NASA TECHNICAL NOTE

NASA TN D-4926

NASA TN D-4926

DESIGN-POINT PERFORMANCE OF A DOUBLE-CONTAINMENT TANTALUM-AND-STAINLESS-STEEL MERCURY BOILER FOR SNAP-8

by James A. Albers, Ronald H. Soeder, and Pierre A. Thollot

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • DECEMBER 1968

NASA TN D-4926

DESIGN-POINT PERFORMANCE OF A DOUBLE-CONTAINMENT TANTALUM-AND-STAINLESS-STEEL MERCURY BOILER FOR SNAP-8

By James A. Albers, Ronald H. Soeder, and Pierre A. Thollot

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – CFSTI price $3.00

ABSTRACT

Experimental data were obtained on the performance of a SNAP-8 tantalum and stainless-steel double-containment boiler. The boiler was a counterflow heat exchanger consisting of seven tubes coiled with a $2\frac{1}{2}$-turn helical shell. The experimental results are presented for a total operating time of 1445 hours. The range of mercury flow rates was from 7500 to 11 800 lb mass/hr (3400 to 5350 kg/hr) and the primary NaK flow was varied from 29 000 to 49 000 lb mass/hr (13 000 to 22 200 kg/hr). The NaK temperature into the boiler was varied from 1272 to 1318° F (962 to 988 K).

DESIGN-POINT PERFORMANCE OF A DOUBLE-CONTAINMENT TANTALUM-AND-STAINLESS-STEEL MERCURY BOILER FOR SNAP-8

by James A. Albers, Ronald H. Soeder, and Pierre A. Thollot
Lewis Research Center

SUMMARY

As part of the SNAP-8 development program, experimental data were obtained on the performance of a tantalum and stainless-steel double-containment boiler tested in the SNAP-8 facility at the Lewis Research Center. The boiler was a helically coiled counterflow heat exchanger consisting of seven tubes approximately 37 feet (11 m) in length in which hot NaK boils mercury. The experimental results presented were obtained during a total operating time of 1445 hours. The range of mercury flow rates was from 7500 to 11 800 pounds mass per hour (3400 to 5350 kg/hr) and primary NaK flow was varied from 29 000 to 49 000 pounds mass per hour (13 100 to 22 200 kg/hr). The NaK temperature into the boiler was varied from 1272 to 1318° F (962 to 988 K). The resultant superheat and terminal temperature difference generally remained constant throughout the boiler history with average values of 265° F (147 K) and 12° F (7 K), respectively. The outlet quality gradually increased from 87 to 100 percent during the first 800 hours of operation and remained essentially constant at 100 percent thereafter.

The NaK shell temperature profiles and boiler inventory history indicated good internal heat transfer performance until the fourth startup. After the fourth startup (at 364 hr of operating time), the NaK shell temperature profiles indicated poor heat transfer in the plug region at the inlet of the boiler, and the boiler inventory history indicated that some or all the tubes in the plug section were flooded. There was a gradual degradation of the boiler internal performance in the plug section from the fourth startup until the completion of testing which was believed to be due to a buildup of mass transfer products on the primary NaK side of the boiler tubes. After the fourth startup, deviation in the inner and outer NaK shell profiles in the preheat and boiling regions increased throughout the duration of testing. This deviation is thought to be due to unequal NaK and mercury flow distributions. Post run disassembly and X-rays of the tube bundle showed that the mercury tube bundle had shifted to near the bottom of the NaK shell. Even with some or all the tubes flooded in the plug region, the overall average outlet performance was within 5 percent of design value. The average superheat length of 22 feet (6.7 m) corresponds to an average quality of 97 percent at approximately 265° F (403 K) superheat. For the above conditions, the NaK temperature profiles indicated little if any heat transfer over the last 22 feet of the boiler indicating considerable margin in the design length of the boiler.

INTRODUCTION

The design of a nuclear Rankine system boiler is dictated by thermal exchange and pressure drop requirements, limitations imposed by the reactor temperature excursions, and the need for long life, stable operation, and geometry suitable for incorporation into a flight configuration. The allowable pressure drop is determined from a tradeoff of the heat-transfer rates required to obtain dry superheated vapor at the boiler outlet and pumping power requirements. Considerations must also be given to limitations on pressure drop imposed by the feed pump capability and boiler stability requirements. The reactor control allows variations in the heating-fluid boiler-inlet temperature which determines the temperature level of the boiling fluid. Considerations in the design must be given to the safety requirements for a man-rated system such as separating the radioactive heating fluid from the boiling fluid by use of two metal tubes as a double containment for the boiling fluid. The design must minimize the amount of liquid carryover to the turbine, which could result in degradation of turbine efficiency and power output. The subject of this report is one of three identical tantalum and stainless-steel boilers which were built as part of the SNAP-8 development effort. This boiler is a counterflow tube-in-tube heat exchanger which uses mercury as the working fluid and the eutectic mixture of sodium and potassium (NaK-78) as the heating fluid. The mercury-containment material was tantalum which was chosen because of its resistance to mercury corrosion at elevated temperature. This unit was tested in the SNAP-8 facility at Lewis Research Center.

Past experimental results with mercury boilers in references 1, 2, and 3 have indicated that an initial operating time period was required before the boilers reached their maximum heat-transfer performance or conditioned state. It is believed that mercury boilers become conditioned when the mercury wets the tube surface which increases the effective heat-transfer surface area in contact with the heated fluid. The degree of wetting depends on the choice of containment material and on the cleanliness of the tube surface.

Several supporting programs were conducted in conjunction with the tantalum and stainless-steel boiler development for SNAP-8. The results of references 4, 5, and 6 indicate a high degree of wettability of tantalum by mercury at elevated temperatures. However, these references also point out that the oxidation of a tantalum boiler surface is a possible mechanism that will decondition a boiler. The design analysis and theoretical studies for the subject boiler are discussed in references 7, 8, and 9. Some single-tube refractory boiler test results are contained in reference 10.

The purpose of this investigation is to experimentally determine the conditioning history and steady-state performance of this tantalum and stainless-steel boiler near its design point. An analysis of boiler performance is presented for an accumulated boiler operating time of 1445 hours. The three primary independent variables in the boiler performance were mercury flow rate, NaK flow rate, and NaK-inlet temperature. Since the test was primarily an endurance test, minimum changes were made in the primary variables. The boiler history is presented for a NaK inlet temperature of $1300^{\circ} \pm 20^{\circ}$ F (975±11 K). Design conditions for the SNAP-8 tantalum stainless-steel boiler are given in table I.

APPARATUS

Experimental System

The test facility incorporated flight-type components, with the exception of the electric heater and the radiator. A schematic diagram of the three-loop SNAP-8 test facility is shown in figure 1. The primary loop contained a pump, a parasitic load resistor, an electric heater, an electromagnetic flow meter, the tube-in-tube boiler and an auxiliary start heat exchanger. The parasitic load resistor was used by the turbine-alternator speed control to dissipate varying amounts of excess electrical energy in the form of heat. An analog computer was used to control the NaK electric heater input power. The auxiliary start heat exchanger was used to heat the third loop NaK during startup. The primary loop NaK was circulated by the pump in order to transfer heat from the electric heater to the NaK side of the mercury boiler. The primary loop flow was regulated by changing the position of the valve located at the pump outlet. The NaK pump was limited to a maximum flow of approximately 51 000 pounds mass/hour (23 000 kg/hr).

The power loop (mercury loop) used AISI type 316 stainless steel from the boiler outlet to the turbine inlet and AISI type 304 stainless steel for the remainder of the loop piping. The components in the loop were the tube-in-tube boiler (fig. 2), the turbine-alternator assembly, condenser, pump, and three venturi flow meters. Liquid mercury flowed from the pump through a gas operated valve, a filter, a flow control valve, and a hydraulic actuated valve. It then flowed through a venturi meter into the boiler. The mercury vapor at the boiler outlet flowed through a venturi meter into the turbine-alternator assembly and then into a condenser where it was condensed, subcooled, and returned to the mercury pump. Another venturi was located between the condenser outlet and pump.

The heat rejection loop consisted of two electromagnetic flow meters, a condenser, a venturi flow meter, two finned air-cooled multi-tube NaK heat exchangers and a pump. The variation of flow through the third loop was achieved by changing the position of the valve at the pump outlet.

Expansion tanks were employed in both NaK loops to account for a change in volume of the working fluid due to temperature variations and to provide a positive pressure at the inlet of each NaK pump. The mercury injection system and the common NaK fill system were valved off during system operation. A common NaK oxide control system consisted of a NaK-to-NaK economizer and a nitrogen to NaK cooler and cold trap. The purpose of this system was to precipitate out oxides from the NaK loops since oxide buildup causes line plugging. Auxiliary vacuum, argon and nitrogen systems, necessary for proper overall system operation were also used in conjunction with the main loops.

Double-Containment Boiler

The double-containment boiler was a counterflow heat exchanger as shown in figures 3(a) through (c). A single inlet tube lead into a plenum where the liquid-mercury flow was distributed into orifices at the entrance to each of seven boiler tubes. These tantalum tubes were 0.75-inch (1.9-cm) outside diameter, 0.040-inch (1-mm) wall thickness and an approximate length of 37.2 feet (11.4 m). Each of these tubes was placed into a 316 stainless-steel tube with an outside diameter of 1 inch (2.5 cm), 0.035 inch (9×10^{-2} mm) wall thickness and an approximate length of 36.9 feet (11.3 m). These seven 1-inch (2.5-cm)-diameter tubes were swaged into an oval shape prior to insertion of the 0.75-inch (1.9-cm)-diameter tubes. The oval shape of the containment tube was to allow for radial movement of the inner tantalum tube which compensates for the difference in thermal expansion between the tantalum and the 316 stainless steel. The void between the outside diameter of the 0.75-inch (1.9-cm)-diameter tube and the inner surface of the oval tube was filled with static NaK, which served as a heat-transfer medium, prior to the startup of the system. The seven double-containment tubes were then placed within a 316 stainless-steel tube with a 5-inch (12.7-cm) outside diameter, 0.095-inch (2.4-cm) wall thickness, and approximately 39.1-foot (11.9-m) length. The completed boiler assembly consisted of straight inlet and outlet sections 69.7 inches (177 cm) and 21.5 inches (55 cm) long, respectively, and a center section consisting of a $2\frac{1}{2}$-turn helix with a pitch of 10.5 inches (27 cm) and a pitch diameter of 48 inches (122 cm). The double-containment-tube bundle was supported within the outer shell by support brackets placed at 15-inch (38-cm) increments throughout the first full turn of the helical section of the boiler, beginning at the plug-section exit. The remaining support brackets were placed at 31-inch (79-cm) increments. A cross section of the boiler double-containment-tube bundle and outer shell are given in figure 4(a).

