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EXPERIMENTAL INVESTIGATION OF CONDENSER PRESSURE CONTROL DURING SNAP-8 STARTUP

I - Inventory Control of Condensing Pressure

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16. Abstract

An inventory method for controlling the mercury condensing pressure during SNAP-8 startup was tested. With this method liquid mercury flows into or out of the system, maintaining pressure equilibrium with a constant pressure reservoir. It was found that to have adequate control sensitivity, the control must operate in the high inventory region of the condenser. Also, the condenser coolant (NaK) flow schedule was found to be a critical factor in achieving satisfactory control during startup. Pressure control was satisfactory for some of the startups; however, it appears doubtful that a NaK flow ramp to the self-sustaining level can be found which would allow satisfactory control for the expected variety of startups.

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SUMMARY

One method considered for controlling the mercury condensing pressure during SNAP-8 startup is the inventory method. With this method liquid mercury flows into or out of the system, maintaining pressure equilibrium with a constant pressure reservoir. Tests were conducted in a one-g field to evaluate this method for controlling condenser outlet pressure during zero-g system startup.

Steady-state condenser performance maps were made at the self-sustaining and design mercury flow rates of the system. It was found that to avoid pressure drop at low condenser inventories and to have adequate control sensitivity, the control must be designed to operate in the high inventory region of the condenser map.

Control performance was investigated for startups to the self-sustaining and design mercury flow levels. The condenser coolant (NaK) flow schedule was a critical factor in achieving satisfactory startups. It was found that the NaK flow schedule must be chosen so that (1) the NaK flow is at a sufficiently high level at all times to avoid condenser inventories associated with significant pressure drop, and (2) the final NaK flow level is sufficiently low to avoid operation with a flooded condenser. From the test data it appears doubtful that a NaK flow ramp to the level required for the self-sustaining mercury flow can be found which would satisfy these requirements for the expected variety of startup conditions.

INTRODUCTION

SNAP-8 is the reactor-powered, mercury Rankine cycle, space power system currently under development (ref. 1). It has liquid-metal heat-transfer loops. A eutectic mixture of sodium and potassium (NaK) is circulated to transfer heat from the nuclear reactor to the mercury boiler. In the boiler, subcooled mercury is preheated, evaporated, and superheated. After passing through the turboalternator, the mercury is condensed and subcooled in a counterflow multitube condenser. The heat rejection loop circulates NaK to transfer heat from the condenser to the radiator where the heat is dissipated to space. This electric generating system is being developed to produce more than 35 kilowatts electric and to operate unattended for several years in space after automatic startup. It will also have shutdown and restart capabilities.

The startup of SNAP-8 has three phases: (1) reactor startup, during which the primary loop is brought to design temperature; (2) power-conversion system startup, during which mercury flow is brought to the self-sustaining level (minimum level for which turbine power is sufficient to maintain system operation); and (3) a phase during which mercury flow is increased from the self-sustaining to the rated level. At the beginning of the second phase, the mercury inventory is injected into the evacuated vapor portion of the mercury loop with a programmed ramp of flow rate against time so that the turboalternator is brought to rated speed. (The portion of the loop from condenser exit to boiler inlet is first filled with liquid mercury.) When the injection process is completed, the mercury pump recirculates the liquid mercury from the condenser. Upon reaching the self-sustaining power level, the mercury flow rate is held constant until transients have settled out. It is then increased in a gradual manner to the full-power value during the final phase.

During power conversion system startup, the condenser pressure will increase from essentially zero to the design value. There may be transient conditions, however, which tend to cause the pressure to rise much higher than the design value. Since condenser inlet pressure is also the turbine back pressure, high inlet pressure must be avoided so as not to lower turbine power. It is equally important to avoid low outlet pressure in order to prevent the mercury pump from cavitating.

Two methods of controlling condensing pressure were experimentally investigated. One method consists of increasing the coolant flow when inlet pressure is above a specified deadband and decreasing the coolant flow when inlet pressure is below the deadband; the test results for this method are reported in reference 2. The other method, which is reported here, uses manipulation of the condenser mercury inventory to maintain pressure at some specified value. With this method, liquid mercury flows into or out of the system in order to maintain the condenser outlet pressure in equilibrium with a constant pressure reservoir. With a properly operating inventory control, the pump inlet pressure will be maintained at an adequate level. If the NaK cooling capacity of the condenser is too high, however, the control of condenser outlet pressure will be accomplished by excessively loading the condenser with inventory. This could result in interfacial or tube-to-tube stability problems in the condenser during zero-gravity operation.

If the NaK cooling capacity is too low, the control will force the condenser to operate with low inventory. This could result in high condenser pressure drop and, consequently, high condenser inlet pressure. The principal question in the investigation, therefore, was whether a suitable NaK flow schedule could be found to avoid both extremes of operation.

The tests were conducted in the W-1 experimental facility at Lewis Research Center. The rig was a test version of the SNAP-8 system containing all major components except the nuclear reactor and radiator. The nuclear reactor was simulated by an analog-computer-controlled electric heater (ref. 3). The radiator was simulated by an analog-computer-controlled air-blast heat exchanger (ref. 4).

Inventory control performance was investigated for startups to the self-sustaining level (phase 2) with emphasis on the effect of the NaK flow schedule. Control performance was also investigated for phase 3 of the startup where the mercury flow is ramped from the self-sustaining level to the rated-power level.

INVENTORY CONTROL METHOD

The inventory method for controlling condensing pressure is explained by reference to the system schematic in figure 1. The inventory control is essentially a mercury in-

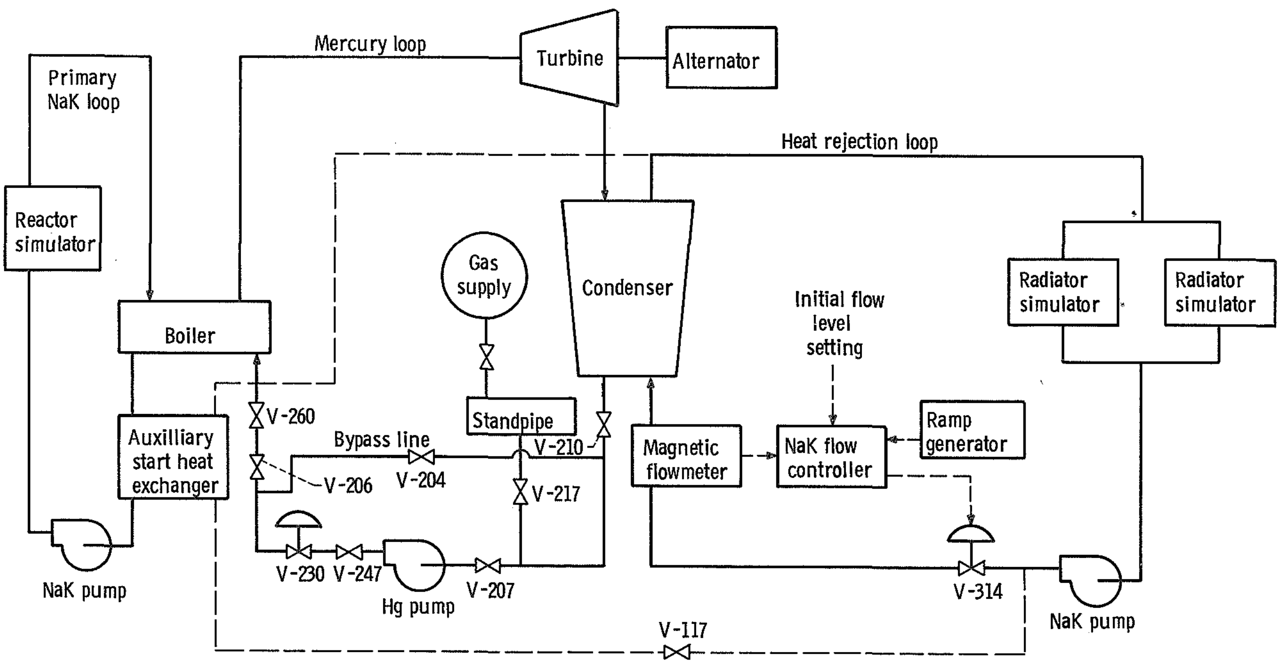


Figure 1. - Schematic diagram of SNAP-8 test system.

jection system (see standpipe, fig. 1) that is left open to the mercury loop at all times; the injection system is tied into the loop between the pump and the condenser outlet. In a zero-gravity environment the injection system reservoir pressure would be set and regulated at the desired value of the condensing pressure. If, for example, the condenser outlet pressure were lower than the reservoir pressure, mercury would be pushed from the injection system to the condenser. The resulting decrease in condensing region heat-transfer area would tend to increase condenser pressure until outlet pressure equaled the set-point reservoir pressure.

