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CONDITIONING AND STEADY-STATE PERFORMANCE OF SNAP-8 TUBE-IN-SHELL MERCURY BOILER

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SUMMARY

As part of the overall SNAP-8 development program, experimental data were obtained from the tube-in-shell boiler tested in the SNAP-8 facility at Lewis Research Center. The boiler was a cross-counterflow heat exchanger consisting of four 1-inch tubes coiled inside a concentric cylindrical annulus. An analysis of the boiler performance is presented for a total operating time of 1087 hours.

The boiler-outlet heat-transfer parameters (such as enthalpy and quality) increased with time to approximately 300 hours of boiler operation and did not appreciably change thereafter. For boiler operation after 300 hours, the average outlet quality was 93 percent with an average superheat of 300° F (170° K). Average outlet absolute enthalpy was 153 Btu per pound (3.55×10^{5} J/kg), which is 5 percent less than design.

Although the boiler mercury-vapor outlet quality and terminal temperature difference remained essentially constant after 300 hours of operation, the boiler internal heat transfer continued to improve. This improvement was indicated by the change in slope of the sodium-potassium (NaK) inner-shell temperature profile which increased with time throughout the boiler operation. This improvement was also indicated by the continued increase in overall pressure drop with operating time. The NaK outer-shell temperature profiles and the boiler mercury inventory indicated that the plug sections of the two outer boiler tubes were flooded.

Performance curves of the boiler indicated that the chosen design NaK- to mercury-flow-rate ratio was above its optimum value. At about 700 hours of operation, the overall pressure drop ranged from 78 to 103 pounds per square inch (5.4 to 7.1×10^{5} N/m^2), which corresponds to mercury-flow rates of 6350 to 9350 pounds per hour (2880 to 4240 kg/hr). There was a slight increase in overall pressure drop with increased pinch-point temperature difference. The NaK side boiler pressure drop ranged from 3 to 6.5 pounds per square inch (2 to 4.5×10^{4} N/m^2, which corresponded to NaK flows of 20 000 to 33 000 pounds per hour (9100 to 15 000 kg/hr), respectively.

INTRODUCTION

Forced-convection liquid-metal heat exchangers have high heat-transfer rates and, hence, are of interest in the design and development of Rankine-cycle space power systems in which the minimization of weight and size of components is a primary interest. In the development phase of any complex system, such as the SNAP-8 power conversion system, several units of a given component are generally evaluated to ensure reproducibility of performance and to aid in the analysis of the test results. The subject of this report is one of four identical cross-counterflow tube-in-shell mercury boilers which were built for the development of the SNAP-8 Rankine-cycle power conversion system. This unit was tested in the SNAP-8 facility at Lewis Research Center. The results of the experimental evaluation of two of the other boilers are reported in references 1 and 2. In the SNAP-8 system, a eutectic NaK mixture (22-percent sodium and 78-percent potassium) is used as the primary fluid to transfer thermal energy from the reactor to the boiler.

Lyon, Foust, and Katz (ref. 3) and Bonilla (ref. 4) were among the first groups in the United States to make extensive studies on boiling mercury. They indicated that the wettability (a surface phenomenon) of the surface by mercury was an important factor in determining boiling film coefficient. A summary of Russian work in boiling heat transfer has been presented in reference 5. A recent literature survey in liquid-metal boiling heat transfer is given in reference 6.

It is important that a boiler operate properly since poor performance (low outlet quality) could allow significant amounts of liquid carryover into the turbine and could result in the degradation of the turbine efficiency and power output. Mercury boiling heat transfer is sensitive to wetting, which is a function of the mercury side-tube surface roughness and/or surface contamination. A boiler operating in a nonwetted or "deconditioned" state characteristically has reduced heat-transfer rates; thus, surface condition is very important. Examples of surface contamination are very lightly held physically adsorbed gas molecules or a thin oxide film. The scrubbing action of high-velocity mercury vapor at operating temperature, over a period of time, removes oxides from the tube surface. This action promotes partial wetting of the mercury tube surface; thus, the heat-transfer performance is increased. Wetting also may be promoted through use of additives as wetting agents. Wetting agents such as magnesium, rubidium, and titanium are getters of oxygen and break down oxide films as well as remove adsorbed gases. However, wetting agents introduce additional unknowns in the system (possible plugging and/or erosion by metallic oxides) and are a poor substitute for system cleanliness. A mercury boiler is considered "conditioned" when it reaches its maximum heat-transfer capability, which is believed to be the result of mercury wetting the tube surface. The degree of wetting depends on the choice of containment material and on the cleanliness of the tube surface. An important problem in the development of the SNAP-8 tube-in-shell mercury boiler is the change in heat-transfer performance of the boiler with time.

Several supporting programs were conducted in conjunction with the SNAP-8 boiler development. The effects of additives on wetting during mercury pool boiling are given in reference 7. An experimental study to investigate the thermal and the dynamic performance characteristics of different boiler plug insert geometries is given in reference 8. The effects of hydrocarbons on boiler performance are discussed in reference 9. Test results of the tube-in-shell boilers reported in references 1 and 2 have shown that, no matter how carefully the cleaning is performed to remove oxides or organic materials, an initial conditioning period was necessary before maximum performance could be obtained.

The purpose of this investigation was to show experimentally the conditioning history and steady-state performance of a SNAP-8 tube-in-shell boiler. An analysis of boiler performance is presented for an accumulated mercury flow time of 1087 hours. The three primary independent variables considered in the boiler performance were mercury-flow rate, NaK-flow rate, and NaK-inlet temperature. Because of NaK pump limitations in the primary loop, only 90 percent of design NaK-flow rate could be obtained; consequently, design mercury-flow conditions could not be imposed on the boiler. Because of this limitation, whenever it is necessary, results are shown on the basis of actual to design ratios of NaK- to mercury-flow rates in order to extrapolate to design conditions. The boiler history is presented with NaK-inlet temperature of $1300^{\circ}\pm20^{\circ}$ F ($980^{\circ}\pm10^{\circ}$ K). Design conditions for the SNAP-8 tube-in-shell boiler are given in table I.

SYMBOLS

A_{th}	cross sectional area of throat
C_D	experimentally determined coefficient of discharge
c_p	specific heat, Btu/(lb mass) ($^{\circ}$F), [J/(kg)(C$^{\circ}$)]
E	thermal expansion factor
f	approach factor
g_c	conversion factor, 32.174 (lb mass)(ft)/(lb force)(sec^2), [1 (kg)(m)/(N)(sec^2)]
h	enthalpy, Btu/lb mass, (J/kg)
h_{fg}	mercury latent heat of vaporization, Btu/lb mass, (J/kg)
I	inventory, lb mass, (kg)
L	tube length, ft, (m)

P	absolute pressure, lb force/sq in., (N/m^2)
PW	thermal power, kW
T	temperature, ^{o}F, (^{o}K)
t	time, hr
W	flow rate, lb mass/sec, (kg/sec)
x	outlet quality, dimensionless
ρ	density

Subscripts:

ac	actual
d	design
Hg	mercury
i	input
in	inlet
liq	liquid
NaK	sodium potassium mixture
out	outlet
pp	pinch point
r	restrictor section
sat	saturation
SH	superheat
T	terminal
v	mercury vapor

APPARATUS

Experimental System

The test facility was built to simulate the SNAP-8 nuclear Rankine-cycle power conversion system. A schematic of the basic simulated SNAP-8 system, shown in figure 1, consisted of three liquid-metal loops. Basically, the primary loop contained an electromagnetic pump, an electric heater, and the tube-in-shell boiler. An analog computer output controlled the NaK electric heater in order to approximate the behavior of the nuclear reactor. The NaK eutectic mixture (22-percent sodium and 78-percent potassium) was pumped in order to transfer heat from the NaK electric heater to the mercury boiler. The primary loop flow was regulated by manually changing a variac which controlled the voltage to the electromagnetic pump. The NaK pump limited maximum flow rate to 40 000 pounds per hour.

The secondary loop (Hg loop) using AISI-type 316 or 304 stainless steel for process piping, basically consisted of the tube-in-shell boiler, the turbine simulator, the condenser, the centrifugal pump with flow controls, and a mercury injection system (see fig. 1). Liquid mercury flowed from the centrifugal pump through a filter, a flow venturi, and a pressure control valve before entering the boiler. At the boiler outlet, mercury vapor flowed through either or both of two venturis each with its own flow control valve. The flow then passed through an air-cooled mercury vapor desuperheater. Resultant temperature and pressure drop from the vapor desuperheat and the venturis were to simulate the SNAP-8 turbine characteristics. Mercury vapor entered the condenser, was condensed, was subcooled, and was pumped to the boiler inlet by a commercial centrifugal pump. A temperature limitation of 300° F (422° K) on the Hg pump bearings restricted the boiler-inlet temperature to below the design value of 515° F (542° K).

The heat rejection loop basically consisted of an electromagnetic pump, a condenser, a bypass flow control valve, and two air-cooled NaK heat exchangers as a radiator simulator. Condenser NaK-flow rate was controlled by a three-way valve which could divide the pump flow between the condenser and the condenser bypass line. Total NaK flow then entered two parallel finned-tube air-cooled heat exchangers. The valves regulating air flow to these heat exchangers could be controlled by an analog computer programed to simulate space radiator characteristics. NaK flow from the radiator outlets returned to the pump and was recirculated through the loop.

Expansion tanks were used in the NaK loops to accommodate the change in volume of the working fluids due to variations in temperature and also to maintain a positive pressure at the inlet of the electromagnetic pumps. The Hg injection system and the common NaK fill system were valved off during system operation. A common NaK oxide control loop, consisting of an economizer, a cooler, and a cold trap, was provided to precipitate oxides from the NaK loops. Auxiliary vacuum and inert-gas-pressurization systems necessary for operation were used in conjunction with the main loops.

Tube-In-Shell Boiler

The boiler was a cross-counterflow tube-in-shell heat exchanger as shown in figure 2. A single inlet tube lead into a plenum where the liquid-mercury flow was distributed into orifices at the entrance to each of four boiler tubes. These tubes were 0.902-inch (0.0229-m) in inside diameter (0.090-in. (0.00228-m) wall thickness) and 60 feet (18.3 m) in length and were coiled on two concentric double lead helices of 19.3 and 21.7-inch (0.490- and 0.551-m) inside diameter. A "plug" at the tube inlet approximately 10 feet (3.048 m) long was used to restrict the flow and thus to increase the liquid velocity. The plug, a 0.60-inch-diameter (0.0152-m) solid rod, was held concentrically from the inside of the tube by two 0.135-inch-outside-diameter (0.00343 m) wire springs coiled 180° out of phase forming two spiral flow paths for the mercury. The wire had a 3-inch (0.0762-m) pitch for the first 3 feet (0.9144 m), a 4-inch (0.1016-m) pitch for the next 2 feet (0.6096 m), and a 5-inch (0.127-m) pitch for the remainder of the plug length. Downstream of the plug, a twisted ribbon insert (0.891 in. (0.0226 m) wide by 0.016 in. (0.00406 m) thick) with a pitch of 7.3 inches (0.185 m) maintained the spiral flow for the remaining 566 inches (14.37 m). This swirl flow, induced by the twisted ribbon, was intended to centrifuge the high-density liquid from the vapor to the outside of the tube passage thereby to enhance the heat-transfer rates. The inlet plug and the ribbon were provided to make the boiler insensitive to gravity forces. A manifold of the four tubes formed a single mercury outlet. The coil tubes were enclosed by a cylindrical annular shell, 24-inch (0.6096-m) outside diameter and 17.6-inch (0.446 m) inside diameter, which forms the NaK-flow passage. The mercury tubes and the plugs were made of AISI 505 (9 chromium - 1 molybdenum) alloy steel while the shell and NaK lines were of AISI 316 type stainless steel. The twisted ribbon inserts and the wire springs were made of low-carbon steel.

Instrumentation

Instrumentation necessary to map the performance of the SNAP-8 tube-in-shell boiler consisted of flowmeters, pressure transducers, and thermocouples. Flow measurement in the NaK loops was by electromagnetic flowmeters. The electromagnetic flowmeter consisted of a permanent magnet, a flow tube, and electrodes. Liquid NaK flow through the tube produced an electromotive force proportional to the volumetric flow rate. NaK temperature was measured by a thermocouple located on the flow tube in order to determine the fluid density for converting volumetric flow measured into weight flow rate. Liquid-mercury flow was measured by a calibrated venturi downstream of the pump. Venturi inlet temperature and venturi pressure drop were measured to determine liquid-mercury flow rate.

A 20-pound-per-square-inch (1.38×10^{5} N/m^{2}) differential pressure transducer and a Bourdon differential pressure gage were used to measure the pressure drop from inlet to throat for the liquid venturi at the boiler inlet. The Bourdon gage was used to check the pressure transducer measurements. The location of instrumentation on the boiler is shown in figure 3. Absolute pressure transducers were located at the boiler inlet and outlet. The inlet transducers had a range of 0 to 500 pounds per square inch absolute (3.44×10^6 N/m^2) while the outlet transducer had a range of 0 to 300 pounds per square inch absolute (2.06×10^6 N/m^2).

Chromel-Alumel thermocouples were used for all liquid-metal temperature measurements. A thermocouple was welded to the NaK inlet and outlet tubes approximately 2 inches (0.0508 m) from the boiler. Three thermocouples were welded on both the inlet and the outlet of the mercury piping (120 degrees apart) and were located 2 inches (0.0508 m) from the boiler.

Two immersion-type thermocouples were located in the turbine simulator line downstream of the boiler outlet. Each was placed in a 1/4-inch (0.00635-m) stainless-steel tube well which was welded to the piping with the capped ends on the centerline of the flow passage. The thermocouples were inserted into the well to make physical contact at the capped ends. One thermocouple was located in the line 10 inches (0.254 m) from the boiler outlet at a 45° angle facing into the stream. The other thermocouple was 2 inches (0.0508 m) further downstream at a 45° angle downstream. The thermocouple, angled away from the flow, read saturation or above saturation temperature depending on the boiler-outlet quality since at times mercury droplets might collect on the probe sensing tip. The thermocouple, angled into the flow, was used to indicate the boiler-outlet superheat temperature.

Both the inner and the outer walls of the boiler shell annulus were instrumented to give an indication of the NaK temperature distribution. The 2 inner mercury tubes had 10 coils each while the 2 outer tubes had 9 coils each. Thermocouples were located along the boiler inner and outer shell between the double tubes spaced 120 degrees apart along the entire length of the tube section. A total of 30 thermocouples were on the inner shell and 27 thermocouples on the outer shell. Table II and figure 3 indicate the thermocouple location along the length of the tube on three vertical planes, planes A, B, and C, along with the elevation from the bottom of the boiler.

All acquired data used in performance calculations were recorded on magnetic tape with an automatic high-speed digital recording system.

PROCEDURE

Calibration

The pressure transducers were calibrated before and after installation in the system, after each shutdown, and after test completion. Preinstallation calibrations were made at room temperature and at the estimated operating temperature to check the signal output, hysteresis, and repeatability. The change in output caused by system operating temperatures was less than 0.4 percent of the maximum output of the transducers. The differential pressure transducers were calibrated by applying pressure to the high-pressure side with the low-pressure side maintained at ambient conditions. Calibration after installation was done in the same manner as the bench calibration, and a calibration curve was plotted. Provision had been made for installation of a reference gage for transducer calibration without removal of the transducers from the system. The transducers could be isolated by use of valves in the system. Absolute pressure transducers were calibrated in the system by first reducing pressure in the loop to less than 0.020 torr (2.66 N/m^2) to set the zero point, and then pressurize to set the span, after which a traverse was made over the pressure range. The reference pressure gage was a precision Bourdon gage (0.1 percent of full scale). Calibration and hysteresis curves of each transducer were then made.

Field strength of the magnets of the electromagnetic flowmeters was checked using a gaussmeter. Alignment of the tube, the magnet, and the electrodes was checked, and a theoretical calibration curve was plotted using the method outlined in reference 10. The theoretical calibration agreed within 1 percent of the factory calibration.

All thermocouples were referenced to a 150° F (339° K) oven and received an electric continuity check. A heat check was made to ensure proper thermocouple lead connection and response to temperature.

Cleaning

The mercury tube-in-shell boiler was cleaned as an individual component before installation in the system. After a vacuum was imposed in the boiler, it was filled with ethyl alcohol as the cleaning solvent. Several soaking periods of 1/2 hour were made until the fluid removed had the same purity as the original alcohol. The boiler was then purged with hot argon for drying. A liquid acetone flush and another hot argon purge followed to remove any remaining residue.