A multi-fluted "plug" at the tantalum tube inlet, approximately 55 inches (140 cm) in length, was used to restrict mercury flow and thus to increase liquid velocity. The plug, a 0.662-inch (1.7-cm) diameter grooved tantalum rod (fig. 4(b)) was fixed at the inlet end by a threaded shaft which was part of the orifice assembly (fig. 3(b)). At the downstream end of the plug was a swirl inducer which extended to within 1 inch (2.5 cm) of the tantalum tube outlet. The swirl inducer consisted of 0.062-inch (0.16-cm) diameter tantalum wire with a pitch diameter of 0.608-inch (1.5-cm) and a pitch of 2 inches (5 cm). This wire was intended to centrifuge liquid from the vapor to the inner wall of the tantalum tube thus promoting increased heat-transfer rates. A secondary effect of the plug swirl inducer combination was to diminish the effect of gravity forces on mercury flow. The manifold for the seven tube bundle lead into a plenum which formed a single mercury outlet.

INSTRUMENTATION

Temperature

Temperature-measuring instrumentation for the boiler consisted of surface thermocouples on the boiler shell, immersion thermocouples in the mercury outlet tube, and surface thermocouples on the inlet and outlet piping for both mercury and NaK. All thermocouples were constructed of Instrument Society of America (ISA) standard calibration K (Chromel-Alumel) wires, except three surface thermocouples on the mercury inlet piping. These were constructed of ISA standard calibration J (Iron-Constantan) wires which were located three inches (7.5 cm) upstream of the boiler inlet. Three thermocouples were welded on the mercury outlet piping, 120° apart (section B-B on fig. 5). Four immersion-type thermocouples were located in a 6.25-inch (16-cm) section welded to the mercury boiler outlet. Immersion thermocouples A and B were located at a 45° angle facing into the stream. In addition, immersion thermocouple A was rotated through an angle of 45° (clockwise) with respect to the vertical centerline of the outlet piping. Immersion thermocouples C and D were set at 45° angle downstream of the flow direction. View C-C and Section B-B on figure 5, show the detail positioning of immersion thermocouples A, B, C, D, as well as the three surface thermocouples on the mercury outlet piping. Two thermocouples were welded to the NaK inlet and outlet transition sections. The NaK inlet thermocouples were placed approximately 5 inches (13 cm) from the vertical centerline of the boiler shell. The thermocouples at the NaK outlet were placed on a transition section approximately 8.5 inches (22 cm) below the horizontal centerline of the boiler shell.

Both the inner and outer radial surfaces of the boiler shell were instrumented with thermocouples to give an indication of the NaK temperature distribution. The thermocouples on the inner surface of the boiler were placed at an angle of 30° (counterclockwise) with respect to a vertical centerline through the boiler shell. Thermocouples on the outer surface of the boiler were placed at an angle of 150° (clockwise) with respect to a vertical centerline through the boiler shell. A total of 43 thermocouples were placed along the inner surface and 21 thermocouples were placed along the outer surface of the boiler. Along the length of the boiler shell only one or two thermocouples were placed at any cross-section of a given station number. The only exception to this thermocouple spacing occurred at station 11, the boiler plug outlet (section A-A, fig. 5). At this particular location four thermocouples were equally spaced around the circumference of the boiler shell. Table II gives the location of all inner and outer thermocouples placed along the boiler shell. All thermocouples were located with reference to the inlet of the boiler plug insert.

Pressure

Static pressures at mercury boiler inlet and outlet piping were measured by inductive, slack-diaphragm Bourdon tube pressure transducers. The pressure drop across the NaK side of the boiler was obtained from a 5 psi (3.5×10^4 N/m^2) differential pressure transducer. A pressure tap at the inlet to the NaK side of the boiler and at the bottom of the auxiliary start heat exchanger (downstream of the NaK outlet side of the boiler) were connected to separate slack diaphragms. These two diaphragms were connected to opposite sides of a central diaphragm by 10 feet (3.1 m) of 1/8-inch (0.32-cm) NaK filled capillary tubing. A mechanical linkage from the central diaphragm converted diaphragm movement into an electrical signal which was recorded as a pressure differential. Both static and differential pressure transducers of this type display negligible zero shift at loop operating temperatures. Zero-shift is absent because the diaphragm of the unit was the only section of the transducer subjected to high temperatures. The main body of the transducer is separated from the slack diaphragm by approximately 10 feet (3.1 m) of 1/8-inch (0.32-cm) NaK filled capillary tubing. The location of pressure taps on the boiler are shown in figure 5.

Flow

The primary loop NaK flow into the boiler was measured by an electromagnetic flow meter. Mercury liquid and vapor flow were measured by calibrated venturi flow meters upstream and downstream of the boiler (fig. 1). The pressure drop from the venturi flow meter inlet to the throat was obtained from a 30 psi (2.1×10^5 N/m^2) and 27 psi (1.9×10^5 N/m^2) differential pressure transducer for the liquid and vapor flow, respectively.

Data Recording

All pressures and temperatures used for analyses were recorded using a central automatic digital data encoder (CADDE). The maximum signal level of a given data channel was 50 mV and the recording rate was 20 channels per second. A data run usually consisted in taking the average of three cycles of 400 channels obtained during a period of 60 seconds. The digitized signal from each channel was received by the central recording station and recorded on magnetic tape. This tape was used with a computer program to calculate system steady-state operating performance.

PROCEDURE

Calibration

The pressure transducers were calibrated before and after installation in the system. The preinstallation calibration of absolute and differential pressure transducers was performed at room and elevated temperature. The calibration at elevated temperature accounted for any change in slope of transducer output due to elevated temperature. The transducer calibrations, after installation in the system, were performed at room temperature and consisted of applying a range of argon gas pressures to the system. The measured electrical output was compared with a precision reference Bourdon gage pressure reading. An additional step required in the calibration of the differential pressure transducers was that the low pressure side of the transducer was opened to atmospheric pressure before a selected range of pressures was applied to the mercury or NaK loop. During calibration of high pressure units (greater than 50 psi a (3.5×10^{5} N/m^{2})) the low pressure transducers were isolated from the main loop to prevent diaphragm damage. Transducer isolation was accomplished through a system of valves and the unit was pressurized with argon gas. The transducer output was then checked against a reference Bourdon gage pressure. The results obtained from the test facility calibration of both types of transducers coincided with the manufacturer's room temperature calibrations.

The venturi meters for measuring mercury liquid and vapor flow rates were water and air calibrated. For the electromagnetic flow meter which recorded primary loop NaK flow into the boiler, the manufacturer's standard calibration supplied with the unit was used. The field strength of the magnets was checked with a gaussmeter. These readings were compared with those supplied by the manufacturer and agreed to within 2 percent.

Cleaning

The mercury boiler was cleaned as an individual component before installation into the system. Initially a vacuum was imposed on the mercury, NaK and static NaK passages. Each passage was then filled with liquid trichloroethane and several soaking periods of one hour were made until the fluid removed had the same purity as the original fluid. Each passage of the boiler was then purged with hot argon for drying.

After the boiler was installed, a vacuum was applied on the mercury loop and liquid trichloroethane was pumped into the mercury loop. After a two 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 final liquid flush was then followed by a hot argon purge to dry and evaporate any remaining solvent.

The entire system was completely checked for helium vacuum leaks prior to the initiation of system operation. A pressure of approximately 0.02 torr (2.66 N/m^2) was measured at a point in the vapor line between the boiler exit and turbine inlet. Leakage was determined by passing helium over the loop components and piping and utilizing a helium leak detector while maintaining a vacuum in the system. A leak rate of less than 10^{-8} cubic centimeter per second was considered to be satisfactory.

To remove NaK oxides in the primary and heat rejection (third) loops a 22-hour hot NaK flush was executed in the primary loop over a temperature range of 375 to 1300° F (465 to 980 K) and a 13-hour hot flush, over a temperature range of 320 to 750° F (435 to 670 K), was performed in the heat rejection loop prior to complete system operation. The oxides were precipitated from the NaK loops by cold traps.

Operation

The boiler steady-state performance data were taken from various conditions throughout the boiler history, since no specific boiler test program was performed. The mercury flow rates ranged from 7500 to 11 800 pounds mass per hour (3400 to 5350 kg/hr) and primary NaK flow ranged from 29 000 to 49 000 pounds mass per hour (13 100 to 22 200 kg/hr). The NaK temperature into the boiler was varied from 1272 to 1318° F (962 to 988 K) by increasing the thermal power output of the NaK heater. The mercury flow and boiler inlet temperature, for a given data run were maintained at a constant value.

RESULTS AND DISCUSSION

Tabulated Data

The experimental and calculated results from data of the boiler history are given in table III for a total boiler operating time of 1445 hours. The measured quantities tabulated are mercury and NaK flow rates, NaK inlet and outlet temperature, mercury inlet and outlet temperatures and pressures. The mercury flow rate presented in the table was determined from the venturi located downstream of the mercury pump. The flow rate measured by this venturi and the one located at the condenser outlet was generally within 200 pounds mass per hour (91 kg/hr) of each other throughout the test program. The NaK inlet temperature that is tabulated is the average of the two thermocouples located at the NaK inlet of the boiler. The thermocouples used to represent the NaK outlet temperature were the two located at the inlet of the auxiliary start heat exchanger (fig. 5) since here the NaK flow would be fully mixed. The mercury inlet temperature shown is the average of the three surface thermocouples located at the boiler inlet. Immersion thermocouple A (fig. 5) was used to indicate the boiler outlet superheat temperature. Three out of the four immersion thermocouples generally were within 2° F (1 K) of each other.

The performance parameters selected to be indicative of the heat-transfer performance of the boiler, as tabulated in table III, are: outlet quality, outlet enthalpy, terminal temperature difference, superheat temperature, pinch-point temperature difference, and overall pressure drop. Terminal temperature difference is the difference between the NaK-inlet and mercury-outlet temperatures. Pinch-point temperature difference is the difference between the NaK and the mercury temperature at the mercury liquid-vapor interface. The method of calculation of the various parameters is given in appendix B.

Boiler History

Operating history. - There was a total of four mercury startups during the two-phase system operation. The first shutdown of the mercury system occurred 10 minutes after the initial startup and was due to turbine-speed-indication problems. The mercury system was restarted and 11 hours later the second shutdown occurred due to a spurious signal in the turbine-alternator protective circuit. The mercury loop was again restarted and ran continuously to a total operating time of 364 hours. At this time the system was shut down due to an accidental manual tripping of an electrical switch. All shutdown circuits functioned normally except the turbine-alternator lift-off seal which was vented to atmosphere instead of a vacuum (due to loss of the vacuum pump). The mercury loop was restarted $3\frac{1}{2}$ hours after the shutdown and ran continuously to a total boiler operating time of 1445 hours. The last shutdown was due to system problems, other than that of the boiler. The total elapsed time from the first startup to the last shutdown was 1500 hours.