The inventory control method appears to be a desirable one because of its inherent simplicity. No control logic is required to make decisions on the basis of a signal from a separate pressure-sensing element, as is the case when coolant flow control is used. Inventory control should be more reliable than a control which requires a separate sensor and logic. In addition, analysis has shown that the inventory control can be very fast compared to other types of control that have been considered (ref. 5).

The inventory control experiments were conducted in a one-g environment using a vertically mounted condenser. Therefore, since the one-g condenser outlet pressure was the sum of the zero-g condenser outlet pressure and liquid gravity head pressure, direct inventory control of zero-g outlet pressure could not be tested. It was necessary to make inlet pressure the controlled variable. Therefore the tested inventory control method is equivalent to the desired method only when there is no significant pressure drop in the condenser. The tests indicated that there was significant pressure drop for inventories less than about 30 pounds (13.6 kg). For inventories greater than 30 pounds (13.6 kg), however, there was apparently little pressure drop and, in fact, some pressure rise over most of this range. Inlet pressure was visually monitored and inventory was controlled by manually adjusting the gas pressure on the mercury in the standpipe.

APPARATUS

Test System

The test system was designed to simulate the basic SNAP-8 system. Essentially all of the major SNAP-8 components except for a nuclear reactor and a radiator were used. A schematic diagram of the basic test system with details relevant to the condenser pressure control is given in figure 1. The analog-computer-controlled reactor simulator in the primary loop serves as the thermal energy source for the test system. A centrifugal pump circulates NaK to transfer this thermal energy to the boiler. During startup, operation of the primary loop occurs before operation of the mercury power generation loop. An auxiliary start heat exchanger is therefore used to transfer the thermal energy to the heat rejection loop during this interval.

In the power generation loop, liquid mercury is supplied to the boiler after passing through various valves (used for startup purposes) from a centrifugal pump. The liquid mercury is vaporized in the boiler and expanded through the turbine to drive an electrical alternator for useful power output. From the turbine the mercury vapor passed downward into the vertically mounted condenser where it was condensed and subcooled before again entering the centrifugal pump.

Prior to startup the vapor portion of the mercury loop is evacuated. A supply of liquid mercury is contained in the standpipe and isolated from the system by valve V-217. A pressurized gas supply regulated by a manual loader in the control room is used to manipulate the flow of mercury from the standpipe during startup. Valve V-210 at the condenser outlet serves to isolate the condenser during startup until condenser pressure builds up.

The thermal energy leaving the mercury stream in the condenser was absorbed by the NaK flowing in the heat rejection loop. This thermal energy was in turn passed on to the radiator simulator as waste heat. The cooled NaK then entered a centrifugal pump, passed through the flow control valve V-314, through a magnetic flowmeter used for flow control and data purposes, and then into the condenser.

Condenser

The SNAP-8 condenser is a counterflow heat exchanger. It is a once-through unit. The unit was vertically mounted in the test facility. Externally it incorporated a tapered outer shell, larger at the top. Internally it contained a header from which the mercury vapor passes downward into 73 uniformly tapered diameter tubes. The tapered tubes have their largest diameter at the mercury vapor end to allow high velocity in the condensing region. The ends of the tapered tubes were fitted with straight sections of tubing before joining the outlet header. Condenser operation was such that these sections were normally in the subcooled region. The tubes were installed with their centerlines angled to provide a constant NaK flow area in order to effect a constant NaK velocity along the critical heat-transfer region of the condenser. The NaK entered the outer shell through a toroidal chamber, was uniformly circulated around the shell, and, after absorbing thermal energy from the condensing mercury vapor, was routed through the outlet toroidal chamber. Mechanical details of the condenser are described in reference 6.

Flow Controller

Feedback control of condenser coolant flow was required for ramps in NaK flow to be possible with the existing system. Accordingly, a coolant flow controller was designed to be operable with the existing flow control valve V-314. Closed-loop operation of the valve allowed commands for coolant flow rate and coolant flow ramps to be followed regardless of the heat rejection loop operating point. The flow controller is described in detail in reference 2.

Instrumentation

The instrumentation required to evaluate the operation of the condenser inventory pressure control consisted of condenser mercury inlet and outlet static pressure transducers, the heat rejection loop NaK flowmeter at the inlet to the condenser, the load cell to indicate the weight change of the mercury in the standpipe, and the circuitry which indicated valve position. The pressure transducers were slack-diaphragm capillary-tube units having an accuracy of 1 percent and operable to high temperatures. The heat rejection loop NaK flowmeter was a magnetic force type utilizing permanent magnets and giving a millivolt output signal proportional to flow rate. The standpipe weight was obtained by weighing the specially supported standpipe with strain-gage-type load cells. The instrumentation for the entire SNAP-8 simulator facility is detailed in reference 7.

The data acquisition system was a computerized digital system that scanned some 400 instrumentation channels approximately every 11.4 seconds. This system was running continuously during a startup test.

PROCEDURE

Startup Test Procedure

With the primary and heat rejection loops in operation the system was taken through the following sequence:

(1) The mercury loop was filled from valve V-210 to valve V-260 (fig. 1).

(2) The mercury standpipe was refilled.

(3) The mercury pump was started and was allowed to run while dead-headed.

(4) With the heat rejection loop pump operating on auxiliary power at 400 hertz, the NaK flow controller was set to the flow desired. Also the desired NaK flow ramp rate was set on the flow controller.

(5) The mercury injection system gas pressure was set at the desired value.

(6) The pump frequency was reduced from 400 hertz to the pump-transfer frequency for those pumps to be bootstrapped. Thus, if the heat rejection loop pump was to be bootstrapped, this frequency reduction would reduce NaK flow from the design level, since V-314 was held fixed.

(7) The auxiliary loop flow was shut off by closing V-117.

(8) The mercury injection valve V-217 was opened in preparation for mercury injection.

(9) Thirty seconds before the beginning of the mercury flow ramp the valve at the boiler inlet V-260 was opened and the mercury flow control valve V-230 was opened slightly to provide a flow feedback signal for the valve controller. At the end of this 30-second period, the mercury ramp to the self-sustaining level began. (The desired mercury ramp rate and maximum mercury flow had previously been set on the computer which controlled the mercury flow control valve.)

(10) As the turboalternator frequency passed through the pump-transfer frequency, the pumps were transferred from auxiliary to alternator power.

(11) Near the end of the mercury flow ramp the condenser isolation valve V-210 was opened. Once this valve was open the standpipe gas pressure was adjusted manually to maintain the inlet condenser pressure at the desired reference value.