After the boiler was installed, a vacuum was applied on the mercury loop, and hot vaporous trichloroethane was allowed to flow through the loop. Samples of the trichloroethane were visually inspected, and the procedure was repeated until no change in solvent color was noted. A vacuum was then applied, and liquid trichloroethane was pumped into the mercury loop. After a 1/2-hour soaking period, the loop was drained by gravity. The liquid flush was repeated until a chemical analysis of the solvent indicated the same composition as the original solvent. The loop was then flushed with acetone followed by a hot argon purge to dry and to evaporate any remaining solvent.

Before and after cleaning, the complete system was checked for vacuum leaks. A maximum pressure of 0.02 torr (2.66 N/m^2) was measured at the condenser inlet and was maintained for at least 24 hours before mercury injection. Leakage was checked by passing helium over the components and piping while maintaining a vacuum in the system with a helium leak detector connected. A leak rate of less than 10^{-8} cubic centimeters per second was considered satisfactory.

Once NaK was placed into the primary and the heat rejection loops, the NaK oxides were removed by a NaK oxide control loop consisting of an economizer, a cooler, and a cold trap. The oxides were precipitated from the NaK loops to an oxide content of 20 parts per million by using the cold trap. The maximum allowable operating oxide content was 50 parts per million.

Operation

The method used to fill the mercury loop is described, since it was pertinent in determining the boiler inventory. First, the mercury injection system was filled with valve 201 closed (fig. 1). Then, with valves 201 and 202 opened and valve 203 closed, mercury was allowed to flow into the dump tank to prevent gas pockets from being formed in the line. With valve 201 closed and valves 202 and 203 opened, a vacuum was pulled on the mercury loop for a minimum of 24 hours to allow for outgassing of the system. Valves 210, 206, and 217 were closed, and the expulsion tank was pressurized through an external nitrogen source. The fill valves 201 and 203 were opened, and the liquid part of the mercury loop between valves 206 and 210 was filled. Valve 206 was opened, and mercury was allowed to enter the boiler-inlet plenum until the boiler-inlet transducer barely registered a pressure reading. Valve 206 was closed, and valve 210 was opened; thus, the condenser could be filled. The mercury level in the condenser was allowed to rise until a predetermined static head in the condenser was reached. This static head varied with the mercury inventory needed for a given test. Valve 210 was closed, and valve 217 was opened to allow the standpipe to be filled to a level such that the total mercury inventory was greater than that required for any system test. After NaK flow was set for given startup condition, valves 217 and 203 were closed, and the mercury pump was started. With valve 210 open, the desired flow rate was set by the dual flow control valves, valve 205 at the pump outlet and valve 206 at the boiler inlet. Changes in mercury inventory were made through the standpipe located at the suction side of the mercury pump. Boiler-outlet pressure was controlled using the two electrohydraulic valves, valves 207 and 208, in the turbine simulator.

No set procedure was used to try to "condition" the boiler during the first two startups. Also, the initial mercury inventory was not determined for these startups.

For the remaining startups, the initial mercury inventory was determined, and an attempt was made to keep maximum vapor velocity in the plug section of the mercury tubes but not at any time let the outlet quality drop below 85 percent. This specification dictated the increase of mercury flow which amounted to about 750 pounds per hour (340 kg/hr). The purpose of this procedure was to scrub the tube walls with high-velocity mercury vapor to promote wetting. The mercury flow was increased as the boiler conditioned until an arbitrary mercury flow rate of 7600 pounds per hour (3450 kg/hr) was reached. On approaching the mercury flow of 7600 pounds per hour, the NaK flow through the boiler was increased to keep boiler inlet temperature at 1300° F (980° K). Because of the primary loop NaK pump limitation in the system, design NaK flow and consequently, design mercury flow conditions could not be imposed on the boiler. After system shutdown, all loops were filled with argon to prevent contamination of the system.

RESULTS AND DISCUSSION

Boiler History and Conditioning

An analysis of boiler performance and time is presented for an accumulated mercury flow time of 1087 hours. The measured and the calculated boiler performance parameters of this history are given in table III. A time history of the boiler parameters is presented in figures 4 and 5 for data runs having boiler NaK-inlet temperature of $1300^{\circ}\pm20^{\circ}$ F ($980^{\circ}\pm10^{\circ}$ K). The performance parameters selected to be indicative of the heat-transfer performance of the boiler included outlet quality, outlet enthalpy, terminal temperature difference, superheat temperature difference, and pinch-point temperature difference. The method of calculation of the various parameters is given in the appendix. A typical illustration of the various boiler parameters is shown in figure 6. Terminal temperature difference is the difference between the NaK-inlet and mercury-outlet temperatures. Superheat temperature difference is the difference between the outlet mercury superheat and the saturation temperature corresponding to the mercury-outlet pressure. Pinch-point temperature difference is the difference between the NaK and the mercury temperature at the mercury liquid-vapor interface.

After the first startup, approximately 40-percent quality was obtained with a mercury flow of 9000 pounds per hour (4080 kg/hr) and NaK flow of 20 000 pounds per hour (9070 kg/hr). This quality corresponded to an outlet enthalpy (defined in the appendix) of 80 Btu per pound (1.86×10^{5} J/kg), which was approximately 50 percent of that required at design rated conditions (162 Btu/lb (3.77×10^{5} J/kg)). During the first run and until the first shutdown, the boiler heat-transfer capability increased with time as shown in figures 4 and 5. After 35 hours of running, the outlet vapor quality reached about

67 percent with 100° F (56° K) superheat and an outlet enthalpy of 110 Btu per pound (2.56×10^5 J/kg). At the beginning of the second startup, the outlet mercury vapor quality was approximately 55 percent with 5° F (3° K) superheat and an outlet enthalpy of about 90 Btu per pound (2.09×10^5 J/kg) (60 percent of rated conditions). This indicated a deconditioning of the boiler since the last shutdown. After the second startup, the boiler-outlet heat-transfer parameters increased with time to approximately 300 hours of boiler operation with no appreciable change thereafter. The design outlet conditions of this boiler are as follows:

Mercury flow, lb/hr (kg/hr)	11 500 (5200)
NaK flow, lb/hr (kg/hr)	42 000 (19 000)
Outlet quality, percent	100
Superheat temperature difference, °F (°K)	210 (117)
Terminal temperature difference, °F (°K)	20 (11.0)
Outlet enthalpy, Btu/lb (J/kg)	162 (3.77×10^5)

At 300 hours of boiler operating time, the boiler parameters were approximately as follows:

Mercury flow, lb/hr (kg/hr)	7500 (3390)
NaK flow, lb/hr (kg/hr)	33 000 (14 950)
Outlet quality, percent	97
Superheat temperature difference, °F (°K)	250 (139)
Terminal temperature difference, °F (°K)	35 (19.5)
Pinch-point temperature difference, °F (°K)	125 (69.5)
Outlet enthalpy, Btu/lb (J/kg)	160 (3.72×10^5)

The outlet enthalpy of 160 Btu per pound (3.72×10^5 J/kg) was 1 percent less than the design value.

Before the third startup, a mercury sample was taken, and the analysis indicated that the mercury was as clean as that originally put into the system. After the third startup, valve 207 (fig. 1) at the boiler outlet was in an open position which reduced boiler-outlet pressure. The lower outlet pressure (lower saturation temperature) increased the pinch-point temperature difference from around 125° F (69.5° K) to about 165° F (92° K). It is believed that this increase changed the heat transfer in the transition boiling regime; thus, the loop heat flux, total heat transferred, and outlet enthalpy were reduced. The outlet quality dropped 5 percent. Slightly less than 1 percent of the total heat load (or 20 percent of the heat not going into heat of vaporization due to reduced quality) went into additional superheat. The mercury-outlet temperature increased 20° F (10° K) and the thermal temperature difference decreased correspondingly. Increase in superheat temperature to 310° F (172° K) was due to the lower outlet saturation temperature in addition to the increase in outlet temperature.

Because of a leakage problem, valve 207 was welded permanently open during system shutdown before the fourth startup. Also because of leakage, valve 208 was welded open before the fifth startup; thus, another boiler-outlet pressure restriction was removed. After 722 hours, the pinch-point temperature difference decreased from 133° to 60° F (74° to 33° K) along with a 50° (28° K) reduction in superheat (fig. 5). These decreases were due to the increase in mercury flow from 7700 to 9300 pounds per hour (3490 to 4210 kg/hr) at a constant NaK flow as shown in figure 4. Examination of figures 4 and 5 indicates that the boiler-outlet conditions remained essentially constant after about 300 hours of mercury flow for the duration of 1087 hours accumulated flow time. After 300 hours, the average vapor quality was 93 percent with an average superheat of 300° F (167° K) corresponding to an average outlet enthalpy of 153 Btu per pound (3.56×10^{5} J/kg), which was 5 percent less than the design value of 162 Btu per pound (3.77×10^{5} J/kg).

Mercury pressure drop is also indicative of the change in performance or conditioning of the boiler. The pressure drop in the boiler tubes is equal to the overall pressure drop minus the pressure drop through the orifices at the entrance of the boiler tubes. Pressure drop through the orifices was obtained from reference 1 in which the entrance restrictor section was assumed to be a smooth tube with a well-rounded entrance and a sudden expansion exit. The pressure drop in the mercury tubes $\Delta P_{(in-out)} - \Delta P_r$ against total boiler operating time is presented in figure 7 for a constant value of an arbitrarily chosen mercury flow of approximately 7500 pounds per hour (3390 kg/hr). The value of $\Delta P_{(in-out)} - \Delta P_r$ increased with boiler operating time which indicated a change in conditioning throughout the boiler history.

A good indication of the change in performance of the boiler can also be obtained by looking at the NaK-shell temperature profiles. Typical inner- and outer-shell profiles at various times during boiler operation are shown in figure 8. The outer-shell profiles indicated that the outer-shell temperatures were always lower than the inner-shell temperatures, and the deviation between the inner- and outer-shell profiles increased with time. The discrepancy between the inner- and outer-shell profiles could not be explained from the available instrumentation. The discrepancy is thought to be due to unequal flow distribution on either or both the NaK and/or Hg sides. Referring to the inner profiles, figure 8(a) indicates that the inner tubes were not conditioned because of the slope of the temperature profile. The slope of the inner-shell profile and a slight superheat length increase with time indicated an improved heat-transfer performance throughout the boiler history (fig. 8). The inner-shell profiles in figures 8(c) to (e), corresponding to boiler time from 220 to 991 hours, indicated partially conditioned inner tubes.

If the outer-shell temperature profiles and known boiler mercury inventory were considered, it was apparent that the plug sections of the two outer tubes were flooded. The calculated boiler mercury inventory, which included the volume of mercury in the tubes as a function of tube length as well as that in the inlet plenum, is shown in figure 9. The plug length is 10 feet (3.048 m), which required approximately 80 pounds (36.2 kg) of mercury to completely fill all four tubes to the end of the plugs. Therefore, for the liquid-vapor interface to be within the plug section of all four tubes, the boiler inventory must be less than 80 pounds (36.2 kg) (design boiler inventory is 20 lb (9.7 kg)). Typical boiler inventories at various times are shown in figure 10 for the operating period of 300 to 518 hours. Boiler inventories were determined by knowing standpipe weight and condenser inventory during startup with all liquid-mercury lines filled and no inventory in the boiler (see PROCEDURE section). The outer-shell temperature profiles (fig. 8) and the boiler inventory shown in figure 10 indicate that the plug section of the two outer tubes may have been flooded. Total boiler inventory was always greater than 50 pounds (22.7 kg) for mercury-flow rates ranging from 38 to 55 percent of design flow. Other boiler inventory runs, which further amplify the possibility of flooding of the plug section of the two outer tubes, will be presented later.

Effect of Variation of NaK-Flow Rate on Boiler Performance for NaK-Inlet Temperature of 1300° F (980° K)

Definition of the effects of variations of boiler independent variables on boiler performance is necessary in order to determine the best operating condition for the boiler. The three independent variables considered were NaK-flow rate, mercury-flow rate, and NaK-inlet temperature. Mercury-inlet temperature was kept essentially constant for a given test series. Boiler performance data for various runs after 200 hours of operation are given in table IV.

The effect of changing NaK flow on boiler performance for NaK-inlet temperature of 1300^{o} F (980^{o} K) is presented in figure 11. The following boiler parameters, terminal temperature difference, superheat temperature difference, pinch-point temperature difference, outlet vapor quality, and the actual to design ratios of NaK- and mercury-flow rates, are plotted with NaK flow for three values of mercury flow. Optimum heat transfer for obtaining maximum quality was reached at a value of NaK flow of about 18 000 pounds per hour (8150 kg/hr) corresponding to a value of 0.7 of $\left(W_{NaK}/W_{Hg}\right)_{ac}/\left(W_{NaK}/W_{Hg}\right)_{d}$. For a further increase in NaK flow, the amount of superheat increased but leveled off at the high NaK flows. The leveling off point depended on the value of mercury-flow rate. Terminal temperature difference decreased with an increase in

NaK flow and leveled off at NaK flows corresponding to values of $(W_{NaK}/W_{Hg})_{ac}/(W_{NaK}/W_{Hg})_d$ at approximately 1.0. Here, the boiler reached its limiting heat-transfer capability since for a further increase in NaK flow the superheat and terminal temperature difference remains essentially constant, indicating that the chosen design NaK- to mercury-flow rate ratio was above the optimum value. For $(W_{NaK}/W_{Hg})_{ac}/(W_{NaK}/W_{Hg})_d$ of 1.0, the pinch point varied from 100° to 150° F (56° to 83° K) for mercury flows considered and increased as NaK flow increased.

A specific boiler thermal power input was required to keep the NaK-inlet temperature at 1300° F (900° K) for a variation in NaK-flow rates as shown in figure 12. Boiler power input increased with an increase in NaK flow at lower NaK flows but leveled off at the higher NaK flows because of the limiting heat-transfer capability of the boiler. The boiler thermal power input leveled off for NaK flows corresponding to design ratio of NaK- to mercury-flow rates.

The effect of changing NaK flow on boiler performance can also be shown by considering pressure drop and inventory change in the boiler (fig. 13). A common reference point (NaK flow of 20 600 lb/hr (11 800 kg/hr)) was chosen for defining the change in boiler inventory. Boiler inventory decreased with an increase in NaK flow, which resulted in a longer two-phase length. This increased length resulted in a slight increase in pressure drop with an increase in NaK flow. For the lowest mercury flow shown, 6150 pounds per hour (2780 kg/hr), the test data were taken 250 hours later than the other two mercury flows. The increased pressure drop was due to improved conditioning of the mercury tubes. Changes in boiler mercury inventory as a function of NaK-flow rate are shown in figure 14 at a boiler operation time of about 800 hours. For all conditions considered herein, the total boiler inventory was greater than 75 pounds (34 kg), which again indicated that the plug section of the two outer mercury tubes may have been flooded. Boiler mercury inventory increased as the mercury-flow rate increased. Total boiler inventory decreased with an increase in NaK flow for the range of NaK flows considered but appeared to be leveling off for each mercury-flow rate.

The plot of NaK side pressure drop with NaK-flow rate is presented in figure 15. This pressure drop ranged from 3 to 6.5 pounds per square inch (2.07 to 4.48×10^4 N/m^2) corresponding to NaK flow of 20 000 to 33 000 pounds per hour (9070 to 14 950 kg/hr).

Effect of Mercury Flow on Boiler Performance for NaK-Inlet Temperature of 1300° F (980° K)

The effect of increased mercury-flow rate on pressure drop and boiler inventory for constant NaK flow and NaK-inlet temperature at 1300° F (980° K) is presented in figure 16.

The increase in boiler inventory was determined from the loss of condenser inventory. Boiler inventory increased 65 pounds for a mercury-flow change from 6300 to 9350 pounds per hour (2850 to 4240 kg/hr). This, along with the NaK outer-shell profile (fig. 8), indicated that the outer tubes took a majority of the boiler inventory. The overall pressure drop increased from 78 to 103 pounds per square inch (5.38 to 7.10×10^5 N/m^2). The overall pressure drop (less the pressure drop in the restrictor section) increased with an increase in mercury flow at a decreasing rate and decreased slightly at the highest mercury flow of 9350 pounds per hour (4240 kg/hr). This characteristic may be attributed to the decrease in two-phase length due to increased inventory with mercury flow which had a larger effect on pressure drop than did the increased velocity. A plot of total boiler mercury inventory and mercury flow is shown in figure 17. During this test the NaK-flow rate was held constant at 33 000 pounds per hour (14 950 kg/hr) while the boiler NaK-inlet temperature was maintained at 1300° F (980° K). The total boiler inventory ranged from 70 to 105 pounds (31.7 to 47.5 kg) for a variation in mercury flow from 5600 to 7600 pounds per hour (2500 to 3440 kg/hr), which indicates that some of the tube plug sections were flooded.