Overall performance. - A time history of the overall boiler performance is presented in figures 6 and 7. Throughout the boiler history the NaK inlet temperature and NaK flow rate were generally kept at $1300\pm20^{\circ}$ F (980 ± 11 K) and 47 500 ± 1000 pounds mass per hour (21 600 ± 450 kg/hr), respectively. The pinch-point temperature difference was generally $100\pm10^{\circ}$ F (55 ± 5 K) corresponding to mercury and NaK flow rates of approximately 10 300 and 47 000 pounds mass per hour (4700 to 21 000 kg/hr) respectively. After 20 hours of operation a quality of approximately 90 percent was obtained corresponding to an outlet enthalpy of 150 Btu per pound mass (3.5×10^{5} J/kg) with a mercury flow rate of 8000 pounds mass per hour (3640 kg/hr). The pinch-point temperature difference was 130° F (70 K) resulting in a high superheat of 285° F (160 K). Mercury flow was increased to 11 500 pounds mass per hour (5240 kg/hr) from 20 to 45 hours, resulting in a reduction in outlet quality, superheat and outlet enthalpy. The overall pressure drop increased from 135 to 170 psi (9.3 to 11.7×10^{5} N/m^{2}) because of the increase in mercury flow. From 45 to 364 hours, the overall pressure drop decreased because of the reduction of mercury flow from 11 700 to 10 500 pounds mass per hour (5300 to 4750 kg/hr). The outlet quality was 94 percent at a boiler operating time of 364 hours corresponding to an outlet enthalpy of 155 Btu per pound mass (3.6×10^{5} J/kg). At 364 hours (beginning of the fourth startup), figure 7 shows a 14 percent reduction in the overall pressure drop indicating a change in the internal performance of the boiler. The causes and/or effect of this change will be discussed in more detail in a later section of the report. Immediately before and after the fourth startup no change was evident in the other boiler outlet parameters except in boiler pinch-point temperature difference. After 800 hours of boiler operation the boiler reached the design outlet quality of 100 percent and design outlet enthalpy of 163 Btu per pound mass (3.7×10^{5} J/kg). The NaK and mercury flow rates from 1400 to 1430 hours were reduced by 13 and 25 percent, respectively. This resulted in a decrease of overall pressure drop, outlet quality, and enthalpy as would be expected. The superheat increased to 320° F (180 K) as the result of lower outlet saturation temperature.

To perceive the change in the boiler performance the pressure drop in the tubes were plotted for constant flow and temperature conditions as shown in figure 8. 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. The pressure drop through the orifices were determined from mercury flow tests. The pressure drop in the mercury tubes for a mercury flow of 10 500 pound mass per hour (4800 kg/hr) was about 90 psi (6.2×10^{5} N/m^{2}) before the fourth startup. After the fourth startup, at

364 hours, there was a 27 percent reduction in the pressure drop indicating a definite change in the internal performance of the boiler. The pressure drop in the mercury tubes from the fourth startup until the end of testing was essentially constant, indicating little change if any in the performance of the boiler.

The large reduction in the pressure drop at the fourth startup may have been the result of flooding some or all the tubes in the plug section of the boiler. The amount of liquid mercury needed to flood the plug section of the boiler tubes can be determined from the calculated boiler inventory. The calculated inventory which includes the volume of mercury in the tubes as a function of length as well as that in the inlet plenum is shown in figure 9. This figure indicates that 25 pounds (11 kg) of liquid mercury is required to completely fill all seven tubes to the end of the plugs including the inlet plenum, (4.6 ft (1.4 m)). The mercury inventories in the boiler during the first 780 hours of operation is shown in figure 10. Boiler inventories were determined by knowing the standpipe weight and condenser inventory during startup with all liquid-mercury lines filled (fig. 1). The total boiler inventory (before the fourth startup) was less than 25 pounds (11 kg) indicating that the liquid-vapor interface was within the plug section of the boiler. The solid line in figure 10 represents the measured inventory after the fourth startup, which included boiler inventory plus leakage. The dotted line in figure 10 represents the estimated boiler inventory. A small leak was observed after the fourth startup at the mercury filter located on the outlet side of the mercury pump. The estimated boiler inventory was between 60 and 70 pounds (27 and 32 kg), indicating that some or all of the tubes in the plug section of the boiler were flooded. The liquid-vapor interface of some tubes could have been inside the plug, while others could have been well beyond the plug section of the boiler.

To obtain a better insight into the fourth startup a time history is presented in figure 11 for various boiler parameters including boiler inventory. These histories were obtained from 33 cycles of continuous data recording during the startup with a recording speed of one complete cycle approximately every 20 seconds. It was assumed that the data for each cycle were recorded at the end of the cycle. The time sequence at the fourth startup was as follows. The mercury pump was started with valves 207, 247, and 204, 100 percent open and valve 230, 20 percent open (fig. 1). Valve 206 was closed and mercury was allowed to flow through the bypass line for approximately 10 minutes. Immediately before injection, valve 230 was opened while valve 204 was closed simultaneously (pressure drop was transferred from valve 230 to valve 204). Valve 206 was subjected to higher pressures resulting in mercury leakage past valve 206 (known from observed turbine rpm). There was a time lag of 30 seconds between mercury injection (valve 206 first opened) and the start of data recording. During the entire startup the primary NaK flow rate was approximately 47 000 pounds mass per hour (21 000 kg/hr). Examination of figure 11 indicates that the boiler inventory, from 50 to 130 seconds, remained essentially at 42 pounds (19 kg) for a liquid flow rate of approximately 2000 pounds mass per hour (900 kg/hr) indicating that some or all the mercury tubes were flooded within the plug section. During this time the outlet quality and enthalpy generally increased while the terminal temperature difference decreased. After reaching 500 pounds mass per hour (2300 kg/hr) at 150 seconds the mercury flow dropped to 2000 pounds mass per hour (900 kg/hr) at 190 seconds. Valves 206 and 230 were wide open in an attempt to maintain mercury flow at 5000 pounds mass per hour (2300 kg/hr). The drop in flow rate resulted from the fact that valve 210 at the condenser outlet was still closed and mercury was not circulating. The boiling off of mercury which remained in the boiler accounts for the decrease in boiler inventory. At about 230 seconds, valve 210 was opened resulting in a sudden increased in mercury flow from 2000 to 11 800 pounds mass per hour (900 to 5400 kg/hr) in 80 seconds and an increase in boiler inventory to 60 pounds (27 kg). This indicated that some or all the mercury tubes within the plug section again flooded. The mercury flow was reduced to about 5000 pounds mass per hour (2300 kg/hr) and was held constant until 430 seconds and then allowed to increase to 6200 pounds mass per hour (2800 kg/hr) after 660 seconds. Even with the reduction of mercury flow the boiler inventory remained at 58 pounds (26 kg) for the duration of the startup. The boiler outlet quality and enthalpy gradually increased to 100 percent and 160 Btu per pound mass (3.7×10^5 J/kg) respectively, which the terminal temperature difference gradually decreased to 20° F (11° K).

Temperature profile. - A good indication of the internal performance of the boiler can be obtained by examination of the NaK-shell temperature profiles. Typical NaK shell temperature profiles throughout the boiler history are shown in figure 12. Refer to figure 5 for thermocouple locations. Figure 12(a) indicates that boiling was initiated in the plug section of the boiler due to the steep slope of the NaK shell temperature profile in the first 4.5 feet (1.4 m) of boiler length. These profiles indicate that substantial boiling occurred in the plug section of the boiler tubes up to the fourth startup at 364 hours (fig. 12(a) to (h)) with an average superheat length of 28 feet (8.5 m). The superheat length as shown in figure 12(a) was defined as the length from the NaK inlet to the point where the NaK temperature begins to fall off. The flatness of the temperature profile in this region indicates little, if any, heat transfer. References 1 and 2 showed that high quality (greater than 95 percent) superheated vapor was produced with superheat lengths less than 10 feet. The above indicates that there was considerable margin in the design length of the boiler. Figures 12(h) to 12(n) indicate a degradation in the internal performance of the boiler in the plug region after fourth startup. This performance degradation can be seen by the flatness of the shell temperature profiles in the plug region. A plot of various profile parameters, to aid in the interpretation of the temperature profiles during the boiler history, are shown in figure 13. Plotted on the figure is temperature difference between the inner and outer shell profiles arbitrarily selected at 4 feet (1.2 m) from the plug inlet. Also shown on the plot is a boiler length parameter which is defined as the total length of the boiler from the plug inlet minus the superheat length obtained from the profiles (fig. 12(a)). This length parameter represents the total boiling length as indicated by the shell profiles. The shell profile parameter is defined as the area above the NaK temperature profile in the preheat and boiling region (fig. 12(a)). Where a deviation in the inner and outer profiles existed an average value was used. This area is proportional to the resistance to heat transfer in the preheat and boiling regions. Care must be taken in interpretation of this parameter where large changes in flow conditions exist. Since NaK flow and NaK inlet temperature were kept essentially constant and since small changes were made in mercury flow, the NaK-shell profile parameter can be used as a measure of the relative change of the internal boiler performance.

Figure 13 indicates an increase in the boiler length parameter from 7 to 12 inches (18 to 30 cm) corresponding to an increase in flow from 8000 to 11 700 pounds mass per hour (3600 to 5300 kg/hr). This can be explained by the fact that more boiling length is required to transfer heat from the NaK to mercury with an increase in mercury flow. Similarly the length parameter decreased from 12 to 9 inches (30 to 23 cm) as the mercury flow decreased to 10 400 pounds mass per hour (4700 kg/hr). The shell profile parameter also increased with an increase in mercury flow due to the increase in preheat and boiling length. As indicated by the temperature difference parameter for the first 40 hours of operation, no deviation in the inner and outer profiles was observed (fig. 12(a) and (b)). As mercury flow was increased from 10 300 to 11 818 pounds mass per hour (4680 to 5370 kg/hr) a slight deviation in the inner and outer shell profiles was observed in the plug region (approximately 30° F (17 K) difference 4 feet (1.2 m) from the plug inlet). This deviation is believed to be due to possible unequal mercury flow distribution and or a slight shift in the tube bundle resulting in some unequal NaK flow distribution. This slight deviation in the inner and outer profiles in the plug region remained until the fourth startup (fig. 12(c) to (g)).

At the beginning of the fourth start, figure 13 indicates a substantial change in the local temperature profiles within the plug region. The shell profile parameter and the boiler length parameter increased approximately 80 percent while the spread in the inner and outer profiles in the plug region doubled. The flatness of the temperature profiles in the plug region after the fourth startup indicates very little if any boiling in the plug. This is the result of some or all the mercury tubes being flooded in the plug section at the fourth startup. The increase spread in the inner and outer temperature profiles is thought to be due to unequal NaK and mercury flow distributions. Unequal NaK flow distribution is the result of shifting of the tube bundle, possibly at the fourth startup. Results of X-rays of the tube bundle after the completion of testing and post run disassembly showed that the tube bundle had shifted to near the bottom of the NaK shell. A cross section of the tube bundle at the end of the plug region is given in figure 14.

Part of the boiler was disassembled after completion of testing and the tube bundle spacer at the 5-foot (1.5 m) location was observed to be collapsed.

Examination of figure 13 indicates a gradual long term degration of the boiler internal performance (within the plug region) from the fourth startup until the completion of testing. The boiler length parameter increased from 15 to 17 feet (4.6 to 5.2 m) while the spread in the inner and outer profiles in the plug region nearly doubled in the last 1000 hours of operation. This gradual degradation of the internal performance of the boiler is believed to be the result of deposit buildup on the NaK side of the boiler tubes. A buildup of mass transfer products were found upon examination of the tube bundle at the completion of testing. The deposit found on the boiler tubes at the inlet end were approximately 0.03-inches thick. A spectrographic analysis indicated that the deposit was primarily NaK and NaK oxide containing major amounts (greater than 10 percent by weight of sample) of chromium and iron, and minor amounts (1 to 10 percent) of cobalt and nickel. Trace impurities of aluminum, silicon, and titanium were also found.