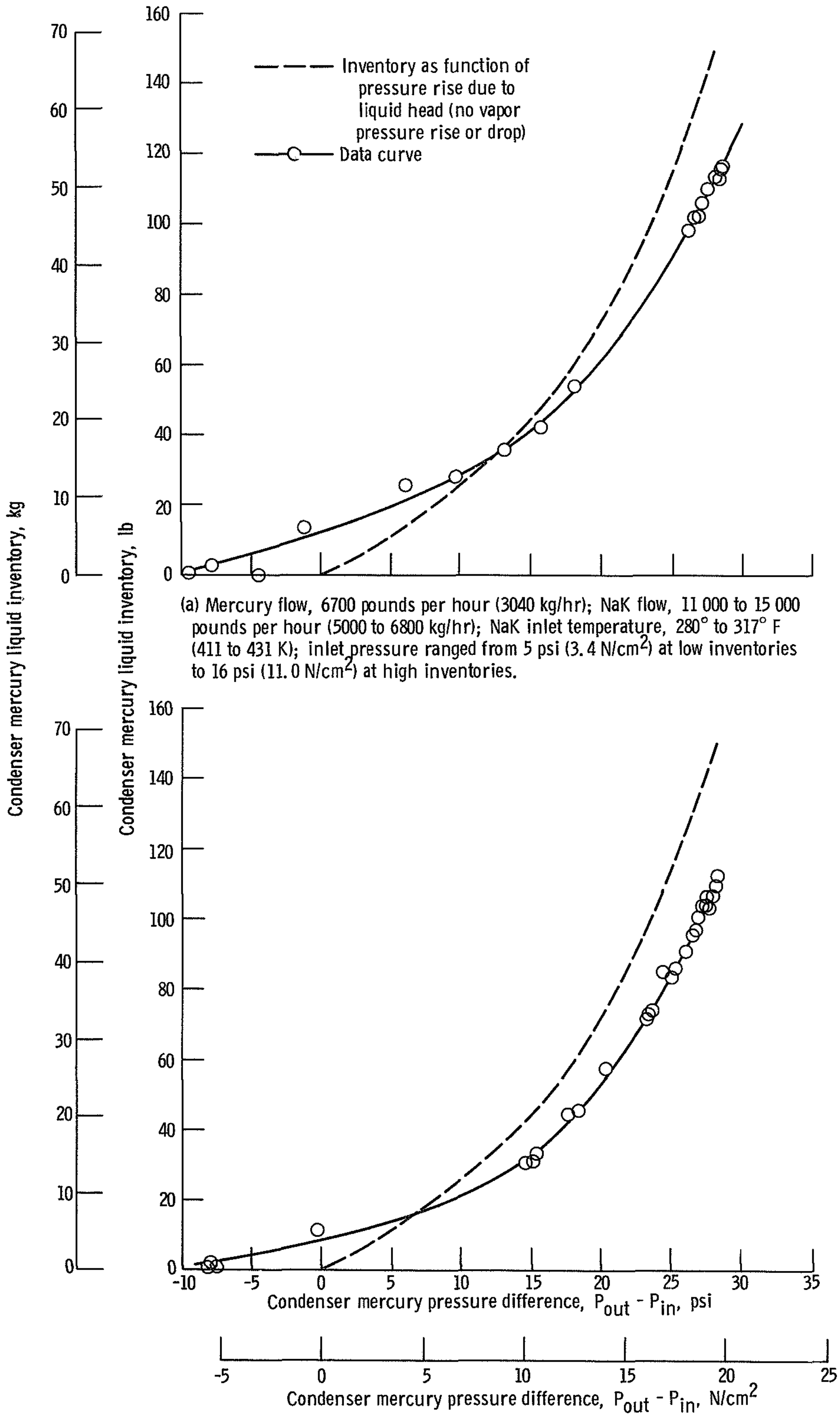
(12) At the end of the mercury ramp the flow controller was actuated to begin the ramp in the heat rejection loop flow. The ramp continued until the plateau flow level had been reached.

After the system had been allowed to stabilize at the self-sustaining level, the mercury and heat rejection loop flows were ramped to the rated levels.

Data Reduction

Condenser inventory was determined by use of the solid curve in figure 2(a) for operation at the self-sustaining level. The first point on the curve was determined by plotting the condenser Δp at what was estimated to be zero condenser inventory. Condenser inventory was assumed to be zero when the pressure at the condenser outlet was equal to the saturation pressure at the outlet. The rest of the curve was generated by recording the change in standpipe weight, when additional mercury was added to the system, and the corresponding change in condenser Δp. The increase in condenser inventory was assumed equal in magnitude to the decrease in standpipe weight (i.e., boiler inventory was assumed constant for the duration of the mapping).

The dashed line is a plot of condenser inventory as a function of condenser Δp due to liquid head alone. The solid curve was intended primarily to provide an estimate of



(a) Mercury flow, 6700 pounds per hour (3040 kg/hr); NaK flow, 11 000 to 15 000 pounds per hour (5000 to 6800 kg/hr); NaK inlet temperature, 280° to 317° F (411 to 431 K); inlet pressure ranged from 5 psi (3.4 N/cm^2) at low inventories to 16 psi (11.0 N/cm^2) at high inventories.

(b) Mercury flow, 12 300 pounds per hour (5600 kg/hr); NaK flow, 29 500 to 41 500 pounds per hour (13 400 to 18 800 kg/hr); NaK inlet temperature, 410° to 480° F (483 to 522 K); inlet pressure ranged from 10.5 psi (7.2 N/cm^2) for low inventories to 27.5 psi (19 N/cm^2) for high inventories.

Figure 2. - Condenser inventory as function of condenser pressure rise.

condenser inventory for the runs discussed in this report. However, the two curves of figure 2(a) also provide an estimate of the pressure rise or drop across the condenser that would exist in a zero-gravity environment. A plot of this zero-g Δp as a function of condenser inventory will be shown and discussed later in this report.

For accuracy in estimating the inventory and pressure drop at the self-sustaining level the inlet pressure should have remained constant at the reference value of 14 psi (9.7 N/cm^2) throughout the mapping. However, the inlet pressure varied from approximately the reference pressure, at high condenser inventories, to as low as 5 psi (3.4 N/cm^2) at low condenser inventories. Consequently, this curve should be least accurate for predicting inventory and pressure drop at the low inventory end. However, another method of estimating condenser inventory, which involved considering the total amount of mercury injected into the system (as calculated from the change in mercury standpipe weight) minus an assumed boiler inventory, yielded reasonable agreement with the predictions of figure 2(a) over the whole range of inventory.

In figure 2(b) a similar curve is shown for the rated level of operation.

RESULTS AND DISCUSSION

Condenser Characteristics

For good control performance the condenser pressure should be more sensitive to condenser inventory than to the other condenser input variables. The relative sensitivities of condenser inlet pressure to condenser inventory and condenser NaK flow at the self-sustaining level of mercury flow can be determined from figure 3(a). The two curves shown are for condenser NaK flows of 12 000 and 15 000 pounds per hour (5450 and 6800 kg/hr). Condenser inlet NaK temperature is higher by 27° F (15 K) for the higher flow level. The change in condenser inlet pressure in going from one to the other flow level would have been greater if the condenser inlet temperature had been the same for both curves.

At a condenser inventory of 50 pounds (22.7 kg), an increase in NaK flow from 12 000 to 15 000 pounds per hour (5450 to 6800 kg/hr) results in a drop in inlet pressure from 8.6 to 5.7 pounds per square inch (5.9 to 3.9 N/cm^2) as seen in figure 3(a). At a condenser NaK flow of 15 000 pounds per hour (6800 kg/hr), an increase in inventory from 50 to about 106 pounds (22.7 to about 48 kg) is required to return the pressure to 8.6 psi (5.9 N/cm^2). Therefore, at a 8.6 psi (5.9 N/cm^2) inlet pressure and a 12 000 pound per hour (5450 kg/hr) NaK flow, a 25 percent increase in NaK flow requires a 112 percent increase in condenser inventory to maintain the same pressure level.