Effect of NaK-Inlet Temperature on Boiler Performance

The effect of NaK-inlet temperature on boiler performance for constant ratios of $\left(W_{NaK}/W_{Hg}\right)_{ac}/\left(W_{NaK}/W_{Hg}\right)_d$ is presented in figure 18. The superheat and pinch-point temperature difference increased with an increase in NaK-inlet temperature. An increase in the actual to design ratios of NaK and mercury-flow rates from 1.17 to 1.74 due to a decrease in mercury-flow rate resulted in an approximate 50° F (28° K) increase in superheat. Since the degree of superheat is a function of mercury-outlet saturation temperature, the high superheat (greater than 300° F (167° K)) for all data considered was a result of lower than design boiler-outlet pressure. This high superheat was due to the fact that the valves at the boiler outlet were in an open position thereby lowering the boiler-outlet pressure restriction. Effect of mercury-outlet back pressure on the superheat temperature difference for a constant value of 1.4 for the ratio $\left(W_{NaK}/W_{Hg}\right)_{ac}/\left(W_{NaK}/W_{Hg}\right)_d$ is shown in figure 19. The mercury-outlet pressure with and without restriction was 225 and 115 pounds per square inch absolute (1.552×10^6 and 7.94×10^5 N/m^2), respectively. The superheat increased approximately 110° F (61° K) which corresponded to a decrease in the boiler-outlet saturation temperature from 1030° to 920° F (828° to 767° K).

The effect of changing NaK-inlet temperature and varying NaK flow on boiler performance is shown in figure 20. The thermal power input of the boiler increased as NaK flow was increased, which resulted in a variation of NaK-inlet temperature. The results indicated that, for an increase in thermal power input to the boiler due to the method of primary-loop operation, there was a slight increase in outlet vapor quality. For an increase in NaK-flow rate, the NaK-inlet temperature decreased 50° to 75° F (28° to 42°K) (over the range of mercury flows considered) from the initial inlet temperature to a minimum inlet temperature, while the amount of superheat increased and the terminal temperature decreased. The effect of changes in NaK flow on boiler performance are much greater than changes in NaK-inlet temperature.

The variation of overall pressure drop with pinch-point temperature difference for constant NaK and mercury flow is presented in figure 21 for operating time between 709 and 991 hours. There was a slight increase in overall pressure drop with an increase in pinch-point temperature difference, which indicates a partially conditioned boiler. A fully conditioned boiler would have a higher rate of change of pressure drop with a given change in pinch-point temperature difference.

SUMMARY OF RESULTS

An experimental study of the conditioning and the steady-state performance of a SNAP-8 tube-in-shell boiler yielded the following principal results:

1. The boiler-outlet heat-transfer parameters (outlet quality and enthalpy, and superheat temperature differences) increased with time up to approximately 300 hours of mercury flow and then remained essentially constant until test termination at 1087 hours of operation.

2. For boiler operation after 300 hours, the average quality was 93 percent at an average superheat of 300° F (170° K), corresponding to an average outlet enthalpy of 153 Btu per pound (3.55×10^{5} J/kg). This enthalpy was 5 percent less than design rated outlet condition of 162 Btu per pound (3.77×10^{5} J/kg).

3. Although the boiler mercury-vapor outlet quality and terminal temperature difference remained essentially constant after 300 hours of operation, the boiler internal heat transfer continued to improve. This improvement was indicated by the change in slope of the NaK inner-shell temperature profile which increased with time throughout the boiler operation. This improvement was also indicated by the continued increase in overall pressure drop with operating time. The NaK outer-shell temperature profiles and the boiler mercury inventory indicated that the plug section of the two outer boiler tubes were flooded.

4. Performance data indicated that the chosen design NaK- to mercury-flow-rate ratio was above the optimum value.

5. At approximately 700 hours of boiler operation, the overall mercury pressure drop varied from 78 to 103 pounds per square inch (5.4 to 7.1×10^5 N/m^2), which corresponds to mercury-flow rates of from 6350 to 9350 pounds per hour (2850 to 4240 kg/hr), respectively.

6. Overall pressure drop increased slightly with increased pinch-point temperature difference.

7. The NaK side boiler pressure drop ranged from 3 to 6.5 pounds per square inch corresponding to NaK flows of 20 000 to 33 000 pounds per hour (9100 to 15 000 kg/hr), respectively.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 17, 1967,
701-04-00-02-22.

APPENDIX - METHOD OF CALCULATION

Pinch-Point Temperature Difference

The pinch-point temperature difference was determined by a heat balance across the mercury-liquid portion of the boiler.

$$W_{NaK}c_{p,NaK}(T_{NaK,pp} - T_{NaK,out}) = W_{Hg}c_{p,Hg,liq}(T_{Hg,pp} - T_{Hg,in}) \tag{A1}$$

Solving for NaK temperature at pinch point (liquid-vapor interface) yields

$$T_{NaK,pp} = \frac{W_{Hg}c_{p,Hg,liq}(T_{Hg,pp} - T_{Hg,in})}{W_{NaK}c_{p,NaK}} + T_{NaK,out} \tag{A2}$$

The thermodynamic properties were determined from references 10 to 12. Saturation temperature of mercury at the pinch point was determined from the saturation pressure. Saturation mercury pressure was obtained by subtracting the pressure drop in the orifices at the entrance of the boiler tubes from the boiler-inlet pressure and by neglecting the liquid pressure drop in the mercury tubes. The pressure drop through the orifices was obtained from reference 1 in which the entrance restrictor section was assumed to be a smooth tube with a well-rounded entrance and sudden expansion exit. Thus the pinch-point temperature difference can be found from

$$\Delta T_{pp} = T_{NaK,pp} - T_{Hg,pp} \tag{A3}$$

Quality

The boiler-outlet quality was determined from heat balance across the boiler where

$$W_{NaK}c_{p,NaK}(T_{NaK,in} - T_{NaK,out}) = W_{Hg}c_{p,Hg,liq}(T_{Hg,pp} - T_{Hg,in}) + W_{Hg}x\left[h_{fg} + c_{p,Hg,v}(T_{Hg,SH} - T_{Hg,sat})\right] \tag{A4}$$

Solving for the outlet quality yields

$$x = \frac{W_{NaK} c_{p, NaK}(T_{NaK, in} - T_{NaK, out}) - W_{Hg} c_{p, Hg, liq}(T_{Hg, pp} - T_{Hg, in})}{W_{Hg}\left[h_{fg} + c_{p, Hg, v}(T_{Hg, SH} - T_{Hg, sat})\right]} \tag{A5}$$

Mercury-Outlet Enthalpy

The outlet enthalpy was determined from the mercury-inlet enthalpy and the change in enthalpy across the boiler.

$$h_{out} = h_{in} + \Delta h \tag{A6}$$

Inlet enthalpy is a function of the liquid temperature (0.0 h at 32^{O} F (274^{O} K)) at the boiler inlet. Change in enthalpy across the boiler was calculated from NaK heat input (assuming a boiler efficiency of unity) divided by the total mercury flow where

$$\Delta h = \frac{W_{NaK} c_{p, NaK}(T_{NaK, in} - T_{NaK, out})}{W_{Hg}} \tag{A7}$$

Mercury-Flow Rate

The liquid flow at the boiler inlet was calculated from the standard incompressible flow equation for a venturi

$$W_{Hg, liq} = A_{th} C_D f E \sqrt{2 g_c \rho_{liq} \Delta P_{liq}} \tag{A8}$$

The density ρ_{liq} was determined from the temperature of liquid mercury. The measured pressure drop ΔP_{liq} was the static pressure drop from the inlet to throat of the venturi.

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TABLE I. - SNAP-8 TUBE-IN-SHELL BOILER DESIGN PARAMETERS

[Boiler size: length, 55 in. (1.398 m); diameter, 24 in. (0.6096 m); weight, 850 lb (385 kg). Tube length, 60 ft (18.3 m).]

Design parameter	Flow rate		Temperature						Pressure				Inventory	
	lb/hr	kg/hr	Inlet		Outlet		Drop		Inlet		Outlet		lb	kg
			^{o}F	^{o}K	^{o}F	^{o}K	^{o}F	^{o}K	psia	N/m^2	psia	N/m^2		
NaK	42 000	19 000	1298	976	----	---	170	94.5	41	2.83	---	-----	150	68
Hg	11 500	5 200	515	542	1280	967	---	----	340	23.42	270	18.62	20	9

TABLE II. - THERMOCOUPLE LOCATIONS ALONG HG TUBE LENGTH

(a) Inner shell

Vertical plane								
A			B			C		
Thermo-couple	Length, ft (a)	Elevation, in. (b)	Thermo-couple	Length, ft (a)	Elevation, in. (b)	Thermo-couple	Length, ft (a)	Elevation, in. (b)
35	2.29	5.13	36	3.95	6.06	37	5.61	7.13
38	7.27	8.12	39	8.92	8.95	40	10.58	9.79
41	12.24	10.67	42	13.90	11.51	43	15.55	12.34
44	17.22	13.23	45	18.88	14.06	46	20.53	14.89
47	22.19	15.78	48	23.85	16.62	49	25.51	17.45
50	27.17	18.33	51	28.83	19.17	52	30.48	20.00
53	32.14	20.89	54	33.80	21.72	55	35.46	22.56
56	37.11	23.44	57	38.78	24.28	58	40.43	25.11
59	42.09	26.00	60	43.75	26.83	61	45.41	27.66
62	47.07	28.55	63	48.73	29.39	64	50.38	30.22

(b) Outer shell

190	2.51	5.23	191	4.45	6.13	192	6.39	7.13
193	8.34	8.18	194	10.28	8.93	195	12.22	9.75
196	14.16	10.73	197	16.11	11.49	198	18.05	12.30
199	19.99	13.29	200	21.93	14.04	201	23.87	14.85
202	25.82	15.84	208	27.76	16.60	204	29.70	17.41
205	31.65	18.40	206	33.59	19.15	207	35.53	19.96
208	37.47	20.95	209	39.42	21.70	209	41.36	22.52
211	43.30	23.50	212	45.24	24.26	213	47.18	25.07
214	49.12	26.06	215	51.07	26.81	216	53.01	27.62

[a]To convert ft to m, multiply by 0.3048.

[b]To convert in. to m, multiply by 0.0254.

TABLE III. - BOILER HISTORY DATA

Run	Measured data									Calculated performance parameters					
	Total boiler operating time, t, hr	Hg flow, W_{Hg}, lb/hr (a)	NaK flow, W_{NaK}, lb/hr (a)	NaK inlet temperature, $T_{NaK, in}$, ^{o}F (b)	NaK outlet temperature, $T_{NaK, out}$, ^{o}F (b)	Hg inlet temperature, $T_{Hg, in}$, ^{o}F (b)	Hg outlet temperature, $T_{Hg, out}$, ^{o}F (b)	Hg inlet pressure, $P_{Hg, in}$, psia (c)	Hg outlet pressure, $P_{Hg, out}$, psia (c)	Outlet vapor quality, x	Pinch-point temperature difference, ΔT_{pp}, ^{o}F (b)	Outlet enthalpy, h_{out}, Btu/lb (d)	Superheat temperature difference, ΔT_{SH}, ^{o}F (b)	Terminal temperature difference, ΔT_{T}, ^{o}F (b)	Overall pressure drop, $\Delta P_{(in-out)}$, psi (c)
199	12.0	8928	19 551	1290	1147	471	976	199	150	0.39	190	80	6	314	49
205	14.5	8866	19 833	1293	1153	477	977	189	150	.40	204	80	7	316	39
207	15.5	8864	20 044	1289	1143	470	978	191	150	.42	194	83	8	311	41
209	17.5	8670	22 052	1305	1170	474	985	196	154	.45	212	86	10	320	42
213	19.5	8531	24 446	1288	1168	469	963	177	134	.45	221	86	10	325	43
216	21.5	7538	23 721	1312	1197	562	963	164	128	.51	252	93	17	349	36
239	35.0	5291	40 700	1320	1260	606	1013	123	101	.68	337	122	104	307	22
244	36.0	5214	38 307	1302	1240	514	989	122	103	.65	339	110	76	313	19
355	48.0	5527	19 955	1296	1203	559	925	123	110	.47	290	87	3	371	13
376	53.5	5071	19 460	1307	1113	550	967	109	96	.51	238	94	64	340	13
382	57.5	5119	14 425	1320	1183	541	1036	118	102	.54	284	98	122	284	16
385	59.5	5177	19 234	1293	1186	550	1041	110	93	.56	291	101	142	252	7
400	67.0	5265	37 936	1317	1256	537	1068	115	101	.62	349	92	158	249	14
404	70.5	5109	33 604	1300	1233	549	1046	113	95	.63	327	108	144	254	18
408	74.5	5078	33 367	1307	1239	566	1053	113	97	.64	333	111	149	254	16
426	84.5	4979	9 266	1311	1092	554	1032	116	101	.57	204	102	122	279	15
434	89.5	4955	9 393	1305	1085	550	1060	117	101	.59	196	104	149	245	16
442	97.5	5091	33 481	1288	1220	642	1120	125	111	.65	297	110	196	168	14
450	105.0	5928	33 606	1314	1224	555	1125	167	145	.73	260	125	160	199	22
457	108.5	7632	38 142	1317	1219	520	1067	207	170	.70	224	120	77	250	37
461	111.0	7507	38 668	1312	1218	511	1104	204	167	.68	228	117	117	208	37
464	113.5	7530	39 072	1306	1202	527	1104	208	170	.78	208	130	114	202	38
479	129.0	8420	39 200	1308	1168	414	1122	182	127	.83	212	136	177	186	45
484	132.0	8950	39 107	1297	1163	410	1088	198	138	.82	189	135	131	209	60
488	135.0	7580	39 351	1282	1172	423	1145	209	173	.80	180	134	153	137	36
492	139.0	7583	38 847	1315	1202	419	1211	212	178	.80	205	134	216	104	34
496	146.5	7843	39 635	1304	1171	384	1138	191	134	.95	199	153	185	166	57
502	153.0	7935	39 018	1292	1172	374	1158	194	136	.82	198	136	203	134	58
510	160.5	7963	39 166	1290	1159	391	1178	197	144	.90	183	147	215	112	53
520	170.5	8141	39 593	1289	1154	365	1160	259	215	.91	130	149	132	129	44
525	175.5	7921	39 400	1297	1162	393	1177	286	241	.94	115	159	129	120	45
528	178.5	8021	38 896	1310	1173	369	1186	303	266	.92	118	150	119	124	37
534	184.5	8021	39 524	1283	1168	363	1160	275	236	.77	125	130	116	123	39
539	191.5	7975	38 823	1289	1153	365	1192	274	233	.91	118	150	150	97	41
567	220.0	7380	28 843	1319	1128	383	1243	235	196	1.00	125	161	231	76	39
582	230.0	6777	38 847	1297	1180	377	1269	215	178	.97	181	159	273	28	37
587	234.0	6510	33 558	1307	1162	379	1277	216	178	1.00	164	162	280	30	38
594	239.0	6506	18 729	1297	1061	379	1234	211	178	.94	82	154	237	63	33
606	248.0	7559	38 787	1297	1145	374	1238	251	206	1.00	124	162	218	58	45
663	277.5	6697	38 725	1280	1161	375	1252	229	187	.95	151	155	247	28	42

[a]To convert lb/hr to kg/hr, multiply by 0.4536.
[b]To convert ^{o}F to ^{o}K, add 460 and multiply by 5/9.
[c]To convert psia to N/m^2, multiply by 6895.
[d]To convert Btu/lb to J/kg, multiply by 2324.

