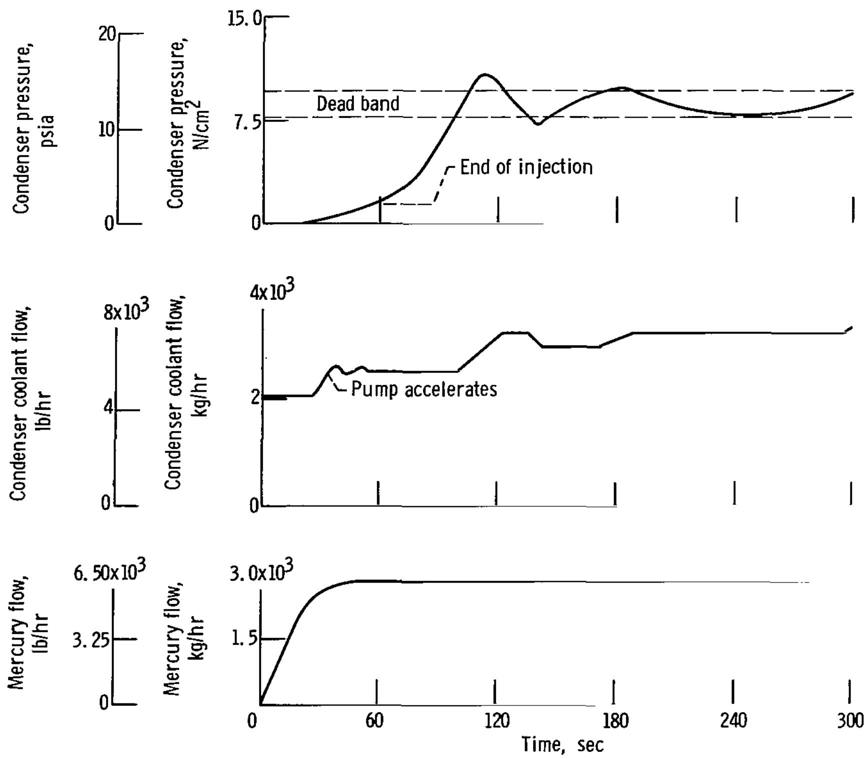

Figure 14. - Performance of condenser pressure control with 30-second mercury flow ramp.

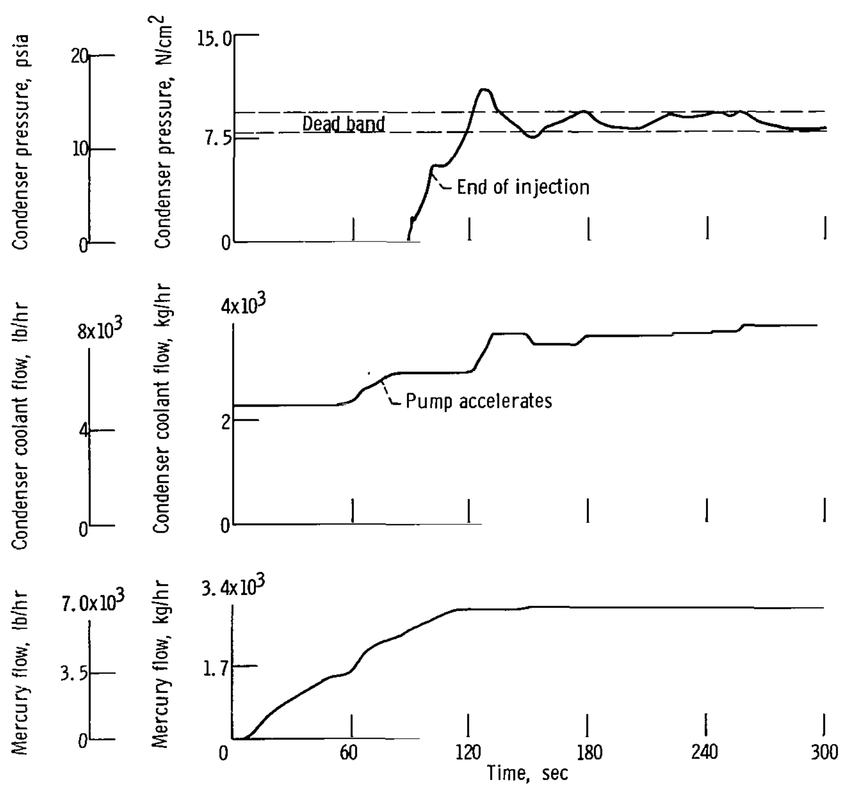

Figure 15. - Performance of condenser pressure control with 100-pound condenser inventory.