Suppose that the pressure is being controlled to 12 psi (8.3 N/cm^2) and the condenser

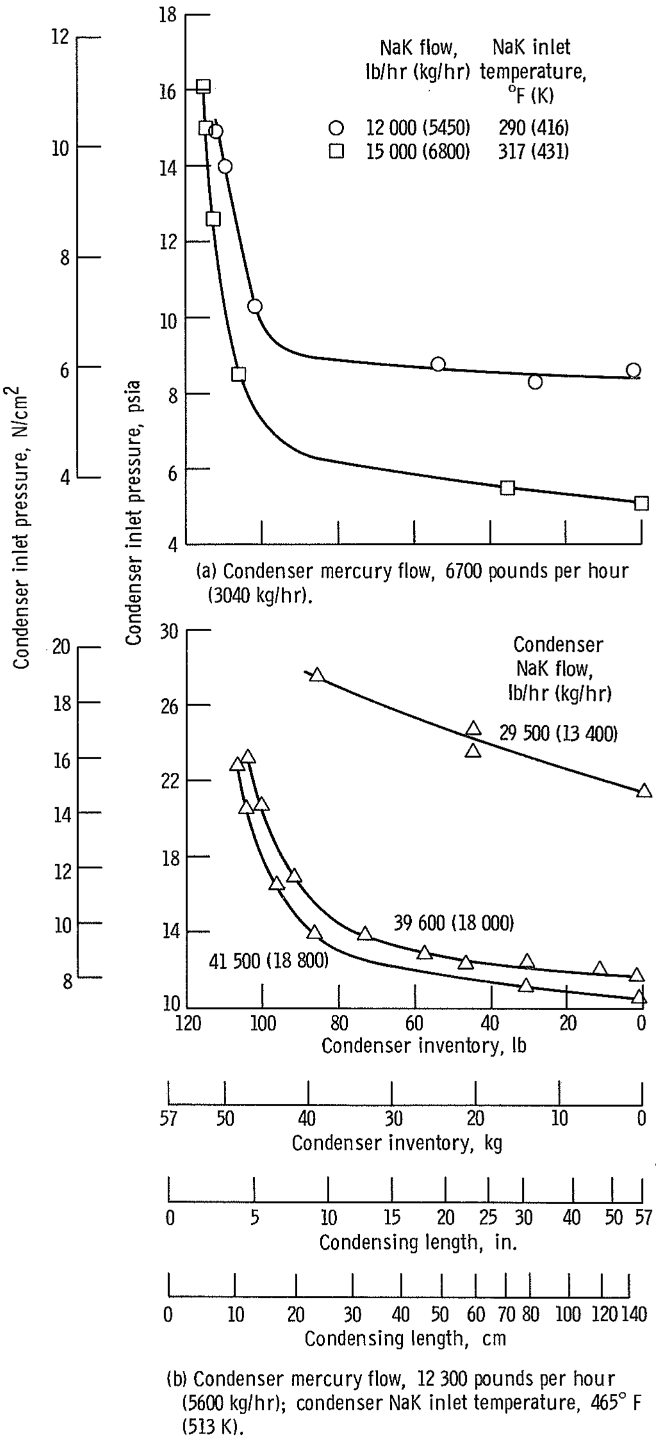
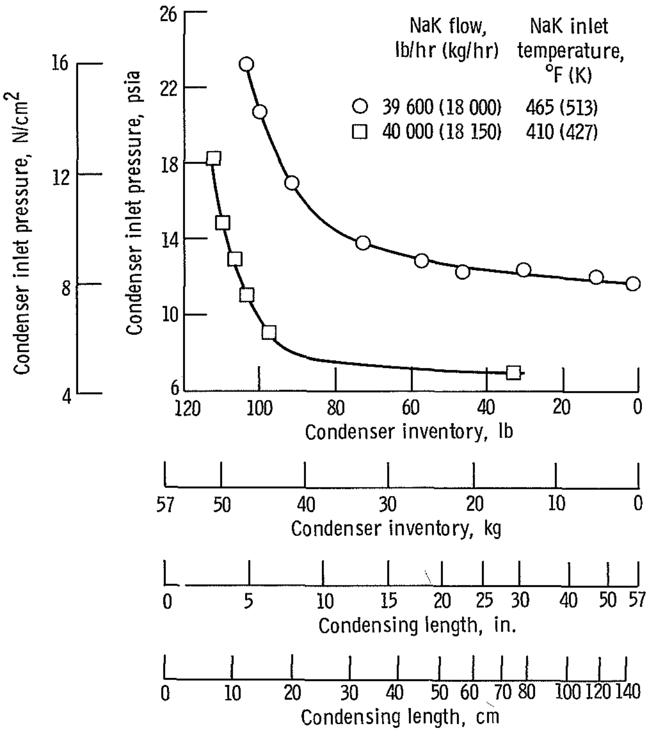


Figure 3. - Condenser inlet pressure as function of condenser inventory.



(c) Condenser mercury flow, 12 300 pounds per hour (5600 kg/hr).

Figure 3. - Concluded.

NaK flow is 12 000 pounds per hour (5450 kg/hr). The inventory would then be about 105 pounds (47.5 kg). A 25 percent increase in NaK flow would reduce the pressure from 12 to 8.4 psi (8.3 to 5.8 N/cm^2). An inventory increase from 105 to 112 pounds (47.5 to 51.0 kg), only 6.7 percent, would compensate for the 25 percent increase in NaK flow and therefore maintain the pressure at 12 psi (8.3 N/cm^2).

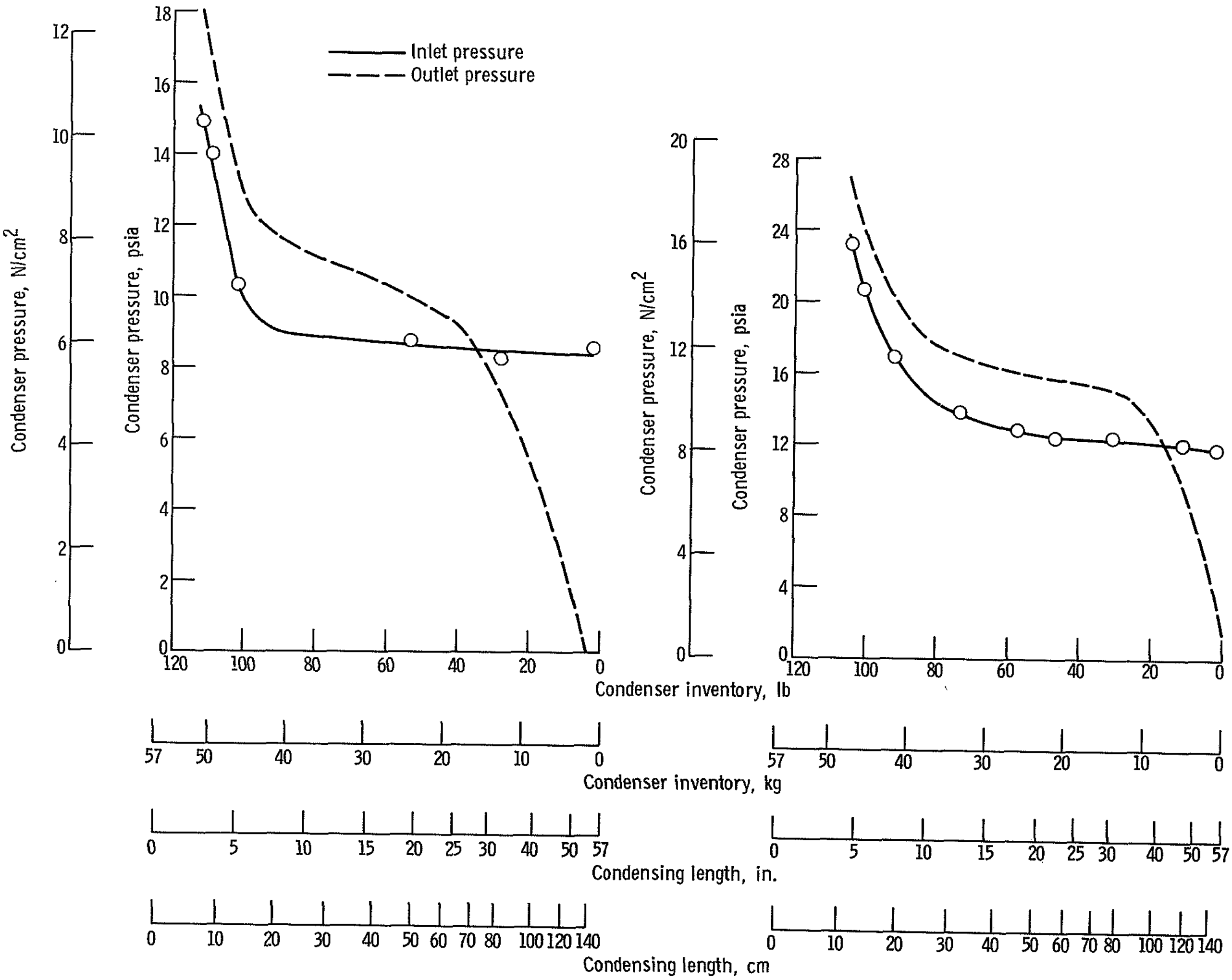
In figure 3(b) characteristics are shown for three condenser NaK flows at a mercury flow of 12 300 pounds per hour (5600 kg/hr). With a 50-pound (22.7-kg) condenser inventory and a 40 000 pound per hour (18 200 kg/hr) condenser NaK flow, a 25 percent decrease in NaK flow produces the same effect on condenser inlet pressure (an increase in inlet pressure of 12 psi (8.3 N/cm^2)) as a 110 percent increase in condenser inventory. With a 100-pound (45.4-kg) inventory and a 40 000 pound per hour (18 200 kg/hr) NaK flow, a 25 percent decrease in NaK flow produces the same effect as a 7.5 percent increase in inventory. (These figures were estimated by extrapolation of the curves.)