TABLE III. - Concluded. BOILER HISTORY DATA

Run	Measured data									Calculated performance parameters					
	Total boiler operating time, t, hr	Hg flow, W_{Hg}, lb/hr (a)	NaK flow, W_{NaK}, lb/hr (a)	NaK inlet temperature, $T_{NaK, in}$, ^oF (b)	NaK outlet temperature, $T_{NaK, out}$, ^oF (b)	Hg inlet temperature, $T_{Hg, in}$, ^oF (b)	Hg outlet temperature, $T_{Hg, out}$, ^oF (b)	Hg inlet pressure, $P_{Hg, in}$, psia (c)	Hg outlet pressure, $P_{Hg, out}$, psia (c)	Outlet vapor quality, x	Pinch-point temperature difference, ΔT_{pp}, ^oF (b)	Outlet enthalpy, h_{out}, Btu/lb (d)	Superheat temperature difference, ΔT_{SH}, ^oF (b)	Terminal temperature difference, ΔT_T, ^oF (b)	Overall pressure drop, $\Delta P_{(in-out)}$, psi (c)
740	304.0	7667	38 965	1317	1179	367	1290	281	231	0.95	137	156	249	27	50
742	306.5	7845	37 720	1304	1161	367	1270	304	258	.94	105	155	209	34	46
743	309.0	7445	38 913	1310	1172	365	1287	272	224	1.00	135	163	252	23	48
758	341.5	7260	35 271	1303	1158	384	1267	269	224	.98	123	160	232	36	45
776	356.5	6416	35 303	1286	1157	387	1354	239	199	.99	139	160	240	32	40
793	372.5	7298	35 606	1282	1136	367	1250	269	224	.99	101	160	215	32	45
861	394.0	4337	20 730	1282	1142	299	1272	126	91	.90	227	149	377	10	35
871	406.0	3713	21 075	1282	1162	307	1272	162	143	.92	203	152	309	10	19
885	426.0	6747	31 899	1306	1163	376	1293	196	141	.93	184	154	332	13	55
891	437.0	7772	33 706	1307	1153	367	1296	232	170	.91	151	151	307	11	62
897	444.5	6821	33 729	1294	1160	380	1281	191	133	.91	185	150	329	13	58
931	463.0	7357	33 373	1280	1134	374	1268	233	174	.91	129	150	275	12	59
988	483.0	7727	33 537	1296	1147	371	1283	234	169	.88	144	147	294	13	65
995	492.5	7798	33 771	1286	1133	373	1273	234	166	.91	129	151	288	13	68
1023	507.5	7783	33 637	1298	1148	384	1290	238	169	.88	141	148	301	8	69
1037	516.5	6900	33 615	1295	1162	390	1288	208	150	.88	173	148	318	7	58
1152	570.0	7429	33 238	1291	1145	355	1279	213	134	.89	157	148	328	12	79
1180	603.5	6319	33 392	1302	1176	357	1289	181	112	.90	207	151	377	13	69
1252	683.0	7455	33 800	[e]1304	1148	338	1291	226	140	.96	139	159	332	15	86
1281	709.0	7368	33 800	[e]1299	1148	323	1284	226	138	.93	136	157	337	13	88
1307	725.0	7785	33 600	[e]1311	1153	333	1293	242	146	.91	133	156	327	17	96
1308	727.0	8263	33 600	[e]1301	1136	329	1290	255	156	.89	108	153	314	11	99
1310	729.0	8679	33 600	[e]1295	1116	325	1281	265	163	.92	83	157	298	14	102
1311	731.0	9331	33 600	[e]1295	1101	324	1277	281	178	.94	60	159	281	18	103
1586	771.5	7935	32 879	1302	1139	274	1291	244	151	.89	133	150	241	11	93
1624	793.5	6346	32 962	1308	1174	247	1294	194	116	.92	197	154	284	14	78
1666	827.5	6857	29 515	1309	1145	245	1296	213	129	.93	160	156	280	13	84
1690	934	7355	29 139	1329	1153	252	1321	231	141	.92	157	155	281	8	90
1710	945.5	7692	32 905	1298	1135	266	1285	239	146	.92	131	154	239	13	93
1733	969.5	7633	32 965	1302	1141	282	1293	239	145	.92	136	154	247	9	94
1792	969.5	7677	32 920	1295	1134	280	1284	235	139	.91	133	153	241	11	96
1801	987.5	7554	32 735	1300	1141	275	1285	233	134	.91	141	152	243	15	99
1809	990.5	7634	32 603	1287	1128	278	1278	234	137	.90	128	151	236	9	97
2067	1076	7754	32 465	1282	1117	277	1276	244	142	.92	110	153	226	6	102
2084	1082	9180	32 455	1304	1107	277	1294	296	182	.93	73	154	207	10	114

[a]To convert lb/hr to kg/hr, multiply by 0.4536.
[b]To convert ^oF to ^oK, add 460 and multiply by 5/9.
[c]To convert psia to N/m^2, multiply by 6895.
[d]To convert Btu/lb to J/kg, multiply by 2324.
[e]Heater outlet temperature (approximately NaK inlet temperature).

TABLE IV. - BOILER PERFORMANCE DATA

Run	Measured data									Calculated performance data					
	Total boiler operating time, t, hr	Hg flow, W_{Hg}, lb/hr (a)	NaK flow, W_{NaK}, lb/hr (a)	NaK inlet temperature, $T_{NaK, in}$, ^oF (b)	NaK outlet temperature, $T_{NaK, out}$, ^oF (b)	Hg inlet temperature, $T_{Hg, in}$, ^oF (b)	Hg outlet temperature, $T_{Hg, out}$, ^oF (b)	Hg inlet pressure, $P_{Hg, in}$, psia (c)	Hg outlet pressure, $P_{Hg, out}$, psia (c)	Outlet vapor quality, x	Pinch-point temperature difference, ΔT_{pp}, ^oF (b)	Outlet enthalpy, h_{out}, Btu/lb (d)	Superheat temperature difference, ΔT_{SH}, ^oF (b)	Terminal temperature difference, ΔT_T, ^oF (b)	Overall pressure drop, $\Delta P_{(in-out)}$, psi (c)
557	213.5	7832	39 350	1295	1162	355	1244	238	200	0.92	148	162	224	51	38
559	215	7814	36 350	1157	1157	360	1249	237	196	.91	149	162	235	49	41
564	218	7818	32 300	1210	1151	363	1262	237	194	.90	146	162	249	48	43
568	220	7819	28 841	1306	1125	375	1244	236	193	.93	123	158	232	62	43
570	222	7783	24 930	1292	1089	372	1211	233	196	.90	93	154	196	81	36
573	224	7816	20 683	1287	1052	373	1134	232	192	.88	63	148	121	153	40
577	227	7801	16 500	1300	1016	371	1096	225	189	.85	39	143	88	204	36
582	230	6986	38 847	1299	1180	377	1269	215	177	.91	183	159	272	30	38
586	234	6992	33 408	1299	1163	380	1283	218	177	.89	164	156	287	16	41
589	236	6975	28 058	1308	1144	376	1275	217	179	.91	149	157	276	33	38
592	2375	6927	23 471	1297	1102	379	1252	210	174	.90	118	159	260	45	36
594	239	7103	18 800	1298	1059	379	1234	211	178	.89	81	154	236	64	33
597	242	6971	15 708	1297	1016	377	1168	210	172	.88	46	153	185	129	38
600	244	6981	13 072	1300	977	371	1025	198	172	.87	29	154	33	275	26
603	246	6948	10 832	1297	939	379	989	188	156	.78	11	136	14	308	32
606	248	8000	37 800	1280	1145	374	1238	251	206	.90	125	162	213	42	45
608	250	7994	33 184	1257	1105	372	1205	246	205	.87	90	151	180	52	41
610	252	7924	29 133	1263	1090	369	1194	243	203	.87	83	152	171	69	40
612	254	7931	24 087	1280	1073	377	1190	245	200	.86	69	151	170	90	45
614	256	8032	18 669	1308	1045	367	1171	242	201	.85	55	146	150	37	41
616	2575	7966	16 200	1335	1035	370	1172	242	206	.84	51	146	147	163	36
618	259	7438	16 118	1328	1036	374	1220	231	193	.82	56	153	209	108	38
620	260	7463	18 900	1308	1057	373	1236	233	195	.84	68	158	221	72	38
622	262	7403	23 726	1304	1104	373	1260	235	193	.83	106	155	247	44	42
624	264	7411	28 518	1298	1130	372	1262	236	195	.84	125	156	247	36	41
626	266	7469	34 224	1308	1166	373	1277	239	197	.85	154	157	260	31	42
629	268	7452	38 236	1337	1208	369	1315	240	194	.85	204	160	299	22	46
663	278	7190	38 725	1280	1161	375	1252	229	187	.86	152	156	245	28	42
665	280	7212	33 288	1269	1132	376	1239	236	187	.83	120	154	232	30	49
667	281	7187	29 044	1248	1091	378	1208	226	186	.84	108	137	202	40	40
669	283	7145	23 800	1262	1071	372	1211	224	189	.84	75	154	201	51	35
671	284	7107	19 100	1282	1043	380	1213	222	185	.84	71	199	208	69	37
674	286	7157	15 797	1297	1014	375	1184	228	185	.82	45	147	179	113	43
740	304.0	7667	38 465	1328	1129	367	1290	281	231	.95	137	157	213	38	50
750	320	7459	38 393	1310	1159	370	1267	277	227	1.00	118	162	193	43	50

[a] To convert lb/hr to kg/hr, multiply by 0.4536.
[b] To convert ^oF to ^oK, add 460 and multiply by 5/9.
[c] To convert psia to N/m^2, multiply by 6895.
[d] To convert Btu/lb to J/kg, multiply by 2324.

TABLE IV. - Continued. BOILER PERFORMANCE DATA

Run	Measured data									Calculated performance data					
	Total boiler operating time, t, hr	Hg flow, W_{Hg}, lb/hr (a)	NaK flow, W_{NaK}, lb/hr (a)	NaK inlet temperature, $T_{NaK, in}$, ^oF (b)	NaK outlet temperature, $T_{NaK, out}$, ^oF (b)	Hg inlet temperature, $T_{Hg, in}$, ^oF (b)	Hg outlet temperature, $T_{Hg, out}$, ^oF (b)	Hg inlet pressure, $P_{Hg, in}$, psia (c)	Hg outlet pressure, $P_{Hg, out}$, psia (c)	Outlet vapor quality, x	Pinch-point temperature difference, ΔT_{pp}, ^oF (b)	Outlet enthalpy, h_{out}, Btu/lb (d)	Superheat temperature difference, ΔT_{SH}, ^oF (b)	Terminal temperature difference, ΔT_T, ^oF (b)	Overall pressure drop, $\Delta P_{(in-out)}$, psi (c)
752	322	7447	38 514	1310	1170	364	1287	271	221	1.00	134	163	217	23	50
758	346	7260	35 271	1303	1160	384	1267	269	224	.98	123	160	198	36	45
759	346	7259	35 458	1302	1148	383	1270	260	226	.99	114	162	202	32	34
793	377	7298	35 606	1281	1136	367	1250	269	224	.99	101	161	181	31	45
979	475	6109	33 316	1306	1190	376	1297	194	144	.86	208	144	339	9	50
981	475.5	6111	33 505	1303	1185	376	1290	199	150	.88	199	147	332	13	49
983	476.5	6122	28 392	1310	1168	377	1296	194	145	.90	189	150	338	14	49
985	477.5	6017	24 959	1306	1153	378	1297	189	142	.86	180	150	347	9	47
987	478.5	6137	20 219	1313	1116	380	1297	193	146	.86	146	148	244	16	47
1281	709	7368	33 000	1298	1146	323	1284	226	138	.92	136	153	326	14	88
1282	710	7367		1299	1148	324	1287	226	138	.90	138	153	329	12	88
1283	711	7317		1308	1160	328	1296	225	138	.90	150	150	338	12	87
1284	711	7346		1308	1160	326	1295	226	138	.89	150	149	337	13	88
1285	711	7299		1318	1168	331	1308	226	137	.91	157	152	350	11	89
1286	711	7260		1320	1176	330	1306	226	137	.87	165	147	348	14	89
1287	712	7317		1334	1185	337	1323	227	138	.90	173	151	365	11	90
1288	712	7332		1338	1189	334	1325	230	139	.89	175	151	367	13	90
1289	714	7309		1329	1189	338	1327	229	139	.91	176	152	369	12	90
1290	714	7273		1339	1189	339	1330	228	139	.91	177	153	372	10	89
1291	715	7345		1343	1191	340	1327	231	140	.92	176	152	369	15	92
1292	715	7373		1347	1193	340	1329	232	139	.90	178	151	371	14	93
1293	716	7392		1339	1189	343	1326	232	140	.89	174	152	378	14	91
1295	718	6336		1308	1180	333	1293	196	118	.90	189	150	361	15	78
1296	718	6376		1308	1178	334	1293	196	118	.90	187	152	361	15	78
1297	719	6389		1303	1176	339	1289	196	118	.88	185	148	357	14	78
1298	719	6379		1303	1177	339	1289	197	117	.88	184	148	356	15	80
1299	720	6345		1303	1175	342	1289	196	118	.90	184	150	357	14	79
1300	720	6373		1302	1173	343	1289	197	119	.90	181	153	357	13	79
1301	720.5	6337		1297	1170	342	1286	197	119	.89	178	160	353	11	78
1302	721	6354		1297	1168	345	1282	196	118	.81	177	151	350	15	77
1303	721.8	6334		1280	1153	341	1267	195	116	.90	163	149	335	13	79
1304	721.9	6344		1283	1156	345	1269	194	115	.89	167	149	339	14	78
1586	7765	7935	32 879	1303	1139	274	1291	244	151	.90	133	151	241	12	93
1590	7725	7948	31 197	1309	1133	275	1297	243	150	.90	129	153	248	12	93
1593	773	7991	29 041	1304	1119	277	1295	241	149	.88	120	149	247	9	92

[a]To convert lb/hr to kg/hr, multiply by 0.4536.
[b]To convert ^oF to ^oK, add 460 and multiply by 5/9.
[c]To convert psia to N/m^2, multiply by 6895.
[d]To convert Btu/lb to J/kg, multiply by 2324.

TABLE IV. - Concluded. BOILER PERFORMANCE DATA

Run	Measured data									Calculated performance data					
	Total boiler operating time, t, hr	Hg flow, W_{Hg}, lb/hr (a)	NaK flow, W_{NaK}, lb/hr (a)	NaK inlet temperature, $T_{NaK, in}$, ^{o}F (b)	NaK outlet temperature, $T_{NaK, out}$, ^{o}F (b)	Hg inlet temperature, $T_{Hg, in}$, ^{o}F (b)	Hg outlet temperature, $T_{Hg, out}$, ^{o}F (b)	Hg inlet pressure, $P_{Hg, in}$, psia (c)	Hg outlet pressure, $P_{Hg, out}$, psia (c)	Outlet vapor quality, x	Pinch-point temperature difference, ΔT_{pp}, ^{o}F (b)	Outlet enthalpy, h_{out}, Btu/lb (d)	Superheat temperature difference, ΔT_{SH}, ^{o}F (b)	Terminal temperature difference, ΔT_T, ^{o}F (b)	Overall pressure drop, $\Delta P_{(in-out)}$, psi (c)
1596	773.5	7925	26 180	1308	1099	275	1294	240	150	0.91	103	153	247	14	90
1599	774	7957	23 283	1305	1076	274	1293	236	151	.88	88	149	249	12	85
1624	793.5	6347	32 962	1308	1174	247	1294	194	116	.92	197	153	284	14	78
1628	794.5	6311	31 408	1308	1167	247	1294	194	117	.94	191	154	284	14	77
1631	795.5	6352	29 236	1306	1154	248	1292	193	118	.93	180	154	282	14	75
1634	796.5	6319	26 624	1307	1137	248	1293	193	117	.96	169	158	283	14	76
1637	797.5	6302	22 315	1307	1109	249	1294	193	117	.93	143	154	284	13	76
1640	799.5	6309	14 175	1307	1006	251	1287	186	115	.90	65	149	284	20	71
1643	817.5	4935	33 014	1304	1001	244	1291	151	89	.93	254	152	320	13	62
1646	818.5	4908	29 139	1309	1190	244	1297	150	88	.95	246	155	327	12	62
1649	819	4937	24 596	1307	1169	245	1294	151	89	.92	228	151	323	13	62
1652	820	4943	19 347	1303	1124	247	1289	151	88	.94	190	154	318	14	63
1655	821	4917	14 348	1303	1066	248	1285	150	89	.92	142	152	315	18	61
1658	823	4928	10 016	1309	960	248	1282	147	90	.95	56	156	315	17	57
1561	824	5022	9 897	1270	929	248	1250	142	86	.90	33	149	289	20	56
1564	825	4885	9 998	1348	1009	247	1327	151	88	.94	100	153	356	21	63
1801	988	7554	32 735	1300	1141	275	1285	233	134	.92	141	152	333	15	99
1802	988	7544	32 438	1301	1142	275	1289	234	136	.91	141	152	334	12	98
1803	988	7515	32 541	1307	1146	275	1295	232	134	.92	146	154	345	12	99
1804	988	7665	32 615	1307	1143	275	1296	234	134	.92	143	154	344	11	100
1805	990	7618	32 641	1284	1121	277	1271	233	135	.94	121	154	319	12	98
1806	990	7616	32 725	1286	1123	278	1277	234	136	.94	123	155	322	9	98
1807	990	7620	32 862	1286	1125	278	1277	234	136	.93	124	156	322	10	98
1808	990	7618	32 754	1289	1126	277	1275	235	138	.93	125	155	317	14	96
1809	990	7634	32 603	1287	1121	278	1278	234	137	.93	128	159	323	8	97
1810	990	7612	32 740	1289	1128	278	1279	285	135	.92	127	153	326	10	100
1912	1011	5191	32 725	1295	1186	260	1286	165	95	.94	227	144	301	9	70
1918	1014	5338	30 995	1305	1190	256	1292	169	99	.91	229	140	303	13	70
1921	1015	5250	30 894	1312	1194	256	1298	169	97	.95	234	145	310	14	72

[a]To convert lb/hr to kg/hr, multiply by 0.4536.
[b]To convert ^{o}F to ^{o}K, add 460 and multiply by 5/9.
[c]To convert psia to N/m^2, multiply by 6895.
[d]To convert Btu/lb to J/kg, multiply by 2324.