So far three factors have been considered that have influenced the boiler performance. These were shifting of the tube bundle in the NaK shell, the rapid excursion of mercury flow at the fourth startup, resulting in flooding of the tubes in the plug section and the buildup of mass transfer products on the NaK side of the boiler tubes. Another possible mechanism that will decrease the boiler performance is deconditioning of the inside tube surface with organic decomposition products. In the test system there were several sources for these products such as vacuum pump oil, oil from high temperature leak sealants and the lube-coolant fluid (4P3E) for rotating components. Mercury in-line samples were taken before, during, and after boiler testing and analyzed for contaminants by an infrared technique. The result of eight of the samples analyzed indicated 6 ppm or less of oil contamination, which is not considered sufficient to effect the boiler performance. However, another method using gas chromatography indicated 1.9 percent carbon from a sample of residue taken from the dump tank after testing. This method consisted of dipping a quartz boat into a combustion furnace. The amount of CO_2 burned off was trapped and measured by gas chromatography resulting in a measure of the carbon content. The marked difference between the two analyses was due to the fact that the mercury samples analyzed by the infrared technique were from in-line samples of the operating fluid. The sample used for gas chromatography was from the dump tank residue yielding a sample of greatest contamination. Since gas chromatography is a more refined method for determining carbon content in a sample as compared to the infrared method it is believed that oil contaimination existed in the mercury loop.

It is believed that contamination of the mercury loop occurred at the third shutdown, since a pronounced variation in boiler shell temperature profiles existed at the ensuing startup. This profile variation became more pronounced as testing continued until the final shutdown. Contamination of the mercury loop with lube coolant oil (4P3E) is possible if the turbine lift-off seal seats improperly against the turbine shaft. This seal consists of two separate circular rings with carbon inserts. Each ring is actuated by a common bellows and therefore permits isolation of the turbine mercury vapor and lube coolant circuits. It is possible that mercury and oil vapors could mix in their common vacuum chamber (atmospheric conditions after shutdown) and diffuse into the mercury loop past an improperly seated lift-off seal. An examination of the lift-off seal carbon inserts after final shutdown revealed considerable wear and thus strengthened belief in the vapor diffusion hypothesis.

Boiler Performance

Definition of the effects of variation of boiler independent variables on boiler performance is important in order to determine if off-design operation is detrimental to system performance and to determine the optimum operating condition of the boiler. Although the test was primarily an endurance test, enough changes were made to obtain some off-design performance for three independent variables. The variables considered were NaK-flow rate, mercury flow rate, and NaK inlet temperature. Mercury inlet temperature was kept essentially constant throughout the test program. Boiler performance data were obtained from table III.

Effect of NaK flow on boiler performance. - The effect of NaK flow rate on boiler performance for constant NaK inlet temperature after 1400 hours of operation is shown in figure 15. An increase in NaK flow rate results in an increase in pinch-point temperature difference due to a rise in NaK outlet temperature resulting from an increase in NaK flow rate. A 20-percent increase in NaK flow rate resulted in a 3-percent increase in quality while the other boiler parameters remained essentially constant. Since the range of pinch-point temperature difference considered, 85° to 107° F (47 to 60 K), was well above design value (43° F (24 K)) the increase in NaK flow rate had little effect on boiler performance.

NaK side pressure drop as a function of NaK flow rate is shown in figure 16. This data was obtained after 1380 hours of operation when a shift in the tube bundle is believed to have existed. The NaK side pressure drop ranged from 1.3 to 2.7 psi (9×10^{3} to 18.6×10^{3} N/m^{2}) corresponding to NaK flows of 29 000 to 47 000 pounds mass per hour (13 200 to 21 500 kg/hr). A shift in the tube bundle would not have a significant effect on the NaK side pressure drop since unequal flow distribution would have a self compensating effect on the overall pressure drop of the NaK flowing between the NaK shell and mercury tube bundle.

Effect of mercury flow on boiler performance. - The effect of mercury flow on boiler performance after 13 hours of operation is presented in figure 17. At this time in the boiler history a considerable amount of boiling was occurring in the plug section of the boiler as indicated previously by the NaK temperature shell profiles. An increase in mercury flow rate from 8000 to 11 500 pounds mass per hour (3600 to 5200 kg/hr) resulted in a 5 percent decrease in quality and a 13 percent decrease in superheat while the terminal temperature difference remained essentially constant. A reduction in quality is expected due to an increase in boiling length required to vaporize an increase in mercury flow. The reduction in superheat is due primarily to the increase in boiler outlet pressure with an increase in mercury flow rate.

The effect of mercury flow rate on pressure drop for NaK inlet temperature of 1300° F (980 K) is presented in figure 18. Figure 18(a) represents the condition when a considerable amount of boiling was occurring in the plug section, while figure 18(b) represents the condition when some or all the mercury tubes were flooded. Both cases exhibit a positive slope in the overall pressure drop $\Delta P_{(in-out)}$ as mercury flow rate is increased. This characteristic is attributed to many factors such as, plug geometry, heat flux, boiler inventory, but the main factor that contributes to this positive slope characteristic is the orifices located at entrance to the boiler plug section. The pressure drop of these orifices is a function of mercury flow rate squared. These orifices were included in the boiler design for the purpose of increasing the stability of the boiler. They reduce pressure oscillations in the boiler and eliminate boiler flow maldistribution caused by negative pressure drop against flow characteristics (ref. 11). For boiling within the plug section the overall pressure drop varied from 135 to 170 psi (9.3×10^{5} to 11.7×10^{5} N/m^2) corresponding to an increase in mercury flow rate from 8500 to 11 500 pounds mass per hour (3850 to 5200 kg/hr).

Also shown in figure 18 is the fact that the pressure drop in the mercury tubes without the orifice drop $\Delta P_{(in-out)} - \Delta P_o$ remained essentially constant for the range of mercury flow rates investigated for the case of boiling in the plug region. This may be attributed to the decrease in the two-phase length in the plug section resulting from increased inventory with an increase in mercury flow and also the decline in superheat length as the boiling region expands with increasing flow. The above two factors equalized out the effect of increased velocity with increased flow resulting in the pressure drop in the mercury tubes $(\Delta P_{(in-out)} - \Delta P_o)$ increased from 67 to 98 psi (46×10^{4} to 68×10^{4} N/m^2) with an increase in mercury flow rate from 7500 to 10 500 pounds mass per hour (3400 to 6800 kg/hr). For this case, an increase in boiler inventory corresponding to an increase in mercury flow rate had little effect on the two phase length. Thus the effect of increased velocity with an increase in mercury flow rate results in an increase in pressure drop.

Effect of NaK-inlet temperature on boiler performance. - The effect of NaK-inlet temperature on boiler performance is presented in figure 19. Increasing the NaK inlet temperature results in an increase in the average heating fluid temperature thereby increasing the pinch-point temperature difference. A 45° F (25 K) increase in pinch-point temperature difference resulted in a 45° F (25 K) increase in the superheat outlet temperature corresponding to a 3 percent increase in quality and a negligible effect on terminal temperature difference.

The variation of overall pressure drop with pinch-point temperature difference for constant NaK and mercury flow is presented in figure 20. The overall pressure drop was insensitive to changes in pinch-point temperature difference for the case with all or some of the tubes flooded. One would expect a strong influence on pinch-point temperature difference on overall pressure drop for the case of boiling in the plug.

SUMMARY OF RESULTS

An experimental study of the steady-state performance of the SNAP-8 tantalum stainless-steel boiler yielded the following principal results:

(1) Throughout the boiler history, the overall performance parameters such as superheat and terminal temperature difference were within the design range. The outlet quality gradually increased from 87 to 100 percent for the first 800 hours of operation and remained essentially constant at 100 percent (design value) thereafter. The amount of superheat and terminal temperature difference generally remained constant throughout the boiler's operating history with average values of 265° and 12° F (147 and 7 K), respectively.

(2) The NaK-shell temperature profiles and boiler inventory indicated good internal heat-transfer performance prior to the fourth startup. After the fourth startup, at 364 hours of operating time, the NaK shell temperature profiles indicated degraded heat transfer in the plug region and the boiler inventory history indicated that some or all the tubes in the plug section of the boiler were flooded. There was a gradual degradation of the boiler internal performance (from the fourth startup until the completion of testing). This degradation was believed due to a buildup of mass-transfer products on the primary NaK side of the boiler tubes. After the fourth startup deviation in the inner and outer NaK shell profiles in the preheat and boiling regions increased till the duration of testing. This deviation was attributed to unequal NaK and mercury flow distributions. Results of X-rays of the tube bundle taken after 1445 hours and postrun disassembly showed that the mercury tube bundle had shifted near the bottom of the NaK shell.

Even with some or all the tubes flooded in the plug region the overall outlet performance was still good. The average superheat length was 22 feet (6.7 cm) with an average quality of 97 percent, at approximately 265° F (147 K) superheat. For the above conditions, the NaK temperature profiles indicated little if any heat transfer over the last 22 feet of boiler length indicating considerable margin in the design length of the boiler.

(3) An additional cause of reduced boiler internal heat transfer performance after the fourth startup was oil contamination of the mercury loop. The presence of oil in the mercury loop was verified by a gas chromatography analysis performed on a mercury dump tank sample taken after final system shutdown. It is believed that this oil contamination of the mercury loop occurred at the third shutdown.

(4). For the case with boiling in the plug region (before the fourth startup) and for the case with all or some of the mercury tubes flooded (after the fourth startup) the overall pressure drop increased with an increase in mercury flow indicating that the orifice pressure drop was great enough to overcome any negative pressure drop against flow characteristic.

Due to flooding of some or all the mercury tubes in the plug region there was a 15 percent reduction in the boiler overall pressure drop after the fourth startup. The pressure drop remained essentially constant after the fourth startup with an average value of 105 pounds per square inch (7.24×10^5 N/m^2) corresponding to a mercury flow of approximately 10 200 pounds per hour (4640 kg/hr).

(5) The results indicate a 3-percent decrease in outlet quality for a 20-percent decrease in NaK flow (from design flow) corresponding to a range of pinch-point temperature difference from 85° to 107° F (47 to 54 K). The NaK-side boiler pressure drop ranged from 1.3 to 2.7 pounds per square inch (8.9×10^3 to 18.6×10^3 N/m^2) corresponding to NaK flows of 29 000 to 47 000 pounds per hour (13 200 to 21 400 kg/hr).

A 50° F (28 K) increase in NaK inlet temperature resulted in a 50° F (28 K) increase in superheat with small changes in outlet quality and terminal temperature difference.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 16, 1968,
701-04-00-02-22.