The relative sensitivities of inlet pressure to NaK inlet temperature and inventory at the design flow level can be determined from figure 3(c). It is shown that a 55° F (31 K) increase in inlet temperature increases inlet pressure from 7 to about 12.6 pounds per square inch (4.8 to 8.7 N/cm^2) when starting at the 50-pound (22.7-kg) inventory,

410° F (483 K) NaK inlet temperature point. A 114 percent increase in condenser inventory is required to produce the same effect when starting at the same point. A 55° F (31 K) increase in inlet temperature produces the same effect as a 9.5 percent increase in inventory when starting at the 105-pound (47.5-kg) inventory, 410° F (483 K) point.

Thus, for condenser operation at the self-sustaining and design mercury flow levels, the control sensitivity decreases sharply in passing from the high to the low inventory region. In the low inventory region, inlet pressure is less sensitive to condenser inventory than to the input variables condenser NaK flow and condenser NaK inlet temperature. Therefore, for good control characteristics, an inventory control should be designed to operate in the high inventory region.

Another problem encountered during operation in the low inventory region is pressure drop. In figures 4(a) and (b) are shown inlet and zero-g outlet pressure characteristics



(a) Mercury flow, 6700 (3040 kg/hr); NaK flow, 12 000 pounds per hour (5450 kg/hr); NaK inlet temperature, 290° F (416 K).

(b) Mercury flow, 12 300 pounds per hour (5600 kg/hr); NaK flow, 39 600 pounds per hour (18 000 kg/hr); NaK inlet temperature = 465° F (513 K).

Figure 4. - Condenser inlet and zero-g outlet pressures as functions of condenser inventory.

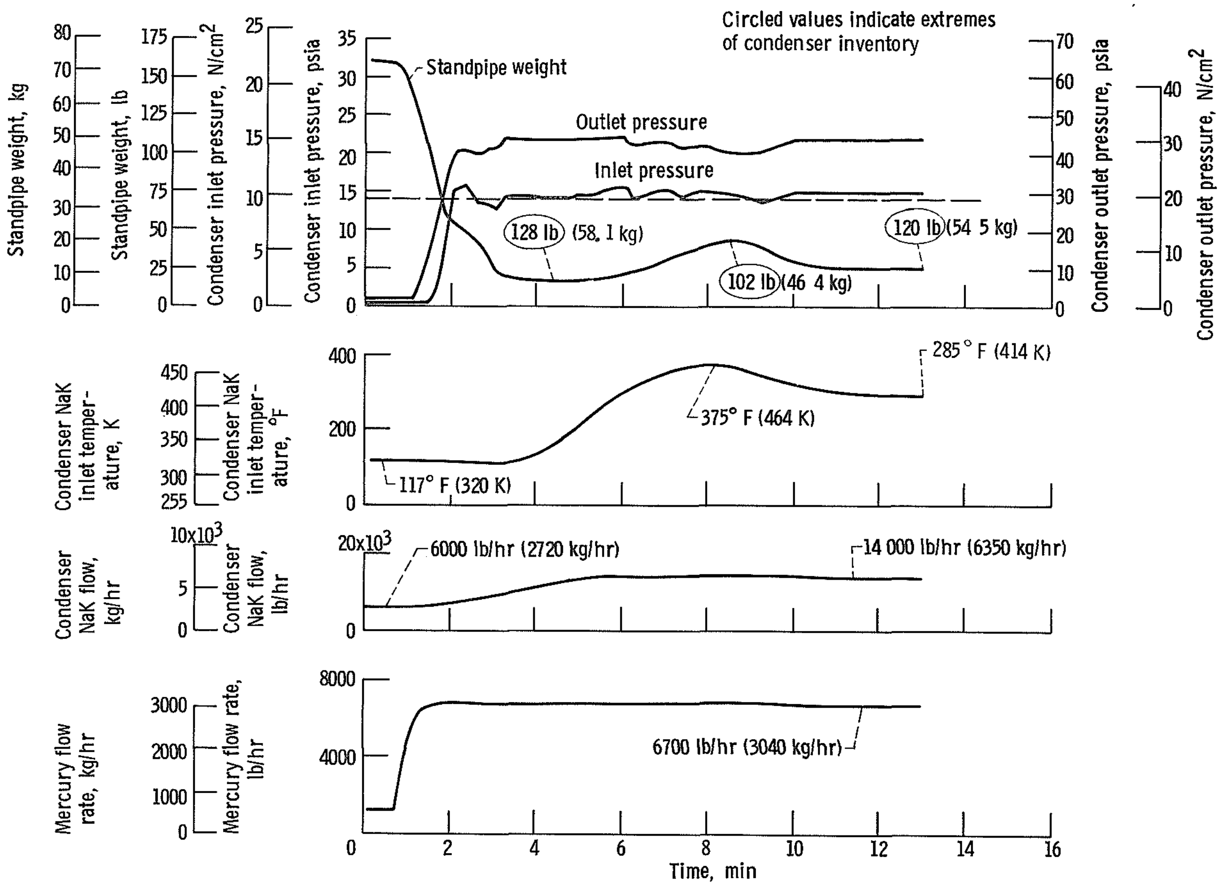
for the self-sustaining and design flow levels; the outlet pressure characteristics were derived by use of the curves of figure 2. It is seen that, with inlet pressure control, the outlet pressure falls below the reference pressure for operation at low inventories. It is also seen that with zero-g outlet pressure control for the same system conditions (with 6 $lb/in.^2$ (4.1 N/cm^2) reference pressure, for example) inlet pressure would lie above the reference pressure; undesirable degradation in turbine power would result if the system were designed for a turbine outlet pressure of 6 pounds per square inch (4.1 N/cm^2). Thus, the problems of pressure drop at low inventories and low control sensitivity at intermediate inventories require that the control be designed to operate in the high inventory region.

It is also seen in figures 4(a) and (b) that zero-g pressure rises of 3 and 1.7 pounds per square inch (2.1 and 1.2 N/cm^2), respectively, are indicated for large condenser inventories. The absolute and relative magnitudes of these pressure rises are such that they cannot be attributed to momentum recover alone. A calculated estimate of the maximum possible pressure rise due to momentum recovery yielded about 0.3 and 1.0 pound per square inch (0.21 and 0.69 N/cm^2) for the self-sustaining and rated flow levels, respectively. Inventory and pressure instrumentation errors could have been responsible for a 2 or 3 pound per square inch (1.4 or 2.1 N/cm^2) error in the condenser Δp. If the outlet pressure curves of figures 4(a) and (b) were shifted downward to give more acceptable values of pressure rise, then the figures would predict larger pressure drops for the low inventory range.

Effect of Coolant Flow Rate on Inventory Range During Mercury Ramp to Self-Sustaining Flow

Some startup tests to the self-sustaining level resulted in transient operation at low inventories even though the final steady-state operating point was in the high inventory region. For a NaK flow schedule which was at a sufficiently high level to avoid even transient operation in the low inventory region, however, the condenser settled out in a nearly flooded condition. Although short periods of operation in a nearly flooded condition presented no problems in the one-g test environment, such operation should be avoided; the operating characteristics of the condenser at such an extreme off-design point are not well known and cannot be reliably predicted.