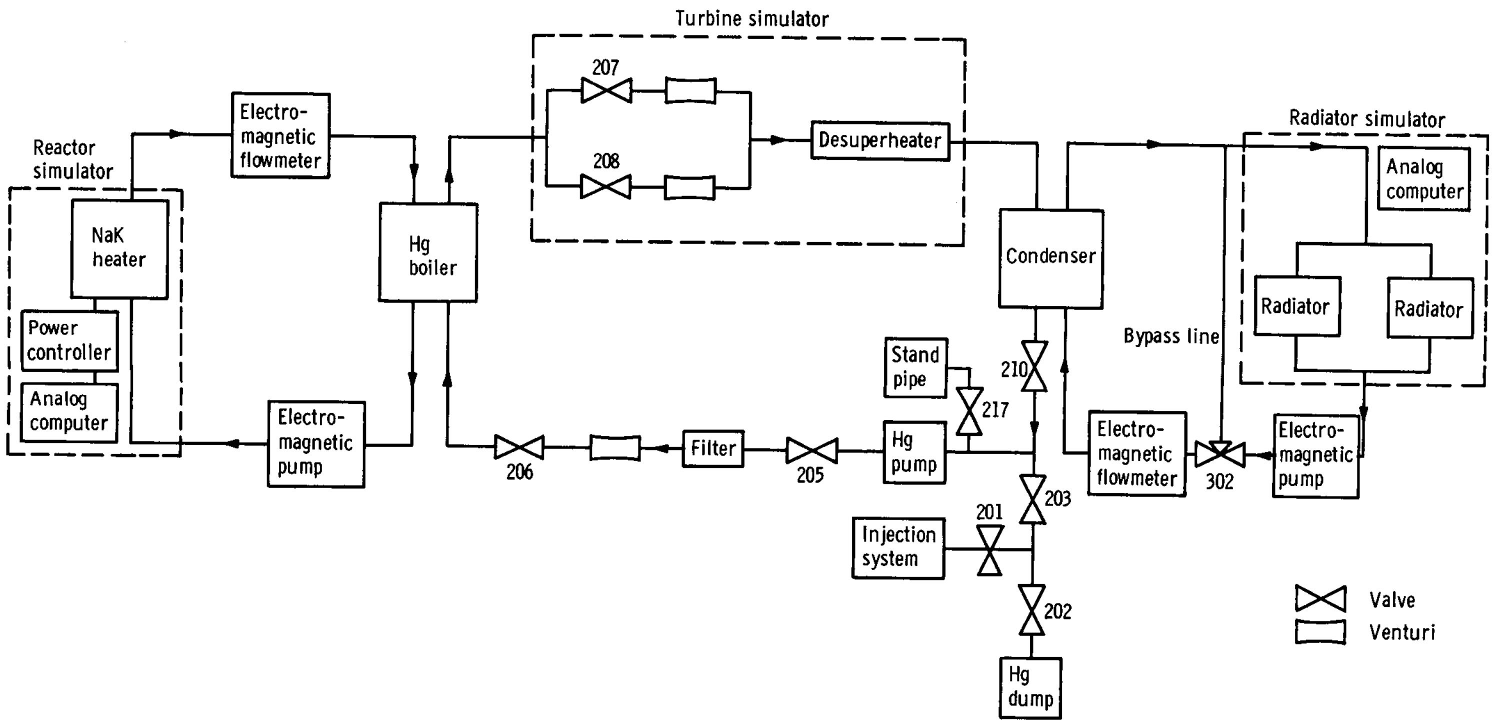


Figure 1. - Basic SNAP-8 simulated system.

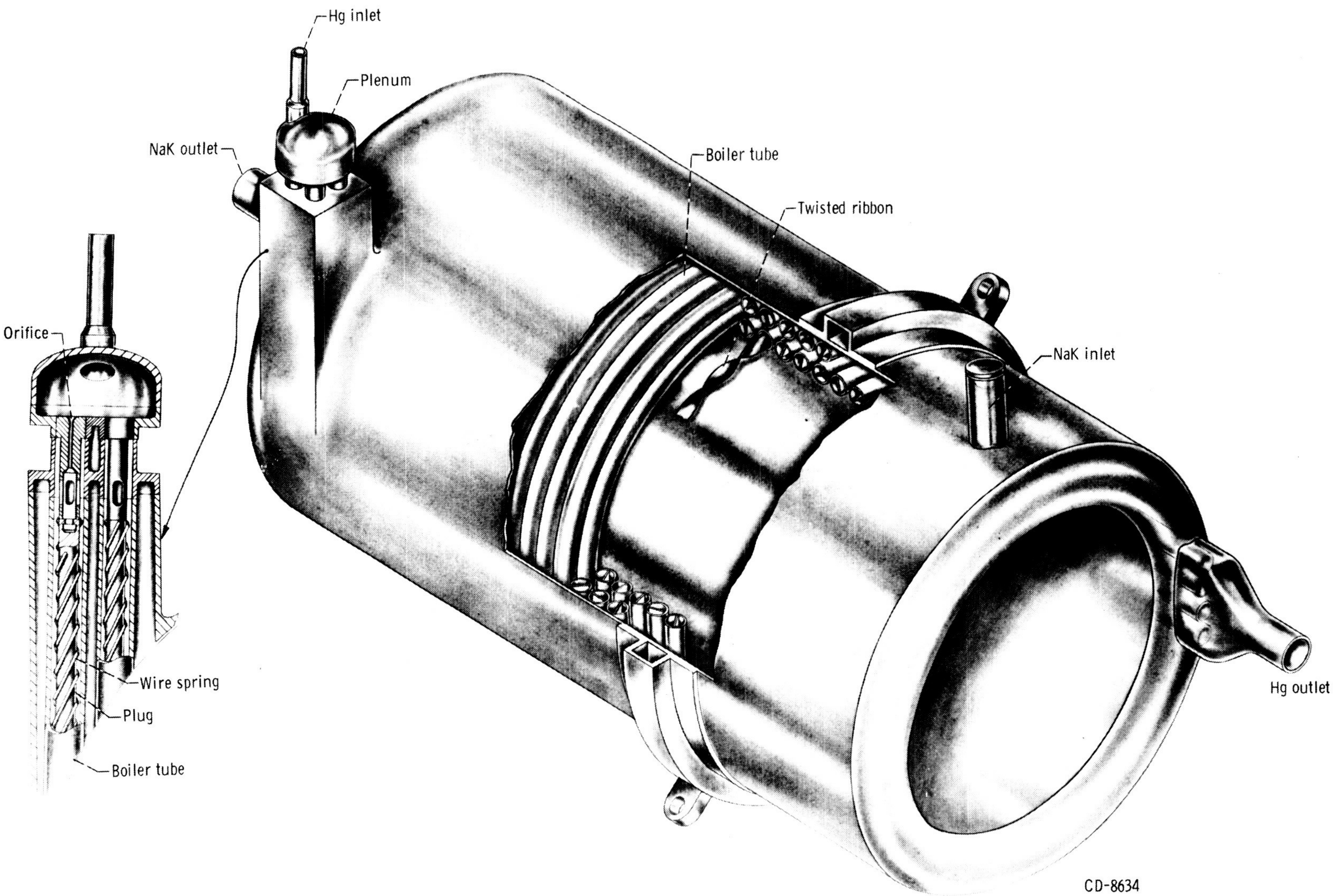


Figure 2. - SNAP-8 tube-in-shell boiler.

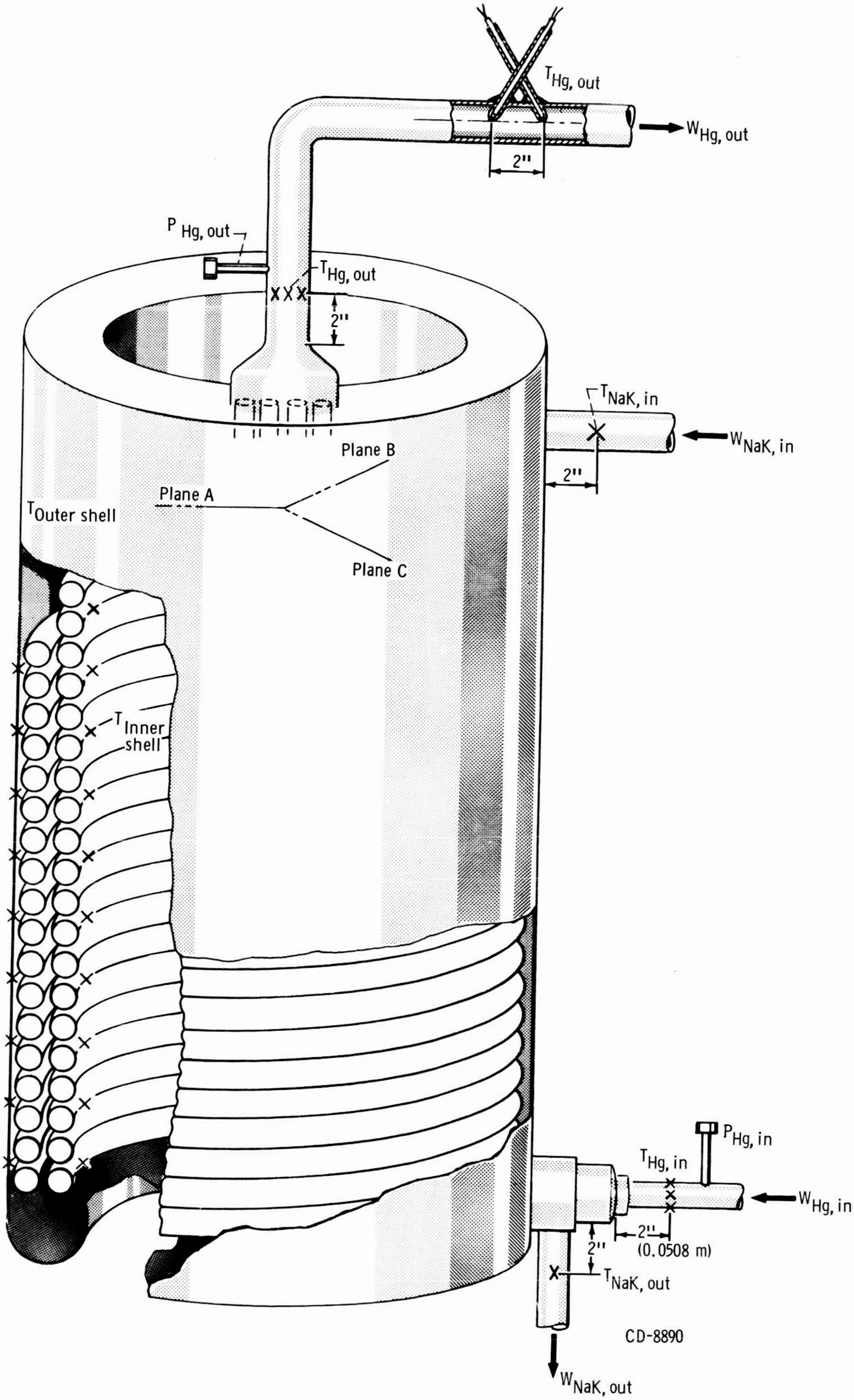


Figure 3. - Location of instrumentation on tube-in-shell boiler.

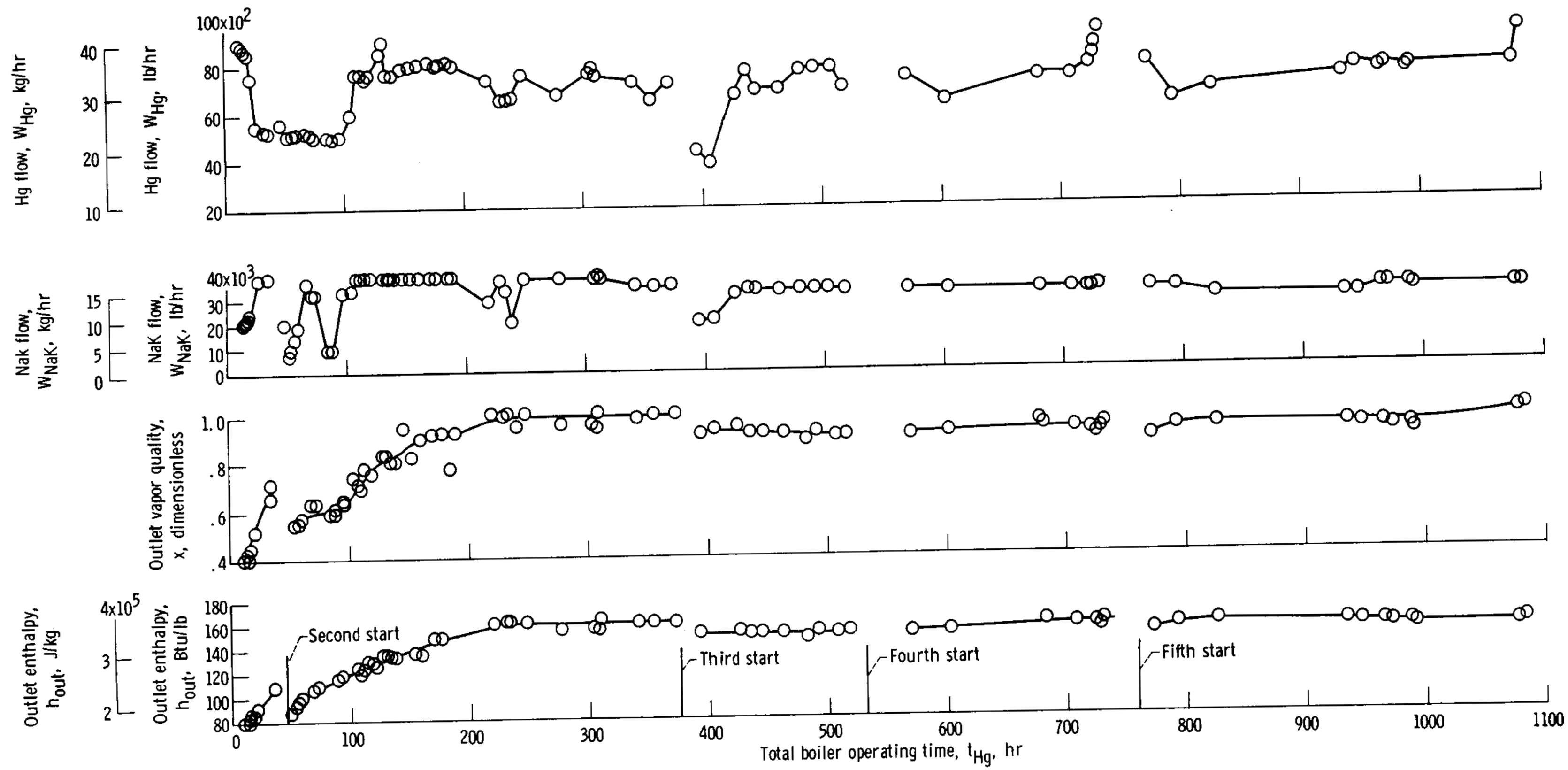


Figure 4. - Variation in boiler parameters during boiler history.