APPENDIX A

SYMBOLS

C_p specific heat, Btu/(lb mass)(^{o}F); J/(kg)(C)

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 distance from reference location, ft; M

P pressure, lb force/sq in; N/m^2

T temperature, ^{o}F; K

t time, hr

w flow rate, lb mass/sec; kg/sec

x outlet quality, dimensionless

Subscripts:

fr flow ratio

hb heat balance

Hg mercury

in inlet

liq liquid

NaK sodium potassium mixture

o orifices

out outlet

pp pinch point

sat saturation

sh Superheat

t total

T terminal

v mercury vapor

APPENDIX B

METHOD OF CALCULATION

Mercury Flow Rate

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

$$w_{liq} = k\, d^2 C_d f E \sqrt{\rho_{liq}\, \Delta P_{liq}} \qquad \text{(B1)}$$

where

k conversion constant

d throat diameter

C_d experimentally determined discharge coefficient

f velocity of appraoch factor

E thermal expansion factor

ρ density

ΔP measured pressure drop from inlet to throat of the venturi

The vapor flow rate at the outlet of the boiler was calculated from the following equation for compressible flow through a venturi

$$w_v = k\, d^2 D_d f E \varphi \sqrt{\rho_v\, \Delta P_v} \qquad \text{(B2)}$$

where

φ net expansion factor

Quality

The boiler outlet quality was determined by both heat balance across the boiler and by taking the ratio of the vapor flow rate out of the boiler to the total liquid flow rate into the boiler. These can be expressed as

$$X_{hb} = \frac{w_{NaK}C_{p,NaK}(T_{NaK,in} - T_{NaK,out}) - w_{Hg}C_{p,Hg,liq}(T_{Hg,pp} - T_{Hg,in})}{w_{Hg}\, h_{fg} + C_{p,Hg,v}(T_{Hg,sh} - T_{Hg,sat})} \tag{B3}$$

and

$$X_{fr} = \frac{w_v}{w_{liq}} \tag{B4}$$

The thermodynamic properties were determined from references 12 and 13. Saturation temperature of mercury at the pinch point was determined from the saturation pressure which was obtained by subtracting the experimental orifice pressure drop from the boiler inlet pressure.

Pinch-Point Temperature Difference

The pinch-point temperature difference is the difference between the NaK and the mercury temperature at the mercury liquid-vapor interface.

$$\Delta T_{pp} = T_{NaK,pp} - T_{Hg,pp} \tag{B5}$$

The NaK temperature at pinch point (liquid-vapor interface) was determined by a heat balance across the mercury liquid portion of the boiler

$$T_{NaK,pp} = \frac{w_{Hg}C_{p,Hg,liq}(T_{Hg,pp} - T_{Hg,in})}{w_{NaK}C_{p,NaK}} + T_{NaK,out} \tag{B6}$$

Mercury-Outlet Enthalpy

The outlet enthalpy of the mercury mixture was determined from the outlet enthalpy of the saturated liquid and vapor plus the enthalpy change due to the superheated vapor

$$h_{out} = h_{liq,out}(T_{sat}) + X_{hb}\, h_{fg}(T_{sat}) + X_{hb}C_{p,v}(T_{sh} - T_{sat}) \tag{B7}$$

REFERENCES

1. Kreeger, A. H.; Hodgson, J. N.; and Sellers, A. J.: Development of the SNAP-8 Boiler. AIAA Specialists Conference on Rankine Space Power Systems. Vol. 1. AEC Rep. CONF-651026, vol. 1, 1965, pp. 285-306.
2. Albers, James A.; Wintucky, William T.; and Gorland, Sol H.: Conditioning and Steady-State Performance of SNAP-8 Tube-In-Shell Mercury Boiler. NASA TM X-1441, 1967.
3. Sellers, A. J.; and Wong, M. K.: Experimental Investigation of Forced Convection Once-Through Mercury Boiler Performance Characteristics. Tech. Memo. 4933:65-8-311, Aerojet-General Corp., Aug. 3, 1965.
4. Brooks, R. D.: SNAP-8 Refractory Boiler Development, Monthly Progress Report for Period Ending August 10, 1967. General Electric Co., Aug. 10, 1967. (Contract NAS3-10610.)
5. Poppendiek, H. F.: Investigation of the Boiler Conditioning and Heat Transfer Characteristics in a Mercury-Tantalum System. Monthly Tech. Progr. Rep., Geoscience, Ltd., Oct. 31, 1967. (Aerojet-General Corp. Contract OP119224.)
6. Poppendiek, H. F.: Investigation of the Boiler Conditioning and Heat Transfer Characteristics in a Mercury-Tantalum System. Monthly Tech. Progr. Rep., Geoscience, Ltd., Nov. 30, 1967. (Aerojet-General Corp. Contract OP119224.)
7. Sellers, A. J., Bodean/Bopean: IBM 7094 Computer Codes for the SNAP-8 Boiler Design Analysis. Rep. TM 4934: 67-475, Aerojet-General Corp., June 28, 1967.
8. Sellers, A. J.: Bare Refractory Double Containment Boiler Design Analysis. Rep. TM 4934: 67-477, Aerojet-General Corp., June 30, 1967.
9. Sellers, A. J.: SNAP-8 Boilers No. 5 and 6 Results of Heat and Momentum Transfer. Rep. TM 4934: 67-481, Aerojet-General Corp., July 17, 1967.
10. Anon.: SNAP-8 Refractory Boiler Development Program, Single Tube Testing, General Electric Co., Mar. 11, 1968. (Contract NAS3-10610.)
11. Schoenberg, Andrew A.; and Packe, Donald R.: Analysis of Pressure-Drop Function in Rankine Space Power Boilers with Discussion of Flow Maldistribution Implications. NASA TN D-4498, 1968.
12. Ross, Daniel P.: Thermodynamic Properties of Mercury. Rep. TM-777, Thompson Products, Inc., June 17, 1957.
13. Weatherford, W. D., Jr.; Tyler, John C.; and Ku, P. M.: Properties of Inorganic Energy-Conversion and Heat-Transfer Fluids for Space Applications. Southwest Research Inst. (WADD TR 61-96), Nov. 1961.

TABLE I. - TANTALUM - STAINLESS-STEEL REFRACTORY

BOILER DESIGN SPECIFICATIONS

Operating parameters:	
Mercury flow rate, w_{Hg}, lb_{mass}/hr; kg/hr	11 500; 5.2×10^3
NaK flow rate, w_{NaK}, lb_{mass}/hr; kg/hr	47 500; 21.5×10^3
NaK inlet temperature, $T_{NaK, in}$, ^oF; K	1280 - 1330; 967 - 1050
NaK temperature drop, T_{NaK}, ^oF; K	170; 94
Mercury inlet temperature, $T_{Hg, in}$, ^oF; K	400 - 500; 480 - 530
Mercury exit pressure, $P_{Hg, out}$, psia; N/m^2	259±5; $181\times10^4\pm3.5\times10^4$
Mercury exit temperature, $T_{Hg, out}$, ^oF; K	1250 - 1300; 950 - 980
Terminal temperature difference, T_T, ^oF; K	30; 17
Pinch-point temperature difference, T_{pp}, ^oF; K	43; 24
Outlet enthalpy, h_{out}, Btu/lb_{mass}; J/kg	163; 3.7×10^5
Containment tube dimensions:	
Total boiler length, ft; m	37; 11.3
Mercury tube inside diameter, in.; cm	0.67; 1.7
Mercury tube wall thickness, in.; cm	0.040; 0.10
NaK containment tube wall thickness, in.; cm	0.035; 0.92
Swirl wire pitch, in.; cm	2.0; 5.3
Swirl wire diameter, in.; cm	0.063; 0.16
Plug insert length, ft; m	4.6; 1.5
Pitch, in.; cm	6; 10.5
Number of passages	16
Cross section area, in.^{2}/passages; cm^2/passages	0.005; 0.13

TABLE II. - THERMOCOUPLE LOCATIONS ALONG BOILER SHELL

Inside surface								
Station number	Length, in.[a]	Length, cm	Station number	Length, in.[a]	Length, cm	Station number	Length, in.[a]	Length, cm
0	-10.5	-27	13	69.5	177	28	199.4	508
1	-4.6	-12	14	73.4	187	29	211.4	538
2	1.4	4	15	79.4	202	30	223.4	568
3	7.4	19	16	85.4	218	31	235.4	598
4	13.4	34	17	91.4	232	32	259.4	659
5	19.4	49	18	97.4	248	33	283.4	721
6	25.4	65	19	103.4	263	34	307.4	781
7	31.4	80	20	109.4	278	35	331.4	844
8	37.4	95	21	115.4	294	36	355.4	904
9	43.4	110	22	127.4	324	37	379.4	965
10	49.4	126	23	139.4	255	38	403.4	1027
11	55.1	140	24	151.4	386	39	427.4	1088
11	55.1	140	25	163.4	416	40	439.4	1120
11	55.1	140	26	175.4	446	41	451.4	1150
12	61.4	156	27	187.4	476			

Outside surface								
Station number	Length, in.[a]	Length, cm	Station number	Length, in.[a]	Length, cm	Station number	Length, in.[a]	Length, cm
4	13.4	34	13	69.4	176	27	187.3	476
6	25.4	65	15	79.3	202	29	211.3	537
7	31.4	80	17	91.3	232	31	235.3	598
8	37.4	95	19	103.3	262	32	259.3	660
9	43.4	110	21	115.3	293	34	307.3	780
10	49.4	125	23	139.3	354	36	355.3	904
11	55.4	141	25	163.3	415	38	403.3	1025

[a]See fig. 5. - reference station at shart of plug inlet.