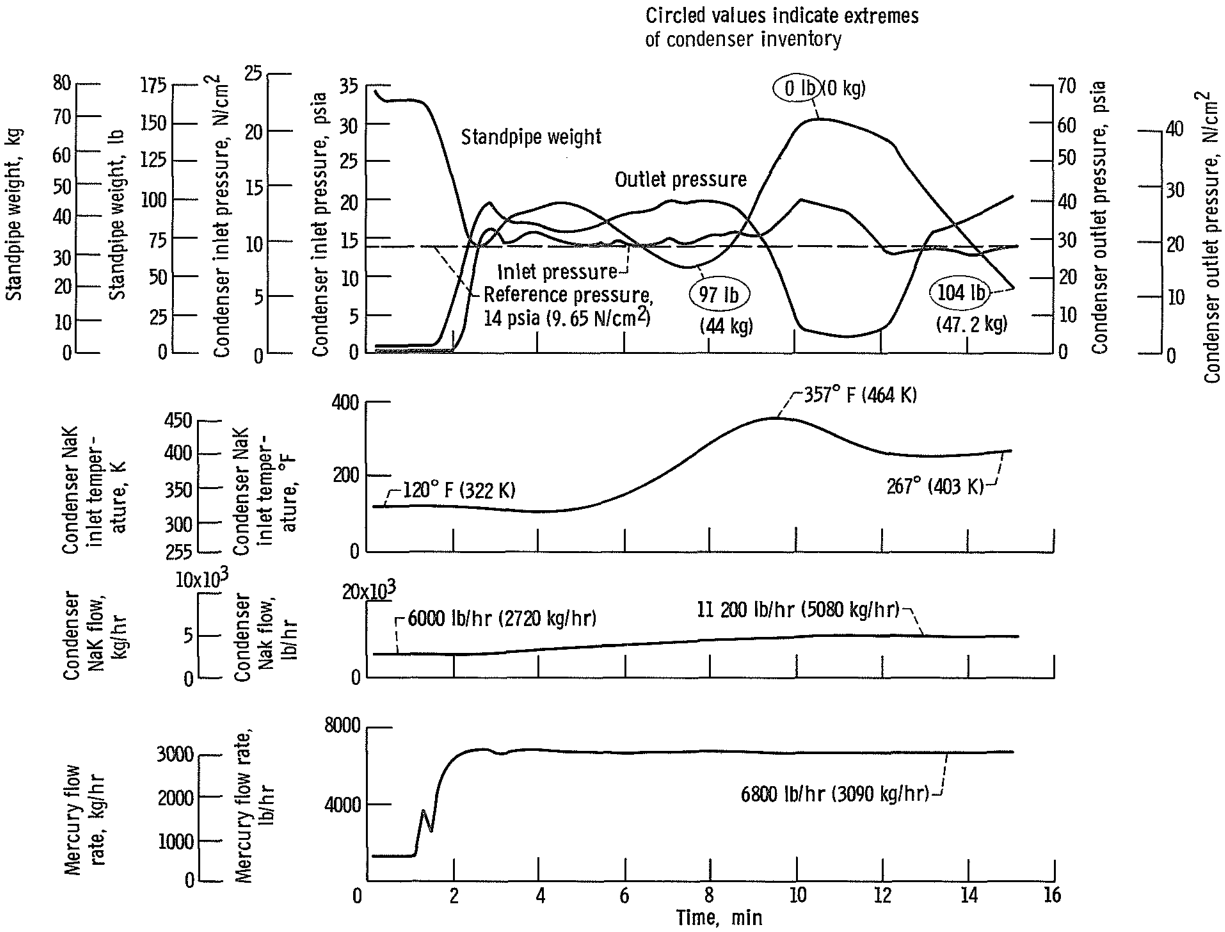
Plots of the condenser variables for a startup which avoided low inventory operation are shown in figure 5(a). The condenser outlet pressure shown in the plot is essentially the sum of the zero-g outlet pressure and the liquid head pressure. Condenser inlet pressure should be equivalent to zero-g outlet pressure for this run since there should



(a) Condenser NaK flow ramped from 6000 to 14 000 pounds per hour (2720 to 6350 kg/hr) at 33 pounds per hour per second (13.6 kg/hr-sec); 30-second mercury ramp to 6700 pounds per hour (3040 kg/hr); no pumps bootstrapped; reference pressure, 14.0 psia (9.65 N/cm²); initial condenser NaK inlet temperature, 117° F (320 K); startup 95.

Figure 5. - Effect of coolant flow rate on inventory range during mercury ramp to self-sustaining level.

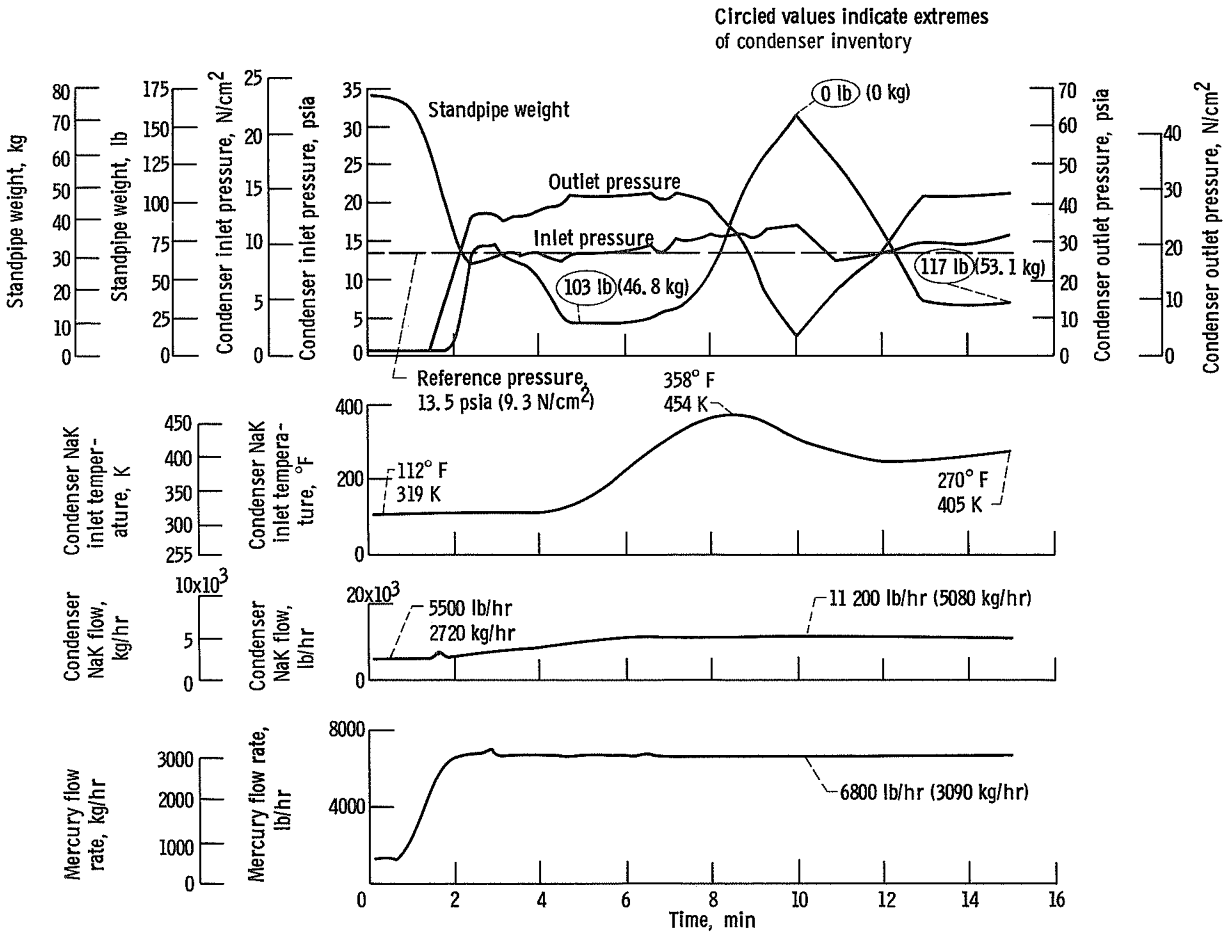
be no pressure drop for such high inventory operation. The NaK flow schedule used was a ramp from 6000 to 14 000 pounds per hour (2700 to 6400 kg/hr) at approximately 33 pounds per hour-second (15 kg/hr-sec). The mercury ramp was 30 seconds in duration and ended at the plateau flow level of 6700 pounds per hour (3000 kg/hr). The NaK ramp began at approximately the same time the mercury ramp ended. The extremes of condenser inventory are indicated in circles on the plot of figure 5(a). Note that maximum condenser inventory corresponds to minimum standpipe weight. The data through 9.5 minutes were plotted by a digital computer at 11.4-second intervals. The plots were extended by use of data taken from continuous recorder traces at 1-minute intervals. The low point in condenser inventory at 8.5 minutes is due to the peak in NaK inlet temperature at about 8 minutes. The steady-state inventory of 120 pounds (54.5 kg) for this run indicates a nearly flooded condenser (condenser is flooded at 125 lb (57 kg)).