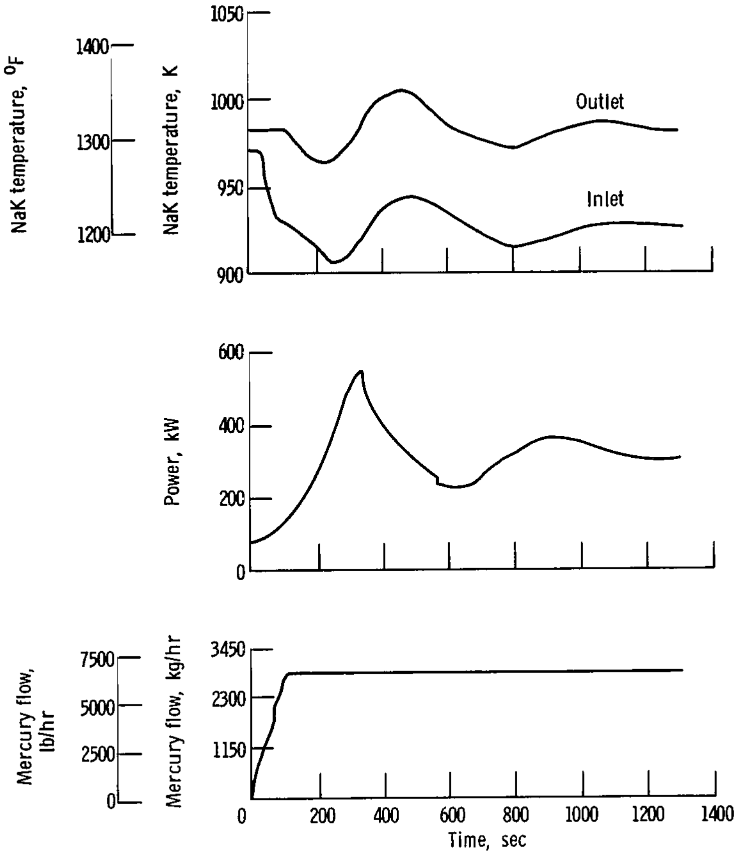

Figure 16. - Reactor-simulator transients dying out after bootstrap operation.

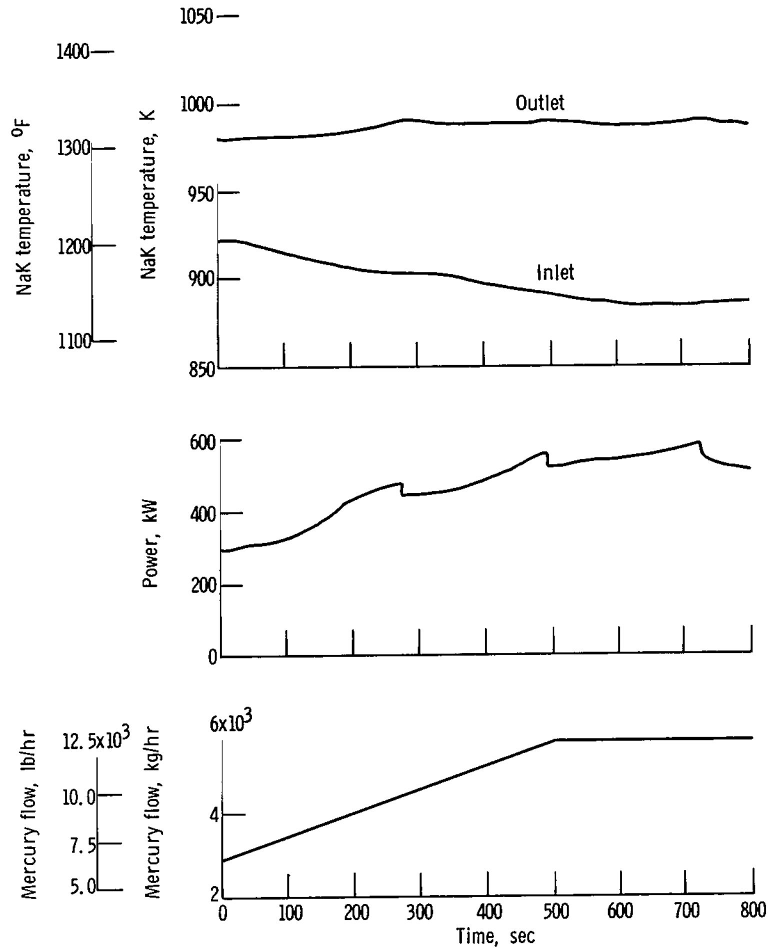

Figure 17. - Reactor-simulator transients for 500-second power ramp.