TABLE III. - EXPERIMENTAL AND CALCULATED RESULTS

Run	Total boiler operating time, t, hr	Mercury flow rate, w_{Hg}		NaK flow rate, w_{NaK}		NaK inlet temperature, $T_{NaK, in}$		NaK outlet temperature $T_{NaK, out}$		Mercury inlet temperature, $T_{Hg, in}$		Mercury outlet temperature, $T_{Hg, out}$		Mercury pressure, $P_{Hg, in}$		Mercury pressure, $P_{Hg, out}$		Outlet vapor quality		Pinch-point temperature difference ΔT_{pp}		Outlet enthalpy, h_{out}		Superheat, ΔT_{sh}		Thermal temperature difference, ΔT_T		Overall pressure drop $\Delta P_{(in-out)}$	
		lb_m/hr	kg/hr	lb_m/hr	kg/hr	^oF	K	^oF	K	^oF	K	^oF	K	psia	N/m^2	psia	N/m^2	X_{fr}	X_{hb}	^oF	K	Btu/lb_m	J/kg	^oF	K	^oF	K	psia	N/m^2
1	18.0	8.0×10^3	3.6×10^3	48.4×10^3	21.9×10^2	1293	975	1181	912	387	471	1281	969	291	200×10^4	152	105×10^4	0.90	0.92	132	73	151	3.5×10^5	289	160	12	7	139	96×10^4
2	19.0	8.1	3.7	48.6	22.0	1301	977	1166	904	390	472	1285	970	291	200	154	106	.90	.94	137	76	155	3.6	310	172	16	9	137	94
3	19.9	8.4	3.8	48.3	21.9	1297	976	1181	912	389	472	1286	970	295	202	160	110	.90	.90	132	73	150	3.5	306	170	11	6	135	92
4	21.0	8.6	3.9	48.9	22.2	1278	965	1159	900	396	476	1266	960	290	200	159	109	.89	.91	115	64	150	3.5	287	160	12	7	131	90
5	22.0	9.1	4.1	48.4	21.9	1301	977	1173	908	406	481	1289	971	308	212	169	116	.90	.93	119	66	154	3.6	300	167	12	7	139	96
6	23.0	9.2	4.2	49.0	22.2	1286	970	1163	903	409	483	1271	963	309	213	172	118		.89	109	60	148	3.5	280	156	15	8	137	94
7	24.0	9.2	4.2	48.6	22.0	1294	975	1170	907	403	480	1280	967	310	214	172	118		.89	115	64	148	3.5	278	154	14	8	138	95
8	26.0	9.3	4.2	48.4	21.9	1301	977	1172	908	413	485	1287	970	316	218	176	121		.91	114	63	151	3.5	293	163	14	8	140	96
9	36.0	9.5	4.3	48.8	22.1	1282	968	1157	899	379	379	1272	963	319	220	175	120	.88	.86	99	55	144	3.4	278	154	10	6	144	99
10	38.7	10.0	4.5	48.6	22.0	1289	971	1155	898	383	468	1275	964	336	232	186	128	.89	.88	101	56	146	3.4	272	151	14	8	150	103
11	39.7	10.3	4.5	48.9	22.2	1282	968	1145	893	382	468	1268	960	342	236	193	133	.89	.88	101		147	3.4	259	144	14	8	149	103
12	41.2	10.8	4.9	49.2	22.3	1272	952	1129	883	389	472	1259	955	357	246	202	141	.90	.89	101		148	3.5	242	135	13	7	155	107
13	45.2	11.6	5.3	49.0	22.2	1281	967	1129	883	397	476	1270	963	382	263	217	149	.89	.86	57		144	3.4	241	134	11	6	165	114
14	50.1	11.8	5.4	49.0		1299	976	1141	890	381	468	1284	970	394	271	221	152	.89	.88	54	30	146	3.4	252	140	15	8	173	119
15	62.6	11.7	5.3	48.9		1303	979	1143	891	401	479	1289	971	391	269	219	151	.89	.90	56	31	150	3.5	258	143	14	8	172	118
16	74.6	11.8	5.4	48.9		1292	974	1137	888	398	477	1279	966	383	264	219	151	.88	.87	55	31	145	3.4	248	138	13	7	164	113
17	85.6	11.8	5.4	48.4	21.9	1301	977	1146	892	399	477	1286	970	387	267	221	152	.89	.86	62	34	144		253	140	15	8	166	114
18	98.1	11.7	5.3	48.9	22.2	1298	974	1143	891	401	479	1285	970	383	264	218	150	.88	.87	61	34	146		255	141	13	7	165	114
19	111.6	11.7	5.3	49.2	22.3	1289	971	1112	874	393	474	1281	969	384	264	219	151	.89	.84	57	32	141		250	139	8	4	165	114
20	123.6	11.7	5.3	48.6	22.0	1306	980	1152	897	403	480	1296	975	378	260	217	149	.88	.87	73	41	145		267	148	10	6	161	111
21	135.6	11.6	5.3	48.7	22.0	1307	981	1154	898	379	479			375	258	215	148	.88	.86	77	43	144		268	149	11	6	160	110
22	146.5	11.5	5.2	48.4	21.9	1310	983	1160	900	388	472			378	260	215	148	.89	.85	79	44	143	3.3	268	149	14	8	163	112
23	158.5	11.6	5.3	47.8	21.7	1309	982	1150	895	389	472			381	263	216	149	.88	.88	69	38	147	3.4	268	149	13	7	165	114
24	169.8	11.6	5.3	47.6	21.6	1307	981	1150	895	391	474	1294	974	381	263	216	149	.88	.86	69	38	145		266	148	13	7	165	114
25	191.5	11.7	5.3	47.5	21.5	1318	987	1158	899	385	469	1301	977	381	263	217	149	.88	.87	78	43	146		272	151	17	9	164	113
26	203.0	11.6	5.3	47.5	21.5	1302	978	1143	891	380	467	1290	972	380	262	216	149	.89	.88	63	35	146		262	145	12	7	164	113
27	215.5	11.7	5.3	47.5	21.5	1296	976	1137	885	378	465	1286	970	376	216	216	149	.88	.87	60	33	145		257	143	10	6	160	110
28	227.0	11.5	5.2	47.7	21.6	1301	977	1144	891	380	467	1289	971	371	214	214	148	.89	.86	69	38	145		262	145	12	7	157	108
29	239.5	11.6	5.3	47.7	21.6	1304	980	1193	890	381	468	1293	973	373	257	215	148	.90	.90	67	37	149	3.5	265	147	11	6	158	109
30	251.8	11.5	5.2	47.6	21.6	1305	981	1143	890	384	469	1292	973	372	256	216	149	.91	.90	67	37	150	3.5	264	147	13	7	156	108

31	265.0	11.6	5.3	47.3	21.4	1302	978	1139	886	391	473	1293	973	370	255	218	115	.91	.90	64	35	150	3.5	263	146	9	5	152	105
32	278.0	11.4	5.2	47.4	21.5	1303	979	1117	875	383	469	1293	973	363	250	215	148	.92	.90	71	39	150	3.5	265	147	10	6	148	102
33	291.6	11.1	5.0	47.6	21.6	1298	974	1143	890	382	468	1288	970	355	245	212	146	.93	.90	75	42	149	3.5	263	146	10	6	143	99
34	303.1	10.6	4.8	47.4	21.5	1303	979	1150	894	379	466	1291	972	338	233	202	139	↓	.93	89	49	153	3.6	275	153	12	7	136	94
35	315.1	10.5	4.8	47.4	21.5	1302	979	1154	896	378	465	1291	972	334	230	199	137	↓	.91	94	52	151	3.5	275	153	11	6	135	93
36	328.5	10.3	4.7	47.5	21.5	1307	981	1155	897	374	463	1292	973	330	227	198	136	↓	.95	97	54	156	3.6	279	155	15	8	132	91
37	341.5	10.5	4.8	47.2	21.4	1304	980	1153	895	380	467	1292	973	333	229	202	139	↓	.91	95	53	152	3.5	276	153	13	7	131	90
38	353.4	10.6	↓	47.2	21.4	1304	980	1151	894	371	462	1294	974	334	230	203	140	.94	.92	93	52	153	3.6	277	154	10	6	131	90
39	362.7	10.6	↓	47.1	21.4	1306	980	1150	894	380	467	1293	973	330	227	205	141	.95	.94	93	52	156	3.6	274	152	13	7	125	86
40	365.2	10.6	↓	47.8	21.7	1292	973	1135	885	408	487	1277	965	331	214	203	140	.97	.98	91	51	159	3.7	260	144	15	8	108	74
41	377.1	10.5	↓	46.9	21.2	1303	979	1149	893	364	457	1291	972	309	213	204	140	.97	.94	106	59	155	3.6	273	152	12	7	105	72
42	385.4	10.4	4.7	46.8	21.2	1304	↓	1150	894	369	461	1291	972	306	211	200	138	.96	.94	109	60	155	3.6	271	150	13	7	106	73
43	386.9	10.3	↓	46.8	21.2	1303	↓	1147	891	384	469	1288	971	308	212	203	140	.98	.98	104	58	159	3.7	271	150	15	8	105	72
44	399.6	10.3	↓	47.0	21.3	1302	↓	1148	892	391	474	1289	971	308	212	204	140	.98	.96	104	58	157	3.7	271	150	13	7	104	72
45	411.7	10.4	↓	46.8	21.2	1303	↓	1152	896	393	474	1292	973	308	212	202	139	.97	.94	109	60	154	3.6	275	153	11	6	106	73
46	424.7	10.3	↓	46.8	21.2	1304	980	1150	894	378	455	1290	972	307	211	201	139	↓	.96	107	59	157	3.7	274	152	14	8	106	73
47	435.7	10.4	↓	46.7	21.1	1304	980	1147	891	377	465	1291	972	313	216	203	140	↓	.97	101	56	158	3.7	273	152	13	7	110	76
48	450.5	10.4	↓	46.9	21.2	1304	980	1151	894	379	466	1292	973	313	216	204	140	↓	.94	105	58	155	3.6	274	152	12	7	109	75
49	461.7	10.5	4.8	46.9	21.2	1305	981	1149	893	395	475	1292	973	312	215	203	140	.96	.96	103	58	158	3.7	275	153	13	7	109	75
50	477.2	10.4	5.2	46.8	21.2	1302	979	1148	892	389	472	1291	972	314	216	204	140	.97	.95	101	56	156	3.6	273	152	11	6	110	76
51	487.7	10.5	4.8	47.0	21.3	1304	980	1150	894	386	475	1289	971	316	218	206	142	.97	.94	103	57	155	3.6	269	149	15	8	110	76
52	490.4	10.8	4.9	46.8	21.2	1301	978	1143	890	396	476	1292	973	327	225	210	145	.96	.94	90	50	154	3.6	269	149	9	5	117	81
53	502.4	10.5	4.8	46.9	21.2	1302	978	1146	891	402	478	1289	971	315	217	204	140	.96	.96	99	55	157	3.7	271	150	13	7	111	76
54	518.1	10.5	4.8	46.7	21.1	1304	980	1148	892	381	468	1291	972	314	216	203	140	.96	.95	102	96	156	3.6	273	152	13	7	111	76
55	531.7	10.4	4.7	46.6	21.1	1303	979	1148	892	386	470	1292	973	315	217	205	141	.97	.95	101	56	156	3.6	273	152	11	6	110	77
56	544.1	10.4	4.7	46.8	21.2	1304	980	1149	893	385	470	1291	972	314	216	204	140	↓	.95	102	96	156	3.6	272	151	13	7	110	77
57	556.2	10.4	4.7	46.9	↓	1303	979	1146	891	384	469	1294	974	314	216	204	140	↓	.97	99	55	159	3.7	276	153	9	5	110	77
58	569.2	10.5	4.8	46.8	↓	↓	↓	1145	↓	379	466	1292	973	315	217	206	142	↓	.97	98	54	158	↓	272	151	11	6	109	75
59	583.7	10.5	4.8	46.8	↓	↓	↓	1146	↓	390	472	1294	974	314	216	206	142	.96	.96	100	55	157	↓	274	152	9	5	108	74
60	596.0	10.5	4.8	46.5	21.0	↓	↓	1146	↓	396	476	1291	972	314	216	207	143	.97	.96	99	55	158	↓	270	150	12	7	107	74
61	610.4	10.4	4.7	46.7	21.1	1304	980	1144	890	395	475	1292	973	316	218	209	144	.98	.99	95	54	162	3.8	270	150	12	7	107	74
62	624.2	10.4	↓	46.7	21.1	1304	980	1145	891	398	476	1296	975	316	218	207	143	.97	.98	97	54	160	3.7	275	153	8	4	109	75
63	636.1	10.3	↓	47.0	21.3	1302	978	1142	889	374	464	1291	972	312	215	207	↓	.98	1.00	96	53	163	3.8	270	150	11	6	105	72
64	648.0	10.4	↓	47.0	21.3	1303	979	1144	890	375	464	1290	↓	314	216	207	↓	.98	.98	97	54	161	3.8	269	149	13	7	107	74
65	660.2	10.4	↓	46.5	21.0	1304	980	1146	891	382	468	1290	↓	316	218	208	↓	.98	.97	97	54	159	3.7	268	149	14	8	108	74
66	677.7	10.3	↓	46.3	21.0	1303	979	1145	891	382	468	1291	↓	316	218	209	144	.99	.97	97	54	160	↓	268	149	12	7	107	74
67	674.3	10.4	↓	46.9	21.2	2194	975	1135	885	381	468	1282	969	322	222	212	146	.98	.96	84	47	157	↓	257	143	12	7	110	77
68	686.4	10.6	4.8	46.7	21.1	1300	977	1140	883	372	463	1288	971	325	224	213	147	.99	.97	88	49	158	↓	262	145	12	7	112	77
69	690.7	10.6	4.8	46.5	21.0	1302	978	1142	889	389	471	1292	973	327	226	215	148	1.00	.94	92	51	155	3.6	264	147	10	6	112	77
70	692.3	10.6	4.8	46.5	21.0	1330	993	1164	901	391	473	1318	986	327	226	214	148	.98	1.00	111	61	163	3.8	291	162	12	7	113	78
71	693.6	10.7	4.9	46.6	21.1	1310	987	1154	896	396	475	1307	981	326	225	213	147	.98	1.00	100	55	163	3.8	281	156	12	↓	↓	↓
72	694.5	10.7	4.9	46.5	21.0	1308	982	1146	891	390	471	1296	976	326	225	213	147	.98	.97	94	52	159	3.7	270	150	12	↓	↓	↓
73	695.2	10.6	4.8	46.7	21.1	1296	976	1139	888	391	473	1283	970	327	226	214	148	.99	.98	82	46	160	↓	256	148	13	↓	↓	↓
74	696.0	10.6	4.8	46.6	21.1	1286	970	1126	880	391	473	1276	964	326	225	214	148	.99	.98	73	41	149	↓	249	138	10	6	112	77
75	696.7	10.6	4.8	47.0	21.3	1277	964	1119	876	392	474	1267	957	325	224	214	148	1.00	.97	66	37	148	↓	241	134	10	6	111	76