(b) Condenser NaK flow ramped from 6000 to 11 200 pounds per hour (2720 to 5080 kg/hr) at 10 pounds per hour per second (4.5 kg/hr-sec); 80-second mercury ramp to 6800 pounds per hour (3090 kg/hr); no pumps bootstrapped; reference pressure, 14 psia (9.65 N/cm^2); initial condenser NaK inlet temperature, 120° F (322 K); startup 69.

Figure 5. - Continued.

Two runs for which the NaK flow was not high enough to avoid low inventory transients are shown in figures 5(b) and (c). The NaK ramps used were from 6000 to 11 000 pounds per hour (2700 to 5000 kg/hr) (for both runs) at rates of 10 and 20 pounds per hour-seconds (4.5 and 9.1 kg/hr-sec), respectively. The mercury ramps were about 60 seconds in duration for both runs and ended at 6800 pounds per hour (3100 kg/hr). It is assumed that this longer mercury ramp duration, as compared to 30 seconds for the run of figure 5(a), does not have a significant effect on the range of inventory required for control. Large pressure drops across the condenser are seen to occur at the zero inventory condition for both runs. In figure 5(b) a pressure drop of 14 pounds per square inch (9.7 N/cm^2) occurs at 10 minutes. In figure 5(c) a pressure drop of 13 pounds per square inch (9.0 N/cm^2) occurs at 10 minutes.



(c) Condenser NaK flow before bootstrapping, 5500 pounds per hour (2500 kg/hr); condenser NaK flow after bootstrapping, ramped from 6000 to 11 200 pounds per hour (2720 to 5080 kg/hr) at 20 pounds per hour per second (9.1 kg/hr-sec); 60-second mercury ramp to 6800 pounds per hour (3090 kg/hr); HRL pump bootstrapped from 220 cps; reference pressure, 13.5 psia (9.30 N/cm²); initial condenser NaK inlet temperature, 112° F (318 K); startup 73.

Figure 5. - Concluded.

TABLE I. - REQUIRED INVENTORY RANGES

Figure	NaK ramp, lb/hr (kg/hr)	Inventory peak before temperature peak, lb (kg)	Low point inventory, lb (kg)	Approximate steady-state inventory, lb (kg)
5(a)	6000 to 14 000 (2700 to 6400) at 33 lb/hr-sec (15 kg/hr-sec)	128 (58)	102 (46.5)	120 (54.5)
5(b)	6000 to 11 000 (2700 to 5000) at 10 lb/hr-sec (4.5 kg/hr-sec)	97 (44)	0 (0)	111 (50.5)
5(c)	6000 to 11 000 (2700 to 5000) at 20 lb/hr-sec (9.1 kg/hr-sec)	117 (53)	0 (0)	103 (47)

Table I summarizes the inventory ranges required for control for the three runs of figure 5.

What is really of interest in the case of the runs of figures 5(b) and (c) is what should be expected if the runs were repeated in a zero-g environment with outlet pressure control. An estimate of the operating point for such a control in zero-g can be made for the 10-minute point of figure 5(b). If the characteristics of figure 4(a) are moved upward so that the (8.5 psi inlet pressure, 0 lb) (5.9 N/cm^2, 0 kg) point is translated into the (20 psi inlet pressure, 0 lb) (13.8 N/cm^2, 0 kg) point of figure 5(b) at 10 minutes, the result is shown in figure 6. Although the magnitude is of course questionable, the indication is that the inlet pressure would have been significantly greater than the 14 pounds per square inch (9.7 N/cm^2) reference outlet pressure for the system conditions of figure 5(b) at 10 minutes.

Thus there appears to be a relatively narrow range of NaK ramp rates which would avoid both transient operation with large pressure drops and self-sustaining operation at nearly flooded conditions. It appears doubtful that a NaK flow ramp could be found which would be satisfactory for all of the expected variety of startups. A more complicated NaK flow schedule to the plateau level with a peak flow level above the plateau, to compensate for the peak in inlet temperature, would probably be somewhat better than a simple ramp.

Inventory Control for Complete Startup to the Design Flow Level

A startup consisting of an initial mercury ramp to the self-sustaining level followed

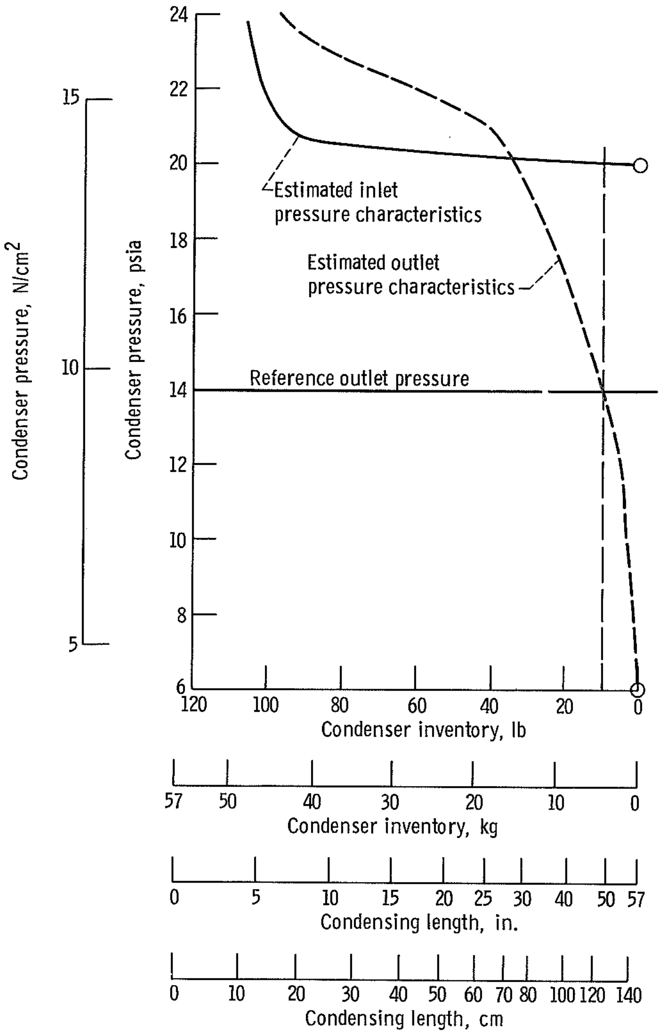


Figure 6. - Estimated condenser operating point in zero-g with outlet pressure control system conditions (for 10-min point of run of fig. 5(b)). NaK inlet temperature, 350° F (450 K); NaK flow rate, 10 000 pounds per hour (4540 kg/hr); mercury flow rate, 6800 pounds per hour (3090 kg/hr).

by another ramp to the design level and then a ramp down to the self-sustaining level is shown in figure 7. (The data were replotted from recorder traces on a compressed scale.) The initial mercury ramp was of approximately 60 seconds in duration to 6850 pounds per hour (3100 kg/hr); the flow remained constant at this value for 22 minutes. At the end of the mercury ramp, the NaK flow was ramped from 5000 to 10 000 pounds per hour (2270 to 4540 kg/hr) at about 20 pounds per hour-second (9.1 kg/hr-sec). Some values of condenser inventory are shown in circles at the low and high points of the standpipe weight trace. At the 11-minute point the condenser inventory was 6 pounds (2.7 kg) and the condenser pressure drop was 13 pounds per square inch (9.0 N/cm^2).