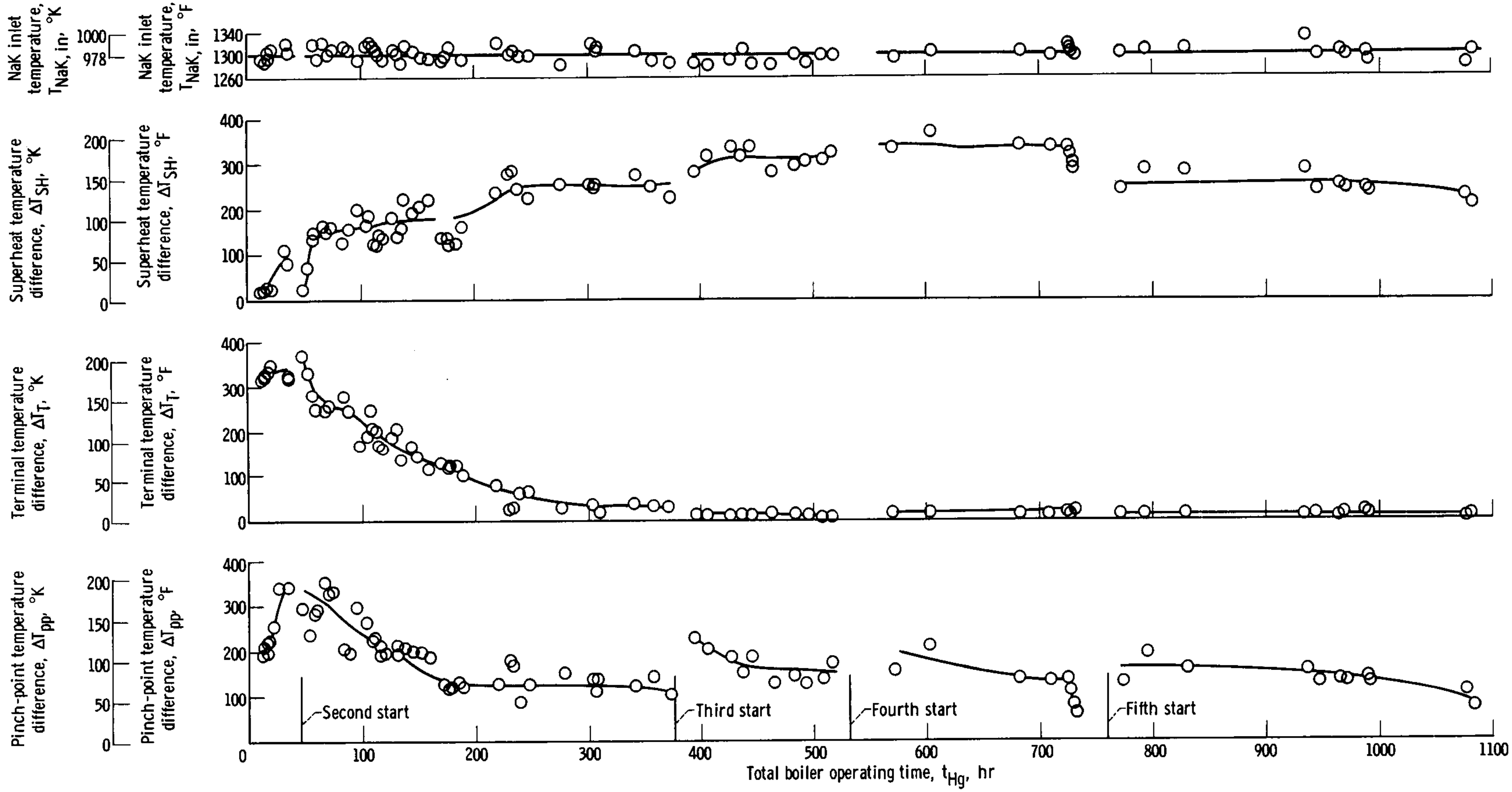


Figure 5. - Variation in boiler parameters during boiler history.

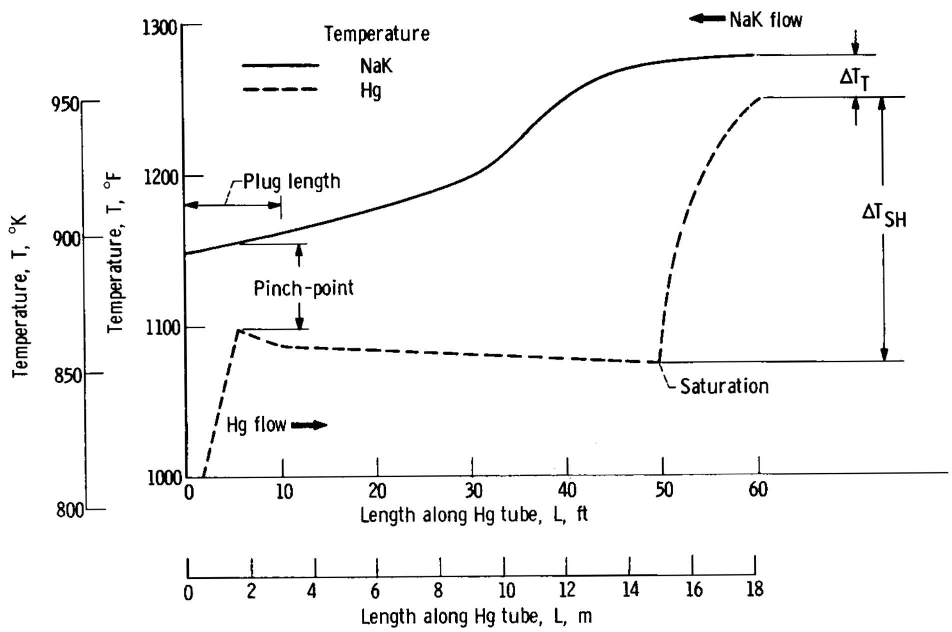


Figure 6. - Various boiler parameters.

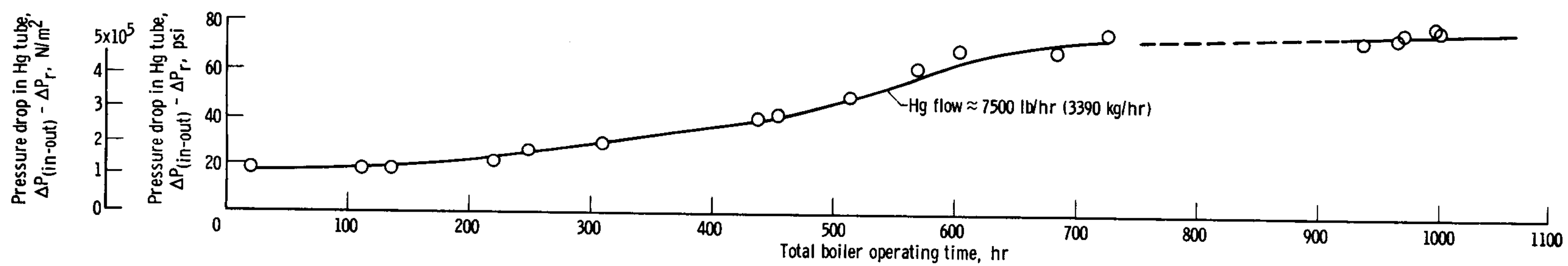
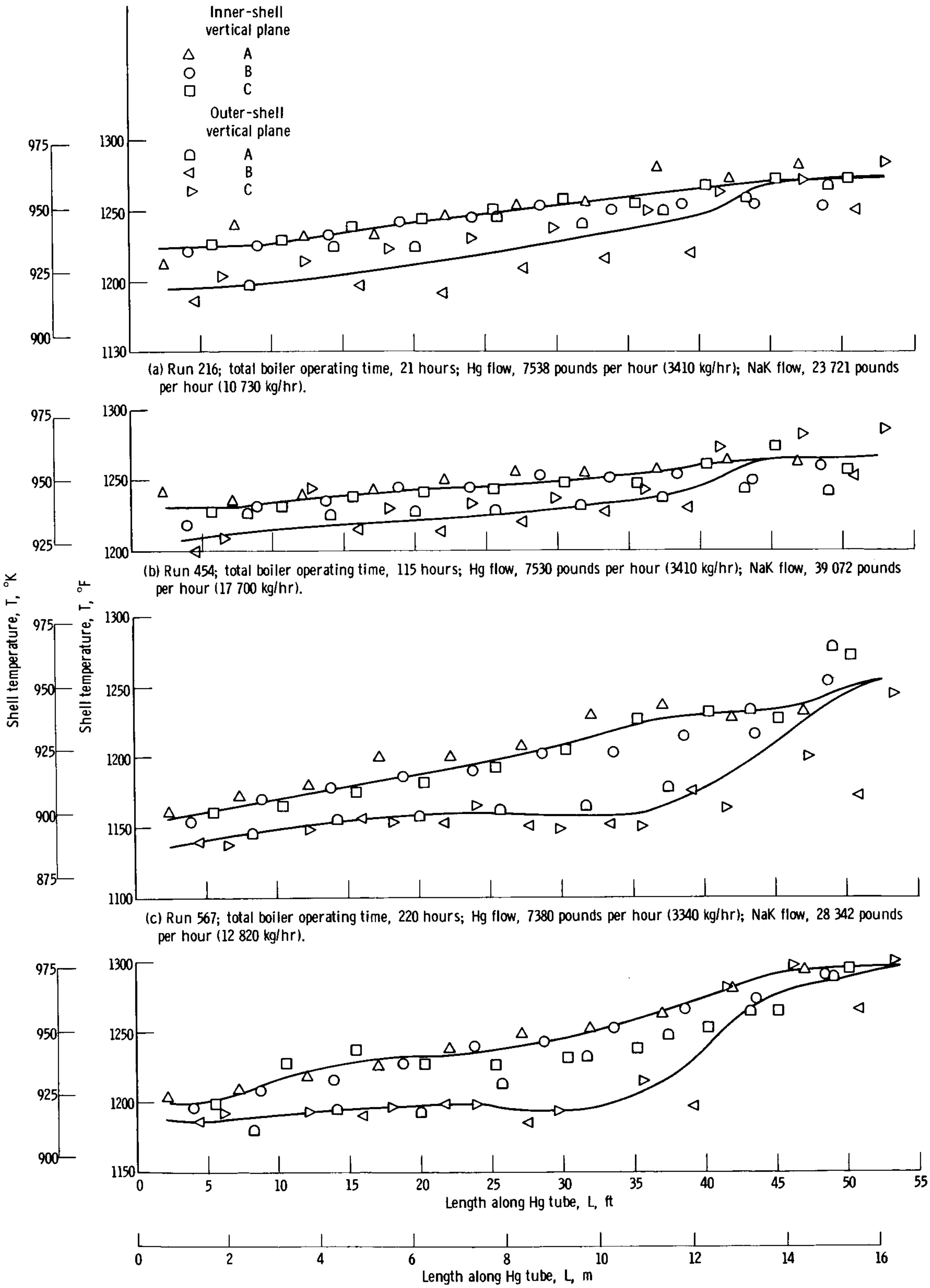


Figure 7. - Variation in boiler pressure drop during boiler history.



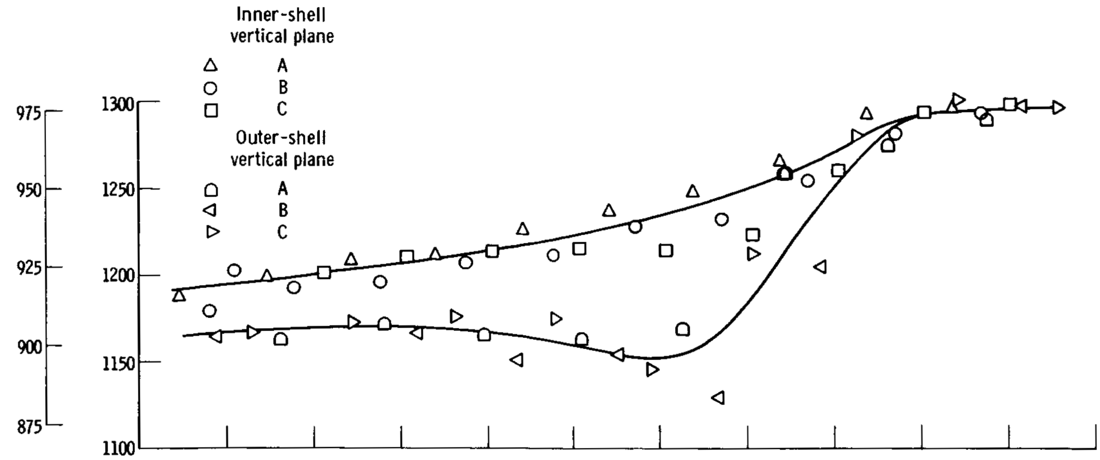
(a) Run 216; total boiler operating time, 21 hours; Hg flow, 7538 pounds per hour (3410 kg/hr); NaK flow, 23 721 pounds per hour (10 730 kg/hr).

(b) Run 454; total boiler operating time, 115 hours; Hg flow, 7530 pounds per hour (3410 kg/hr); NaK flow, 39 072 pounds per hour (17 700 kg/hr).

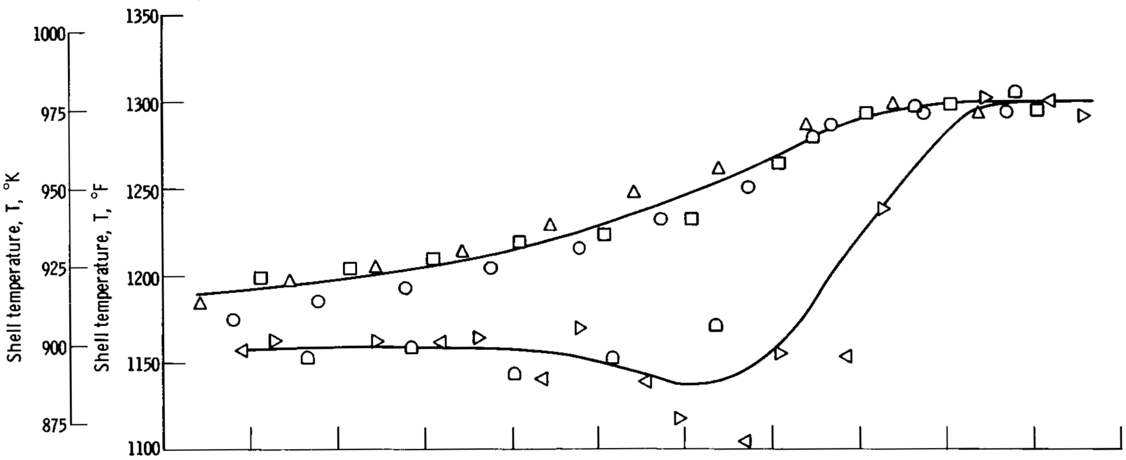
(c) Run 567; total boiler operating time, 220 hours; Hg flow, 7380 pounds per hour (3340 kg/hr); NaK flow, 28 342 pounds per hour (12 820 kg/hr).

(d) Run 743; total boiler operating time, 310 hours; Hg flow, 7445 pounds per hour (3370 kg/hr); NaK flow, 38 919 pounds per hour (17 610 kg/hr).

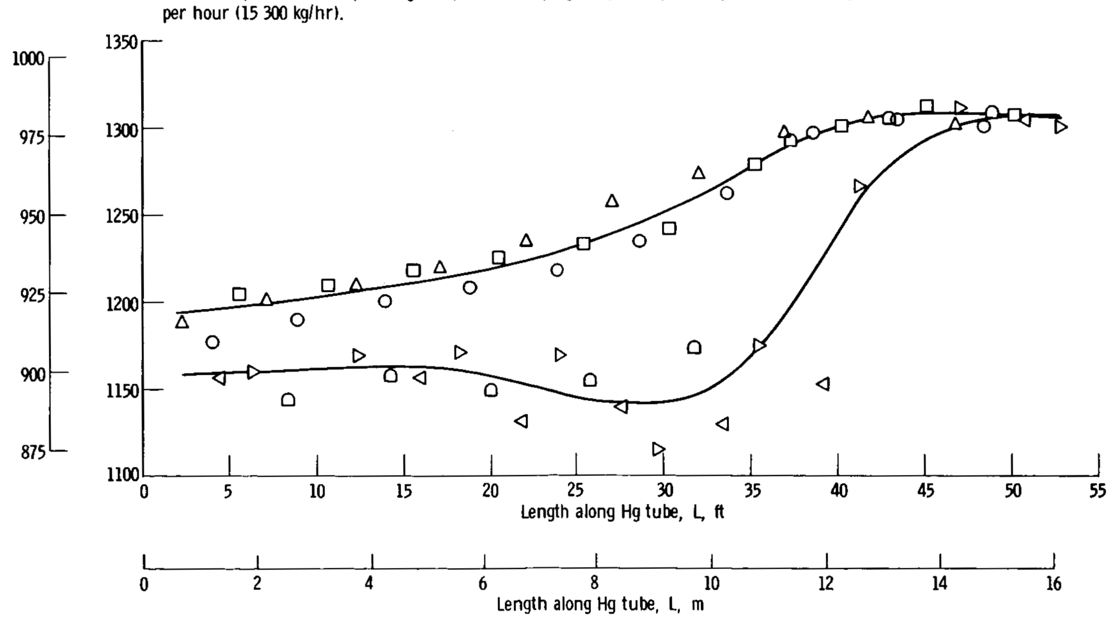
Figure 8. - Typical NaK temperature profiles during boiler history.



(e) Run 891; total boiler operating time, 437 hours; Hg flow, 7272 pounds per hour (3290 kg/hr); NaK flow, 33 706 pounds per hour (15 260 kg/hr).