TABLE III. - *Concluded.* EXPERIMENTAL AND CALCULATED RESULTS

Run	Total boiler operating time, t, hr	Mercury flow rate, w_{Hg}		NaK flow rate, w_{NaK}		NaK inlet temperature, $T_{NaK,in}$		NaK outlet temperature $T_{NaK,out}$		Mercury inlet temperature $T_{Hg,in}$		Mercury outlet temperature, $T_{Hg,out}$		Mercury pressure, $P_{Hg,in}$		Mercury pressure, $P_{Hg,out}$		Outlet vapor quality		Pinch-point temperature differance ΔT_{pp}		Outlet enthalpy, h_{out}		Superheat ΔT_{sh}		Thermal temperature difference ΔT_T		Overall pressure drop $\Delta P_{(in-out)}$	
		lb_m/hr	kg/hr	lb_m/hr	kg/hr	^oF	K	^oF	K	^oF	K	^oF	K	psia	N/m^2	psia	N/m^2	X_{fr}	X_{hb}	^oF	K	Btu/lb_m	J/kg	^oF	K	^oF	K	psia	N/m^2
76	706.3	10.4×10^3	4.7×10^3	46.8×10^3	21.2×10^2	1300	977	1141	889	380	467	1292	973	321	221×10^4	213	147×10^4	1.00	.99	90	50	161	3.8×10^5	266	148	8	4	108	74×10^4
77	718.6			46.9	21.2	1303	979	1195	891	377	465	1290	972	318	219	210	145	.98	.97	96	53	158	3.7	266	148	13	7		
78	730.4			46.7	21.1	1300	977	1144	890	378	466	1288	971	319	220	211	145	.99	.96	94	52	157	3.7	263	146	12	7		
79	744.3			46.9	21.2	1293	973	1138	886	377	465	1282	969	318	219	210	145	.99	.96	89	49	157	3.7	259	144	11	6		
80	756.3			46.8	21.2	1302	978	1142	889	376	465	1290	972	318	219	212	146	1.00	.99	92	51	162	3.8	265	147	12	7	106	73
81	772.4			46.6	21.1	1304	980	1141		386	470	1288	970	319	220	211	145	.99	1.01	90	50	163	3.8	264	147	16	9	108	74
82	782.2			46.7	21.1	1299	976	1142		383	469	1288	970	320		212	146	1.00	.97	91	51	158	3.7	263	146	11	6	108	
83	784.1			46.7	21.1	1303	979	1142		389	472	1292	973	319		212	146	.99	.99	92	51	161	3.8	264	147	11	6	107	
84	810.2			46.5	21.0	1305	981	1139	886	377	465	1292	973	320		212	146	1.00	1.03	88	49	163		267	148	13	7	108	
85	822.1	10.3		46.6	21.1	1301	977	1141	889	374	464	1292	973	318	219	211	145	1.00	.98	92	51	161		268	149	9	5	107	
86	834.1			46.5	21.0	1302	978	1143	890	377	465	1288	970	319	220	212	146	1.01	0.99	92	51	161		264	147	14	8	107	
87	848.1			46.6	21.1	1301	977	1140	888	374	464	1291	972	315	217	211	145	1.00	1.00	92	51	163		267	148	10	6	104	72
88	860.1			46.6	21.1	1303	979	1141	889	373	463	1294	974	318	219	215	148	1.01	1.01	91	51			267	148	9	5	103	71
89	871.1			46.4	21.0	1303	979	1139	886	379	466	1291	972	319	220	214	148	1.02	1.02	88	49			264	147	12	7	105	72
90	884.1			46.7	21.1	1302	978	1139		377	465	1290	972	319	220	216	149	1.02	1.02	88	49			262	145	12	7	103	71
91	896.3			46.6	21.1	1302	978	1138		370	461	1292	973	318	219	214	148	1.02	1.04	88	49			265	147	10	6	104	72
92	908.7			46.5	21.0	1303	979	1139		378	466	1288	970	315	217	210	145	1.00	1.03	91	51			264	147	15	8	105	
93	921.2	10.2		46.8	21.2	1303	979	1143	890	381	468	1291	972	316	218	212	146	1.01	1.01	93	52			266	148	12	7	104	
94	933.7	10.3		46.8	21.2	1302	978	1143	890	372	462	1293	973	315	217	211	145	1.00	1.00	94	52			269	149	9	5	104	
95	945.2	10.2	4.6	46.8	21.2	1300	977	1146	891	379	466	1292	973	313	216	210	145	1.00	.98	98	54	159	3.7	269	149	8	4	103	71
96	956.9	10.3	4.7	46.4	21.0	1304	980	1143	890	376	465	1288	970	314	216	212	146	1.01	1.01	95	53	163	3.8	263	146	16	9	102	70
97	969.3	10.3	4.7	46.8	21.2	1301	977	1138	886	382	468	1287	969	319	220	214	148	1.02	1.02	87	48			260	144	14	8	105	72
98	981.2	10.2	4.6	46.5	21.0	1301	977	1142	889	382	468	1291	972	312	215	211	145	1.01	1.01	95	53			267	148	10	6	101	70
99	993.3	10.1	4.6	46.5	21.0	1315	985	1155	896	388	472	1304	979	313	216	211	145	1.01	1.01	107	59			279	155	11	6	102	70
100	1005.2	10.2	4.6	46.5	21.0	1304	980	1149	893	385	470	1290	972	313	216	212	146	1.01	.98	101	56	159	3.7	265	147	14	8	101	70
101	1019.1	10.0	4.5	46.6	21.1	1303	979	1142	889	375	463	1291	972	310	214	211	145	1.03	1.04	95	53	163	3.8	267	148	12	7	99	68
102	1031.1	9.9	4.5	46.4	21.0	1304	980	1144	891	375	463	1292	973	310	214	211	145	1.04	1.04	97	54			268	149	12	7	99	68
103	1039.2	10.2	4.6	46.4	21.0	1303	979	1144	891	382	468	1290	972	316	218	215	148	1.03	1.00	94	52			263	146	13	7	101	70
104	1051.1	10.2	4.6	46.7	21.1	1302	978	1144	891	377	465	1288	970	318	219	215	148	1.04	1.00	93	52			260	144	14	8	103	71
105	1063.1	10.3	4.7	46.5	21.0	1302	978	1141	889	377	465	1292	973	315	218	211	145	1.00	1.00	93	52			268	149	10	6	104	72