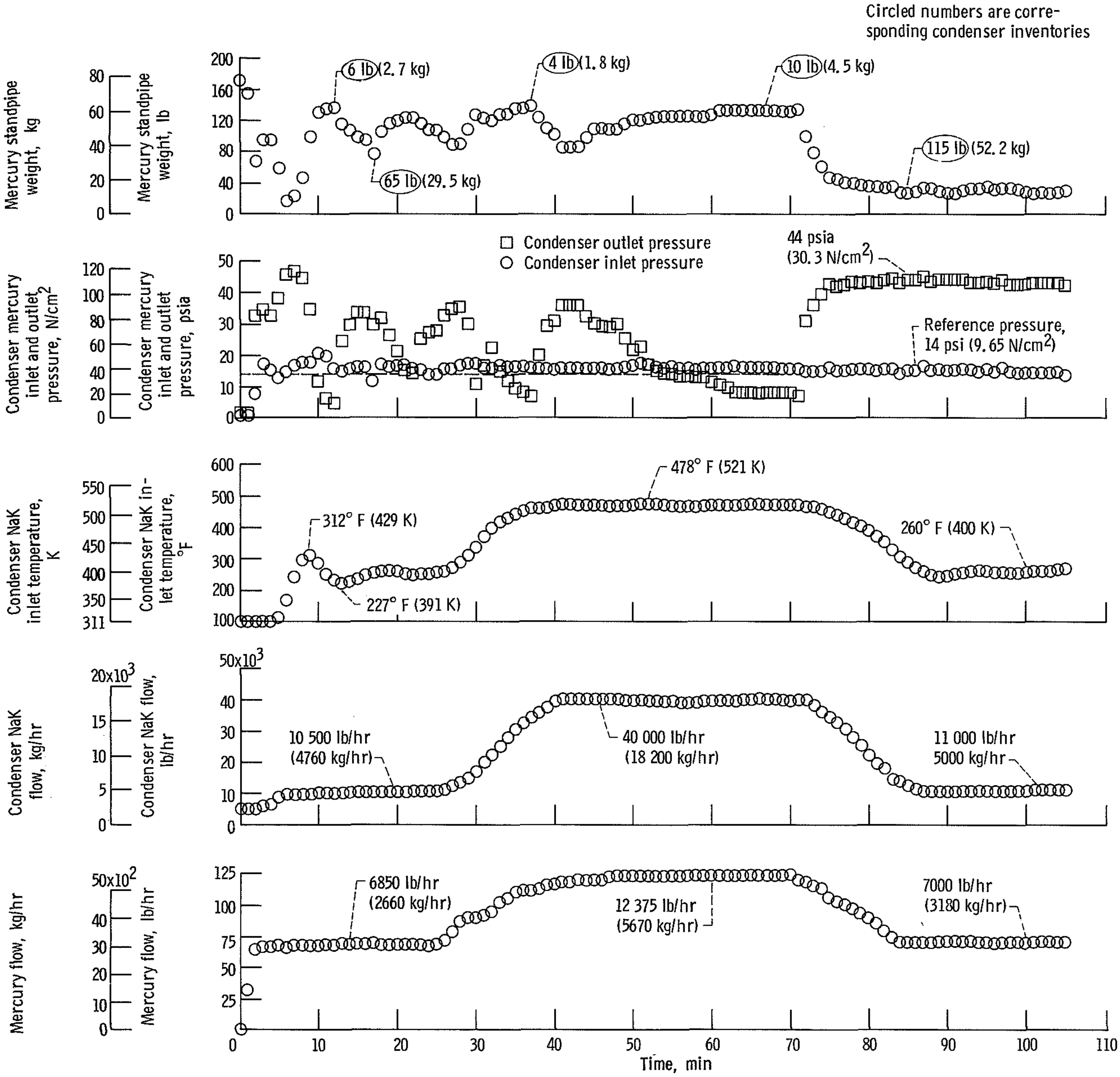


Figure 7. - Startup to rated level (startup 98-1).

Thus the NaK flow schedule to the plateau level was not satisfactory; this outcome could have been predicted by comparison with the NaK flow schedules of figure 5.

Throughout the period at the plateau flow level (11.0 to 22.0 min) the condenser inventory fluctuates in the range from 6 to 65 pounds (2.7 to 29.5 kg) even though the NaK and mercury flows are relatively constant. These fluctuations are apparently the result of the small variations in NaK inlet temperature throughout this period. This result is consistent with the relatively low sensitivity of inlet pressure to inventory that was observed in the medium to low inventory range.

The mercury flow begins to increase toward the design flow level at 24 minutes. The NaK flow is increased from 10 500 pounds per hour (4770 kg/hr) at 25 minutes to 40 000 pounds per hour (18 200 kg/hr) at 40 minutes by means of three short ramps. Pressure drops of 6 and 9 pounds per square inch (4.1 and 6.2 N/cm^2) occur at 30 and 37 minutes, respectively. These values correspond to condenser inventories of 17 and 4 pounds (7.7 and 1.8 kg), respectively. At 48 minutes the mercury and NaK flow levels and the condenser NaK inlet temperature had reached their final values. Condenser inventory did not reach steady-state, however, until about 64 minutes; at that time an 8 pound per square inch (5.5 N/cm^2) pressure drop existed across the condenser. Other conditions at this point are 10-pound (4.5-kg) condenser inventory, 40 000 pound per hour (18 200 kg/hr) NaK flow rate, 12 375 pound per hour (5 600 kg/hr) mercury flow rate, and 478° F (521 K) condenser NaK inlet temperature; inlet pressure was 16 pounds per square inch (11 N/cm^2), which was 2 pounds per square inch (1.4 N/cm^2) higher than the desired reference value.

Again, what is really of interest here is how an outlet pressure control would have performed in a zero-g environment for the final ramp to the design level. Unfortunately, performance for such a control cannot be estimated very well except at the final steady-state conditions. The design level characteristics of figure 4(b) should closely approximate the characteristics for the system conditions of figure 7 at 64 minutes if the figure 4(b) curves are shifted upward so that the inlet pressure curve falls on the (16 psi, 10 lb) (11 N/cm^2, 4.5 kg) point. It can then be seen that zero-g outlet pressure control at 14 pounds per square inch (9.7 N/cm^2) should correspond to about the same system conditions; then pressure drop would be about 2 pounds per square inch (1.4 N/cm^2) and turbine back pressure would be 2 pounds per square inch (1.4 N/cm^2) above the 14 pounds per square inch (9.7 N/cm^2) reference value.

A ramp down in mercury flow begins at 70 minutes (see fig. 7). The ramp ends after about 14 minutes at 7000 pounds per hour (3180 kg/hr). The reduction in NaK flow begins at 72 minutes and ends at 11 000 pounds per hour (5000 kg/hr) after 15 minutes. The condenser inventory goes to 115 pounds (52.2 kg) at the beginning of the flow change and remains about there.

CONCLUDING REMARKS

The inventory method of condenser pressure control maintains the mercury outlet pressure at a selected value by variations of the liquid mercury inventory in the condenser. The control, however, must operate within a limited range of inventories. If the control withdraws too much inventory, large condenser pressure drops occur. With this situation the inlet pressure may be too high to satisfy the turbine back pressure requirement. Operation with a nearly flooded condenser should be avoided also, since potential problems exist for such operations in zero-gravity.

The condenser NaK flow schedule was a critical factor in achieving a satisfactory range of inventories during the tests of this control method for SNAP-8 startup. From the data it appears that the range of NaK flow schedules that are suitable for given startup conditions is rather narrow. The task of defining a suitable schedule for the variable conditions that may exist from one startup to another is difficult and perhaps impossible. This control method, therefore, is not a practical one for SNAP-8 startup. The method, however, may be suitable for long-term control of condenser pressure at the design operating point.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 24, 1970,
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