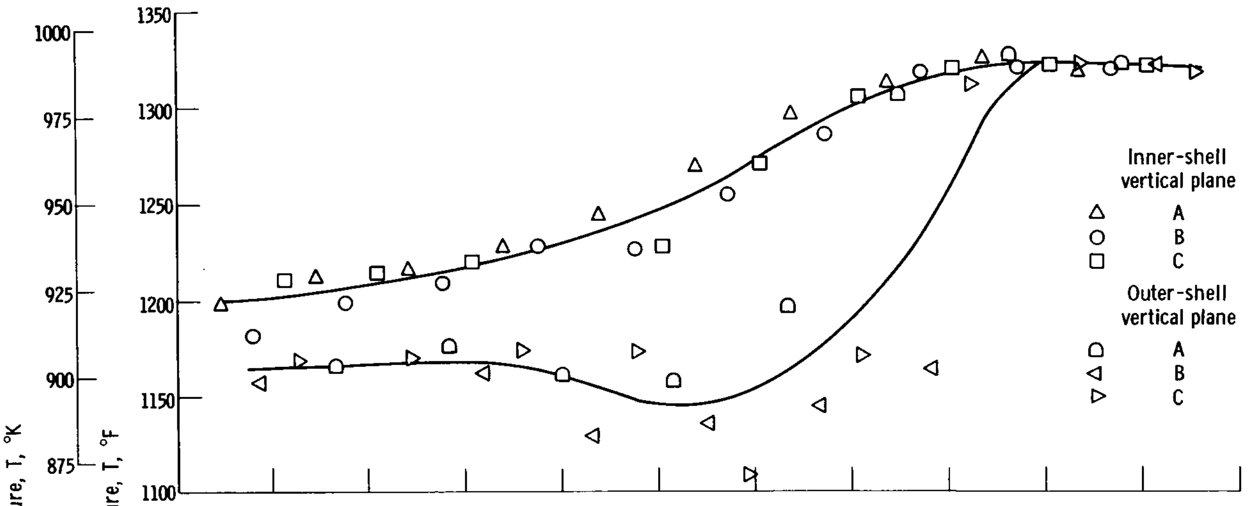


(f) Run 1252; total boiler operating time, 683 hours; Hg flow, 7455 pounds per hour (3380 kg/hr); NaK flow, 33 800 pounds per hour (15 300 kg/hr).

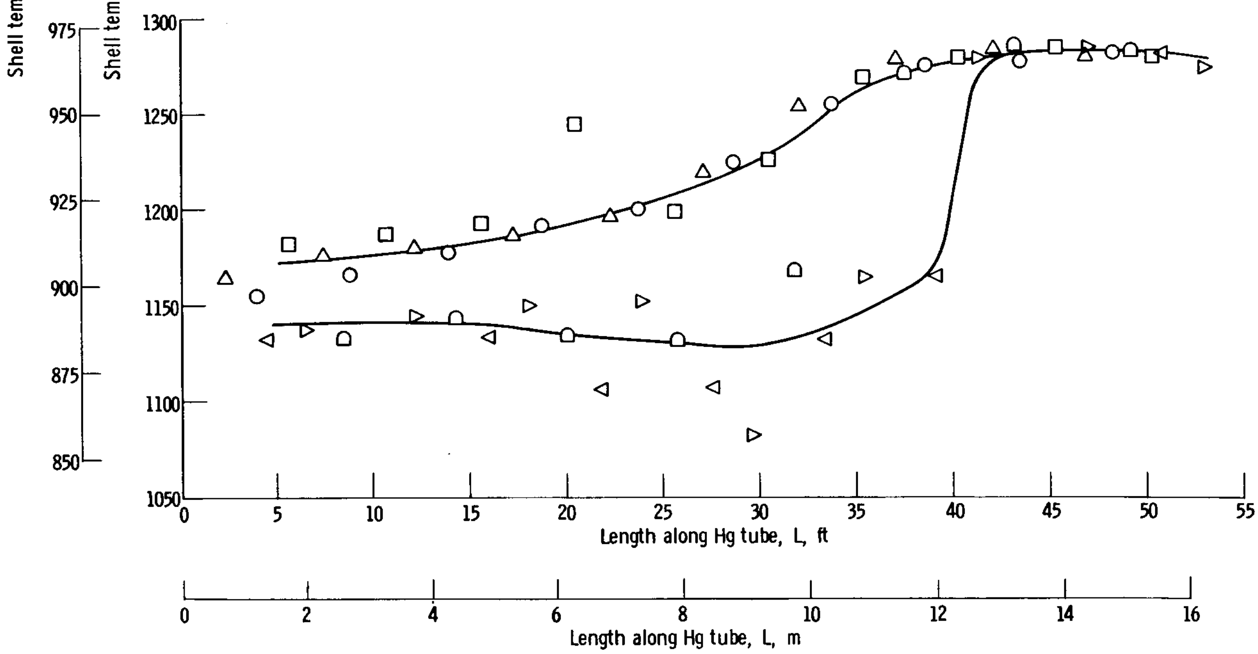


(g) Run 1307; total boiler operating time, 725 hours; Hg flow, 7735 pounds per hour (3500 kg/hr); NaK flow, 33 600 pounds per hour (15 210 kg/hr).

Figure 8. - Continued.



(h) Run 1690; total boiler operating time, 934 hours; Hg flow, 7355 pounds per hour (3300 kg/hr); NaK flow, 29 139 pounds per hour (13 200 kg/hr).



(i) Run 1809; total boiler operating time, 991 hours; Hg flow, 7634 pounds per hour (3455 kg/hr); NaK flow, 32 603 pounds per hour (14 770 kg/hr).

Figure 8. - Concluded.

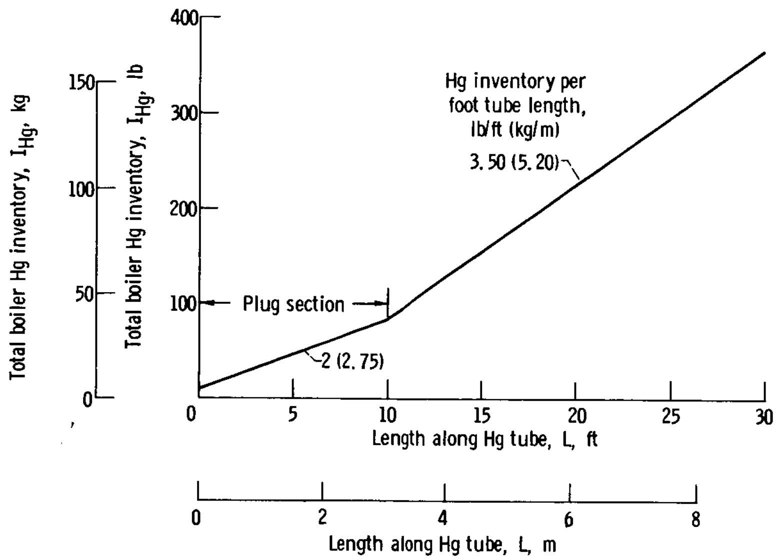


Figure 9. - Plot of calculated total boiler inventory against length along Hg tube.

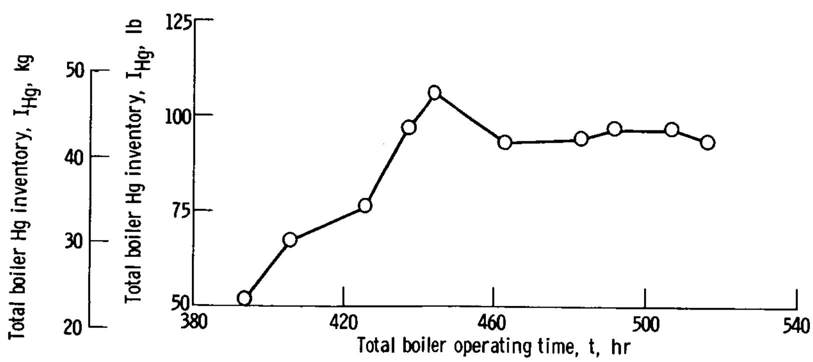


Figure 10. - Total boiler inventory and total boiler operating time for runs 861 to 1307.

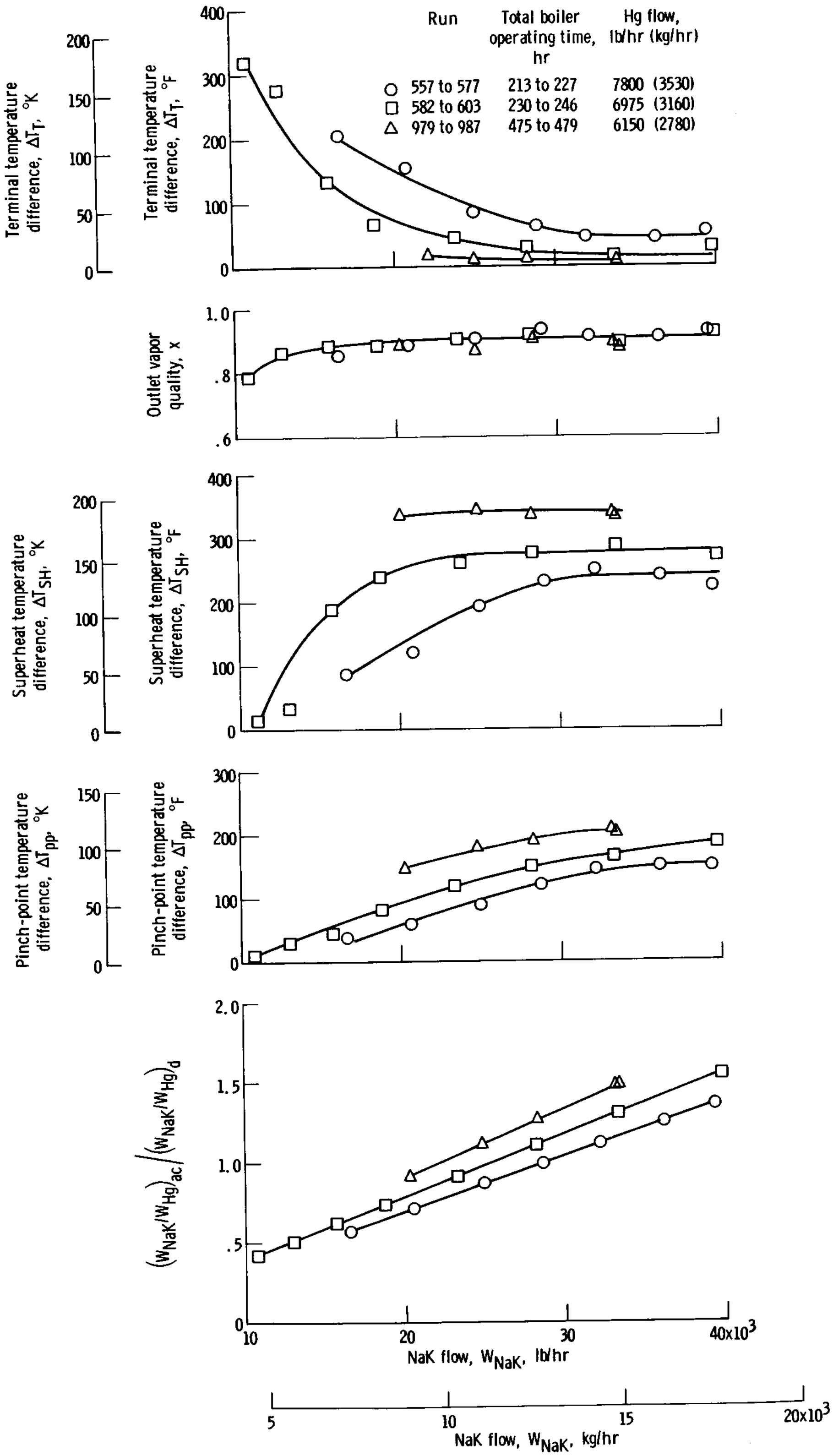


Figure 11. - Effect of NaK flow on boiler performance for NaK-inlet temperature of 1300° F (980° K).

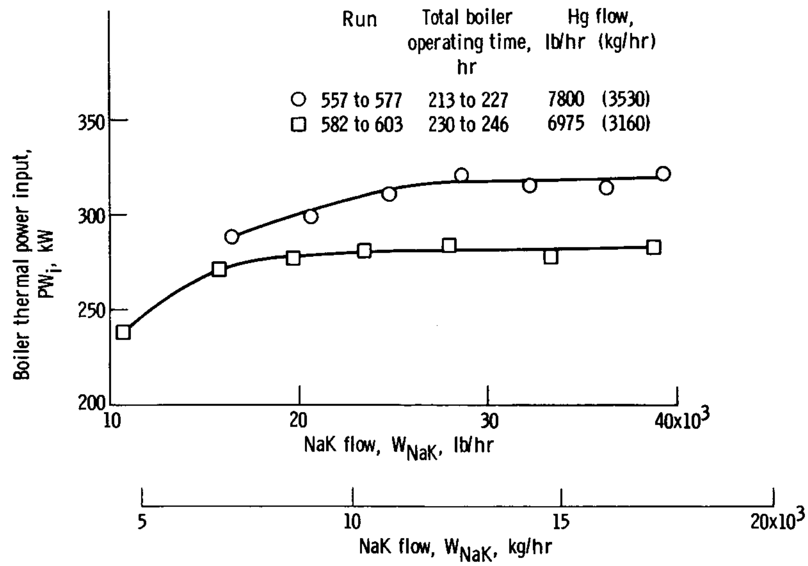


Figure 12. - Boiler thermal power input required to keep NaK-inlet temperature at 1300° F (980° K) for variation in NaK flow.

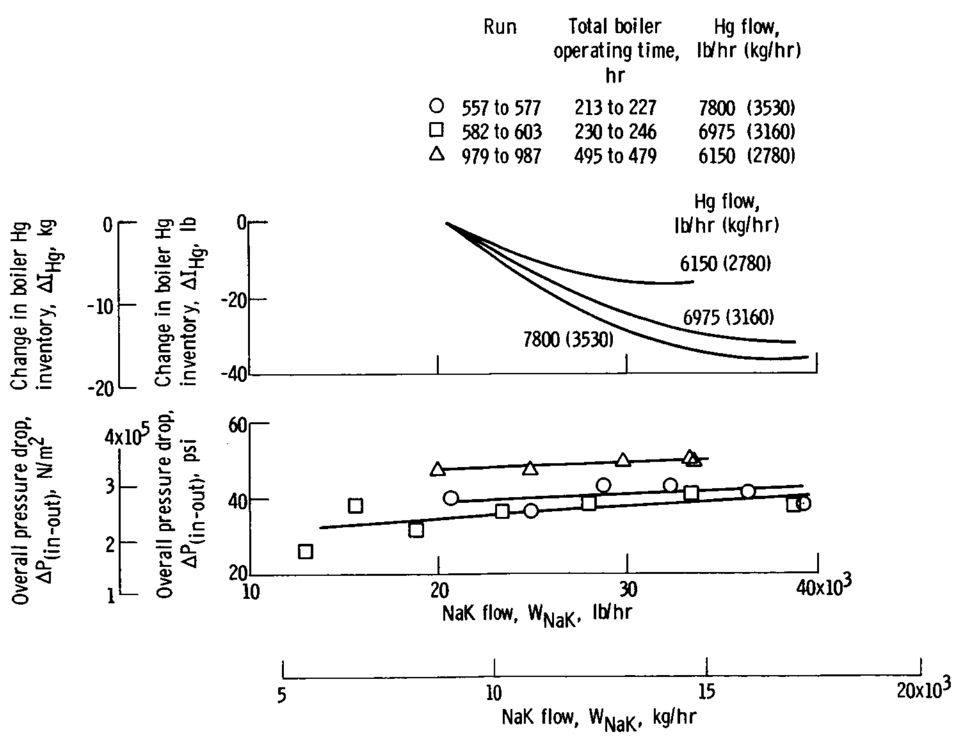


Figure 13. - Effect of NaK flow on pressure drop and inventory change for NaK-inlet temperature of 1300° F (980° K).