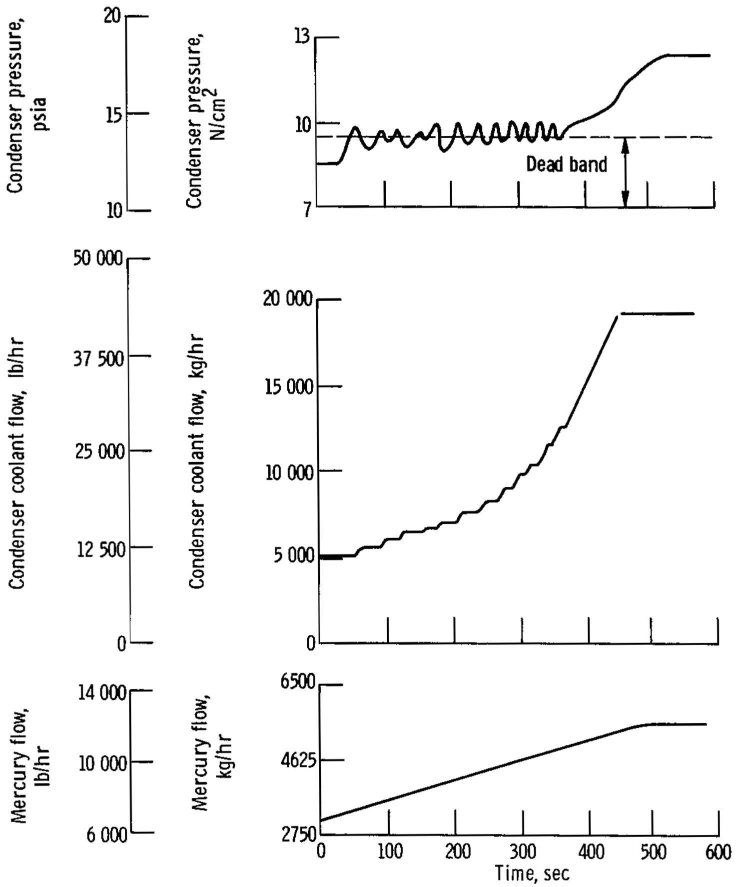

Figure 18. - Inadequate control of condenser pressure during 500-second power ramp.

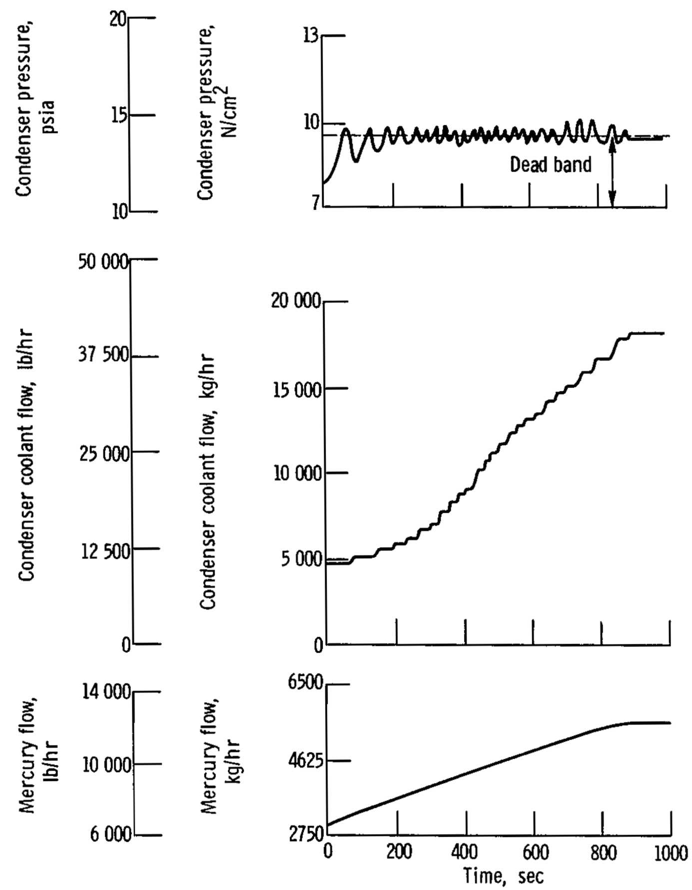

Figure 19. - Acceptable control of condenser pressure during 900-second power ramp.

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