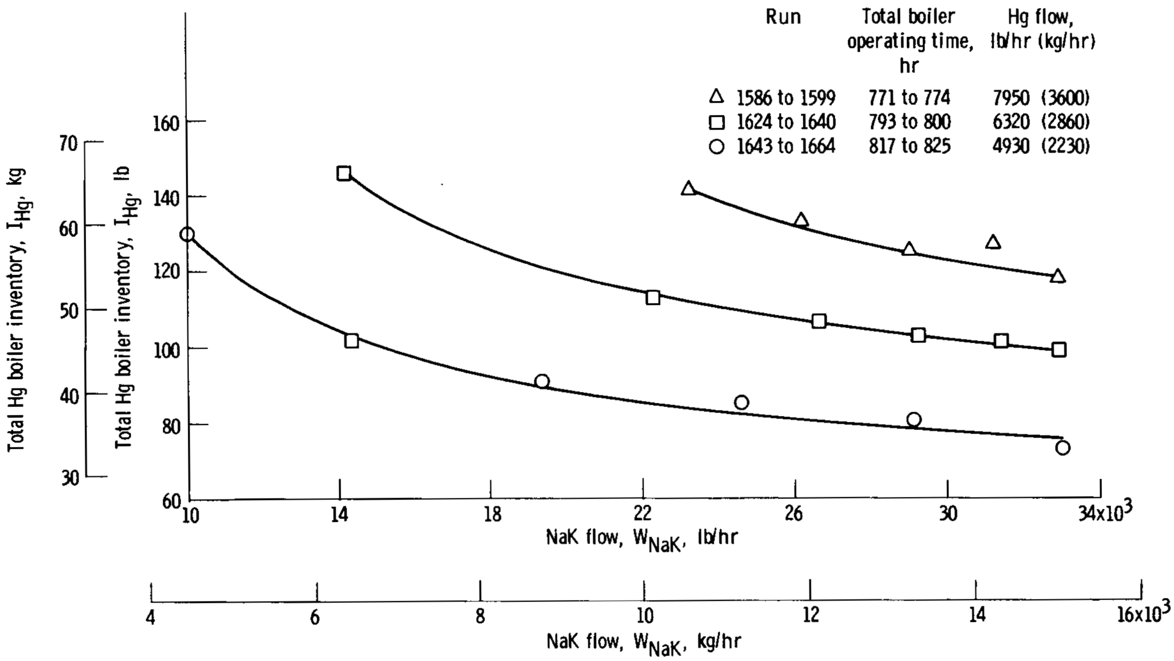


Figure 14. - Effect of NaK flow on total boiler Hg inventory for NaK-inlet temperature of 1300° F (980° K).

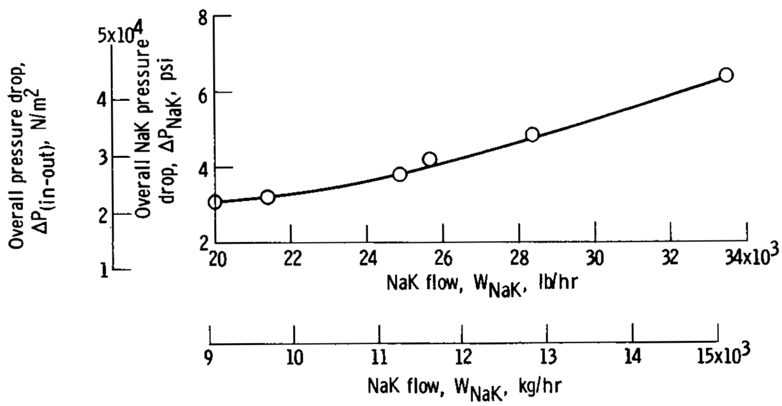


Figure 15. - Plot of NaK side pressure drop through boiler against NaK flow.

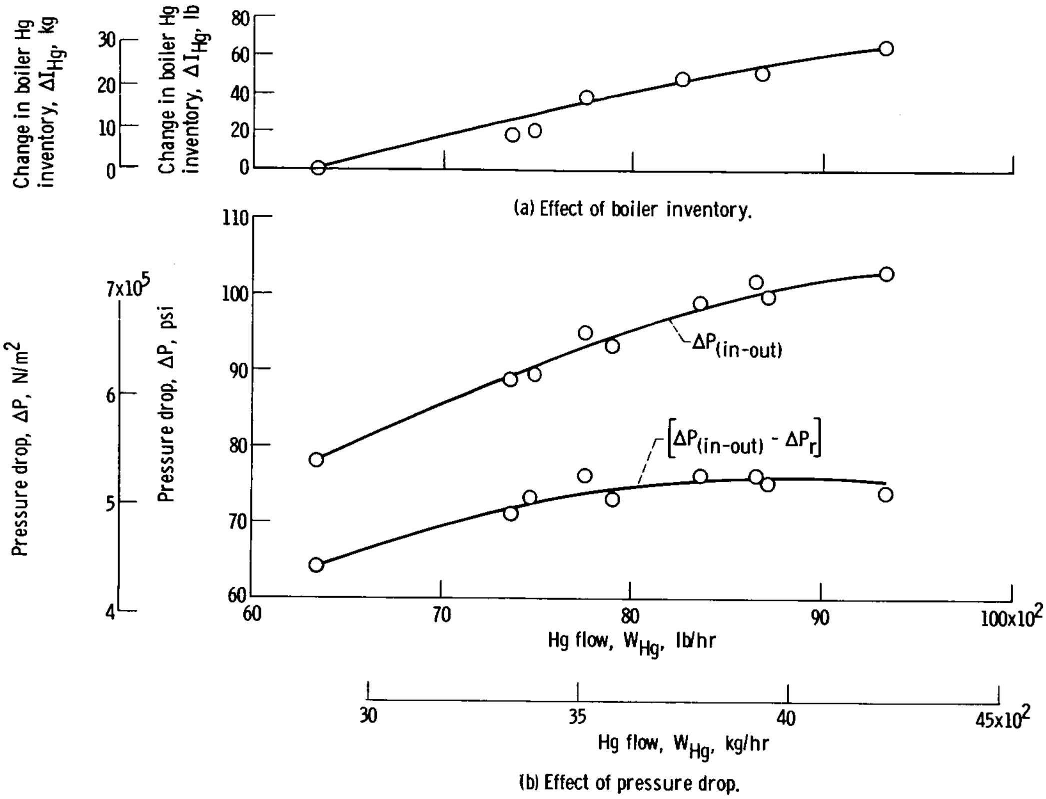


Figure 16. - Effect of Hg flow on pressure drop and change in boiler inventory for NaK-inlet temperature of 1300° F (980° K). Runs, 1252 to 1311; total boiler operating time, 683 to 731 hours; NaK flow, ≈34 000 pounds per hour (15 400 kg/hr).

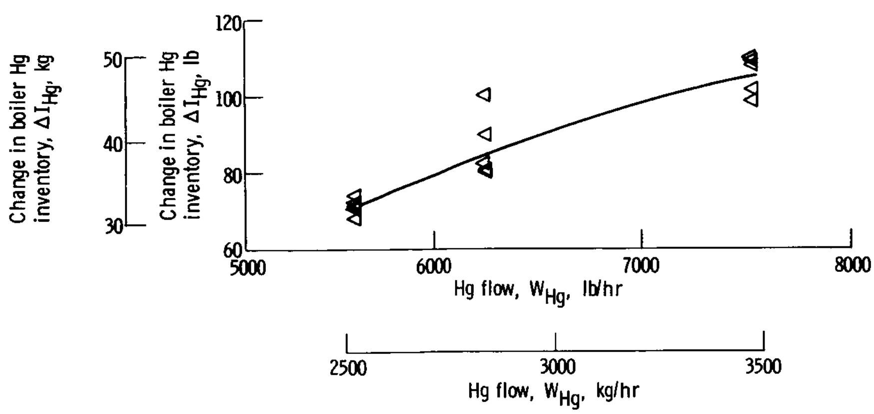


Figure 17. - Effect of Hg flow on total Hg boiler inventory for NaK-inlet temperature of 1300° F (980° K). NaK flow, ≈33 000 pounds per hour (14 950 kg/hr); total boiler operating time, 987 to 1017 hours.

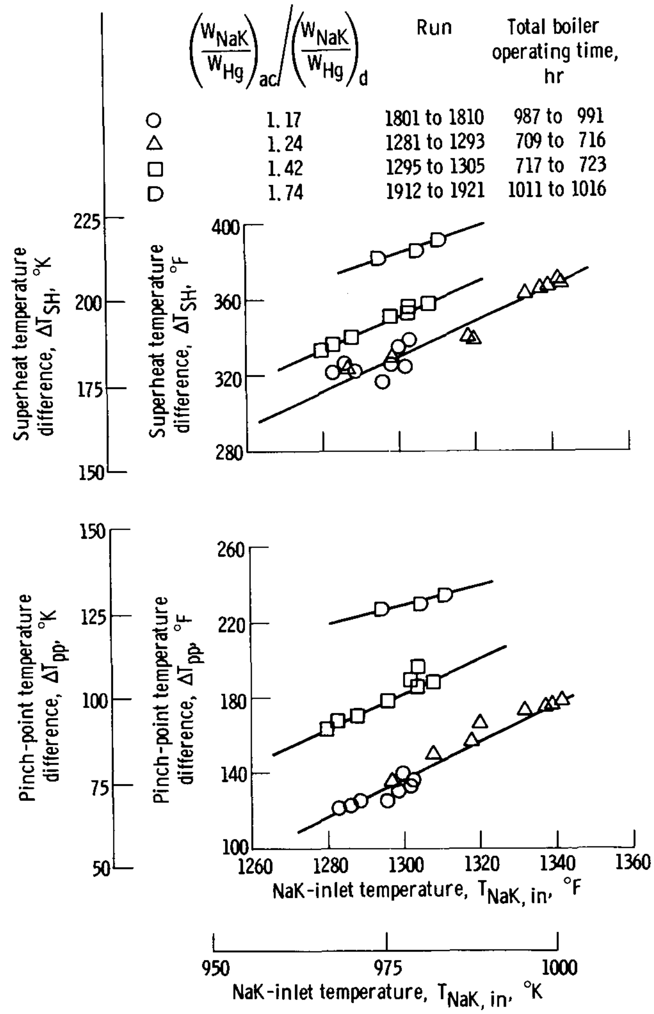


Figure 18. - Effect of NaK-inlet temperature on boiler performance.

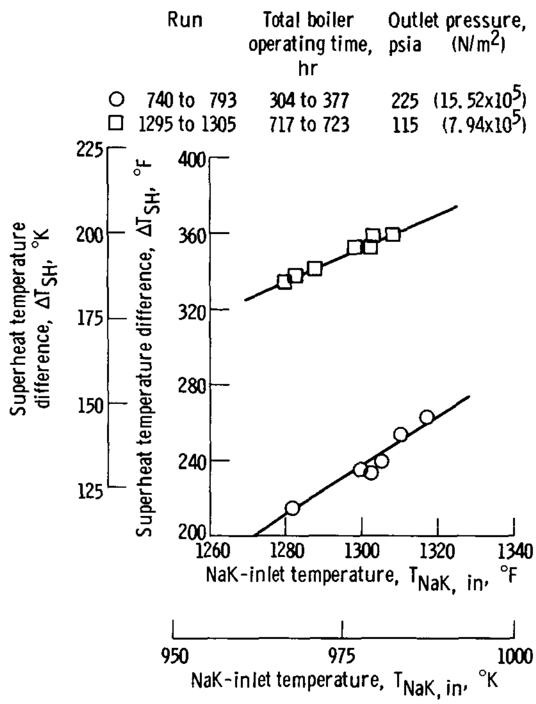


Figure 19. - Effect of boiler-outlet pressure restriction on boiler performance. $(w_{NaK}/w_{Hg})_{ac}/(w_{NaK}/w_{Hg})_d \approx 1.4$.

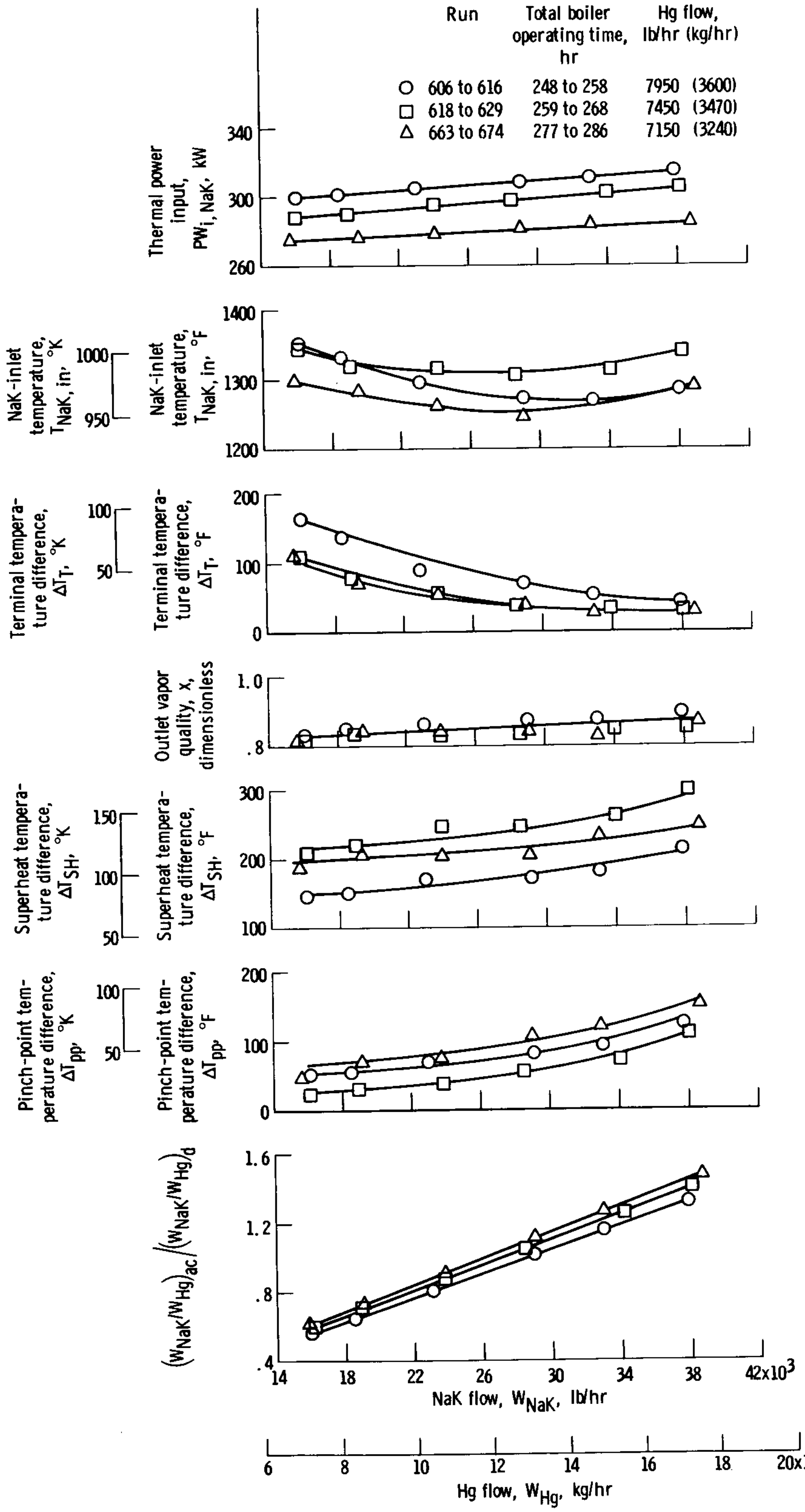


Figure 20. - Effect of NaK-inlet temperature and NaK flow on boiler performance.

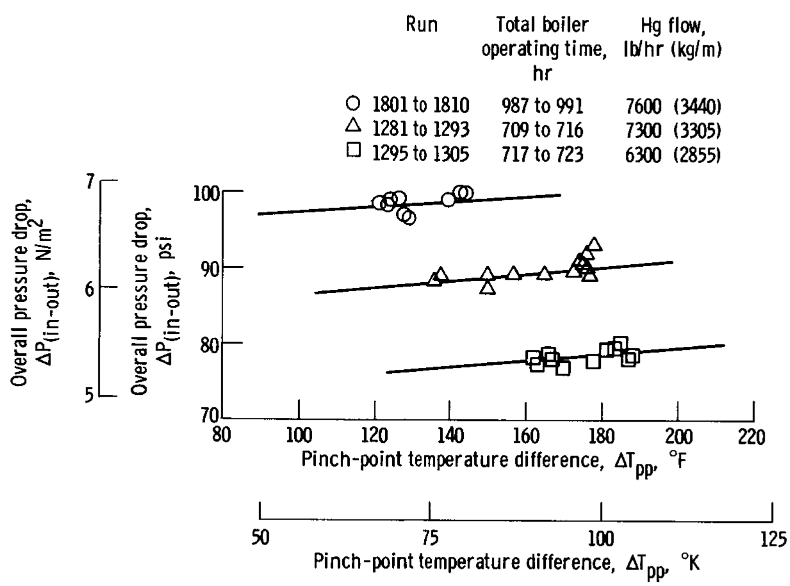


Figure 21. - Variation of overall pressure drop with pinch-point temperature for constant flow conditions. NaK flow, 34 000 pounds per hour (15 400 kg/hr).