106	1075.1	10.2	4.6	46.5	21.0	1301	977	1144	891	373	463	1289	971	319	220	217	150	1.04	.98	93	52	160	3.7	260	144	12	7	102	70
107	1087.1			46.5	21.0	1303	979	1145		380	466	1288	971	315	218	214	148	1.03	.99	96	53	161	3.8	261	145	15	8	101	70
108	1100.7			46.6	21.1	1303	979	1144		383	468	1292	973	317		217	150	1.04	1.00	94	52	163		262	145	11	6	100	69
109	1113.1			46.6	21.1	1302	978	1145		383	468	1290	972	315		216	149	1.04	.99	96	56	162		262	145	12	7	99	68
110	1125.1			46.6	21.1	1302	978	1140	888	376	464	1291	972	317		213	147	1.03	1.02	90	50	163		265	147	11	6	104	72
111	1137.1	10.0	4.5	46.5	21.0	1300	977	1146	891	385	469	1285	969	308	212	209	144	1.02	.99	100	55	162		262	145	15	8	99	68
112	1149.1	10.2	4.6	46.7	21.1	1305	981	1146	891	380	466	1289	971	313	216	212	146	1.02	1.00	99	55	163		264	147	16	9	101	70
113	1161.2	10.0	4.5	46.7	21.1	1299	976	1144	891	371	462	1287	969	308	212	212	146	1.03	.99	100	50	161		262	145	12	7	106	73
114	1175.2	10.0		46.7	21.1	1303	979	1150	894	382	467	1290	972	302	208	208	143	1.01	.99	108	60	162		268	149	13	7	104	72
115	1187.1	9.9		46.4	21.0	1292	973	1137	885	384	469	1283	967	305	210	209	144	1.04	1.00	93	52	162		260	144	9	5	96	66
116	1199.1			46.3	21.0	1305	981	1147	891	382	467	1289	971	305	210	208	143	1.02	1.01	104	58	163		267	148	16	9	97	67
117	1211.2			46.1	20.9	1305	981	1148	892	383	468	1288	970	305	210	208		1.02	1.01	104	58	163		266		17	9	97	67
118	1223.2			46.5	21.0	1302	978	1149	892	383	468	1288	970	308	212	208		1.04	.99	103	57	161		267		14	8	100	69
119	1235.2			46.5	21.0	1302	978	1147	891	384	469	1290	972	306	211	209	144	1.04	1.01	101	56	163		267		12	7	97	67
120	1247.3	10.1	4.6	46.3	21.0	1304	980	1148	892	386	470	1291	972	310	214	209	144	1.01	.98	102	57	160	3.7	268	149	13	7	101	70
121	1257.2			46.3	21.0	1302	978	1150	894	388	471	1290	972	313	216	214	148	1.03	.95	102	57	157	3.7	263	146	12	7	99	68
122	1269.4			46.6	21.1	1304	980	1145	891	376	464	1289	971	314	216	213	147	1.03	1.01	96	56	163	3.8	263	146	15	8	101	70
123	1283.2			46.3	21.0	1303	979	1148	892	378	466	1293	973	315	217	216	149	1.04	.98	99	55	160	3.7	265	147	10	6	99	68
124	1295.2	10.0	4.5	46.5		1304	980	1148	892	392	467	1286	970	314	216	216	149	1.05	1.00	99	55	162	3.8	258	143	18	10	98	68
125	1309.2	10.1	4.6			1304	980	1147	891	382	467	1287	969	315	217	217	14-	1.04		97	54	162		258	143	17	9	98	68
126	1321.2					1303	979	1146	891	376	464	1288	971	314	216	215	148	1.03		97	54	162		260	144	15	8	99	68
127	1333.2					1305	981	1147	891	381	467	1289	971	314	216	214	148	1.03		98	54	163		262	145	16	9	100	69
128	1345.4			46.2	20.9	1305	981	1149	893	384	469	1289	971	314	216	213	147	1.04	.98	100	55	160	3.7	263	146	16	9	101	70
129	1353.3	9.9	4.5	46.2	20.9	1305	981	1154	895	390	472	1292	973	309	213	207	143	1.03	1.01	107	59	159	3.7	271	150	14	8	102	70
130	1358.1	9.7	4.4	46.3	21.0	1303	979	1149	893	377	465	1287	969	299	206	207		1.04	.98	108	60	163	3.8	266	148	16	9	92	63
131	1377.3	9.8		46.6	21.1	1305	981	1155	896	374	463	1294	974	301	207	208		1.03	.98	112	62	160	3.7	272	151	11	6	93	64
132	1389.3			46.3	21.0	1305	981	1156	896	383	468	1292	973	303	209	208		1.03	.96	113	63	158	3.7	270	150	13	7	95	65
133	1402.0			46.4	21.0	1308	982	1152	895	383	468	1293	973	305	210	208		1.05	1.02	107	59	163	3.8	271	150	15	8	97	67
134	1402.8			43.8	19.8	1307	982	1144	890	382	467	1294	974	303	209	207		1.04	1.01	102	57	163	3.8	273	152	13	7	96	66
135	1403.5	9.9	4.5	42.5	19.2	1307		1138	886	384	469	1293	973	308	212	210	145	1.06	1.00	93	52	163	3.8	269	149	14	8	98	68
136	1404.3	9.9	4.5	38.8	17.6	1307		1127	880	384	469	1294	974	308	212	209	144	1.05	.97	85	47	159	3.7	272	151	13	7	99	68
137	1405.7	9.6	4.4	38.6	17.5	1308		1130	882	386	470	1293	973	297	204	201	139	1.04	.98	93	52	160		277	154	15	8	96	66
138	1409.2	9.6	4.4	38.7	17.5	1305	981	1128	880	378	465	1293	973	297	204	203	141	1.05	.97	92	51	159		276	153	12	7	94	65
139	1417.2	9.5	4.3	38.6	17.5	1308	982	1133	884	379	466	1295	975	293	202	203	141		.98	98	54	160		278	154	13	7	90	62
140	1418.9	8.0	3.6	33.2	15.0	1307	982	1142	889	365	458	1294	974	242	167	169	117		.93	138	77	153	3.6	305	169	13	7	73	50
141	1419.2	7.8	3.5	33.0	14.9	1311	983	1144	890	364	457	1289	971	236	166	166	115		.97	143	79	158	3.7	303	168	22	12	70	48
142	1419.3	7.6	3.4	33.3	15.1	1308	982	1151	894	361	456	1294	974	230	158	159	110		.94	155	86	153	3.6	315	175	14	8	71	49
143	1419.6	7.6		29.4	13.3	1308	982	1133	884	367	459	1291	972	224	154	160	111	1.03	.92	142	79	153	3.6	311	173	17	9	64	44
144	1421.2	7.5		29.6	13.4	1306	981	1131	883	366	458	1293	973	227	156	159	110	1.06	.94	137	76	155	3.6	314	174	13	7	68	47
145	1425.2			29.3	13.3	1305	981	1133	884	365	458	1294	974	226	157	157	109	1.04	.91	141	78	151	3.5	315	175	11	6	69	48
146	1433.2			29.4	13.3	1304		1134	884	360	455	1293	973	224	154	159	110	1.05	.90	143	79	150	3.5	314	174	11	6	65	45
147	1441.3			29.5	13.4	1304		1132	883	374	463	1288	970	225	155	158	110	1.05	.92	139	77	152	3.5	310	172	16	9	67	46
148	1443.2	7.8	3.5	29.5	13.4	1305		1126	880	414	486	1289	971	237	163	166	115	1.05	.93	125	69	153	3.6	303	168	16	9	71	49

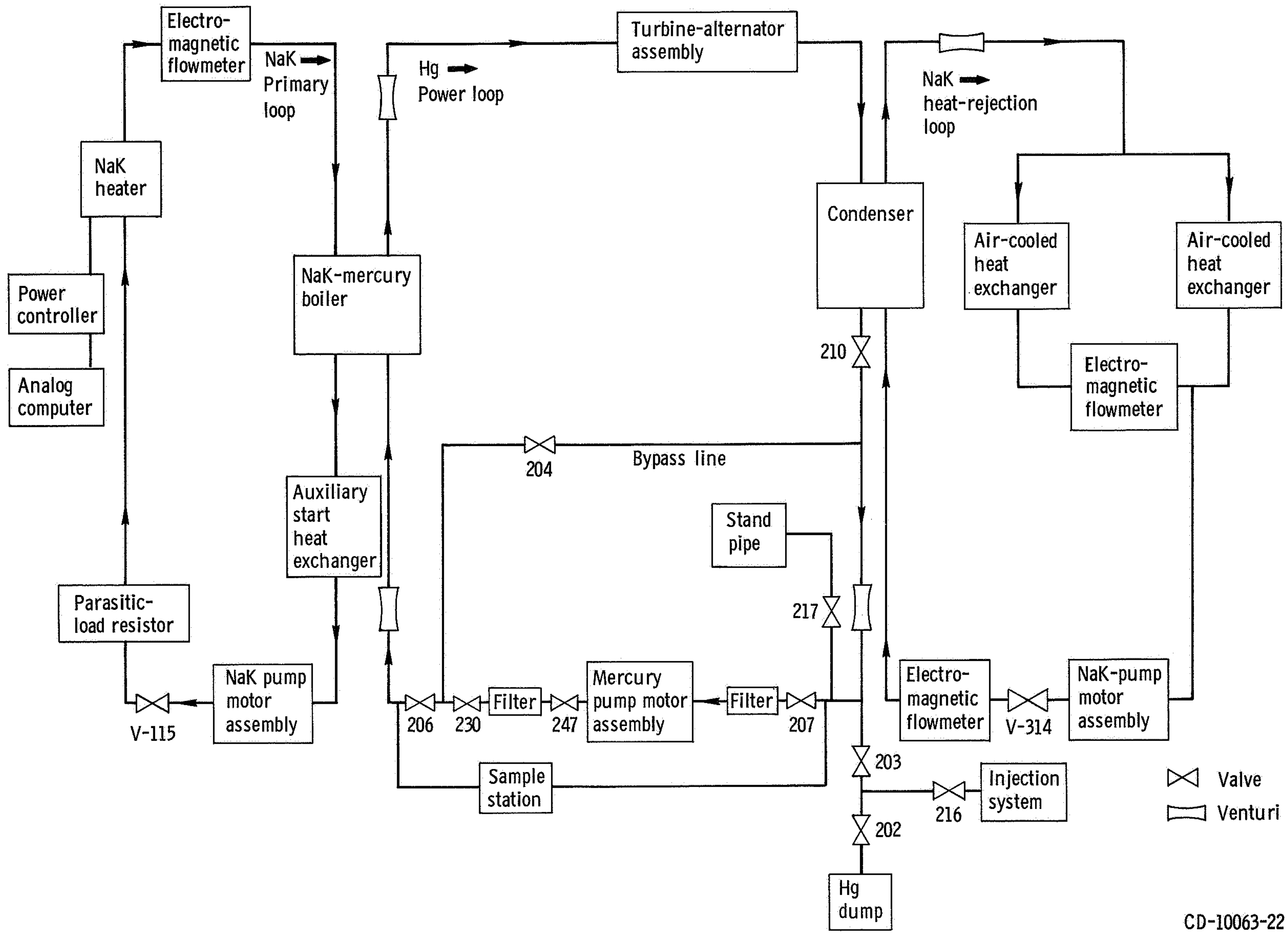


Figure 1. - Schematic of SNAP-8 test facility.

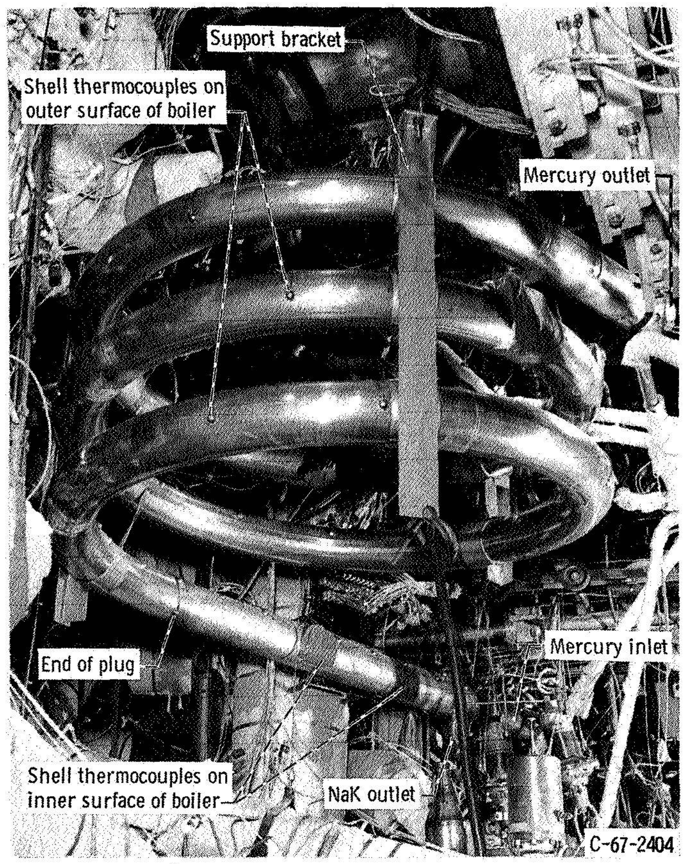
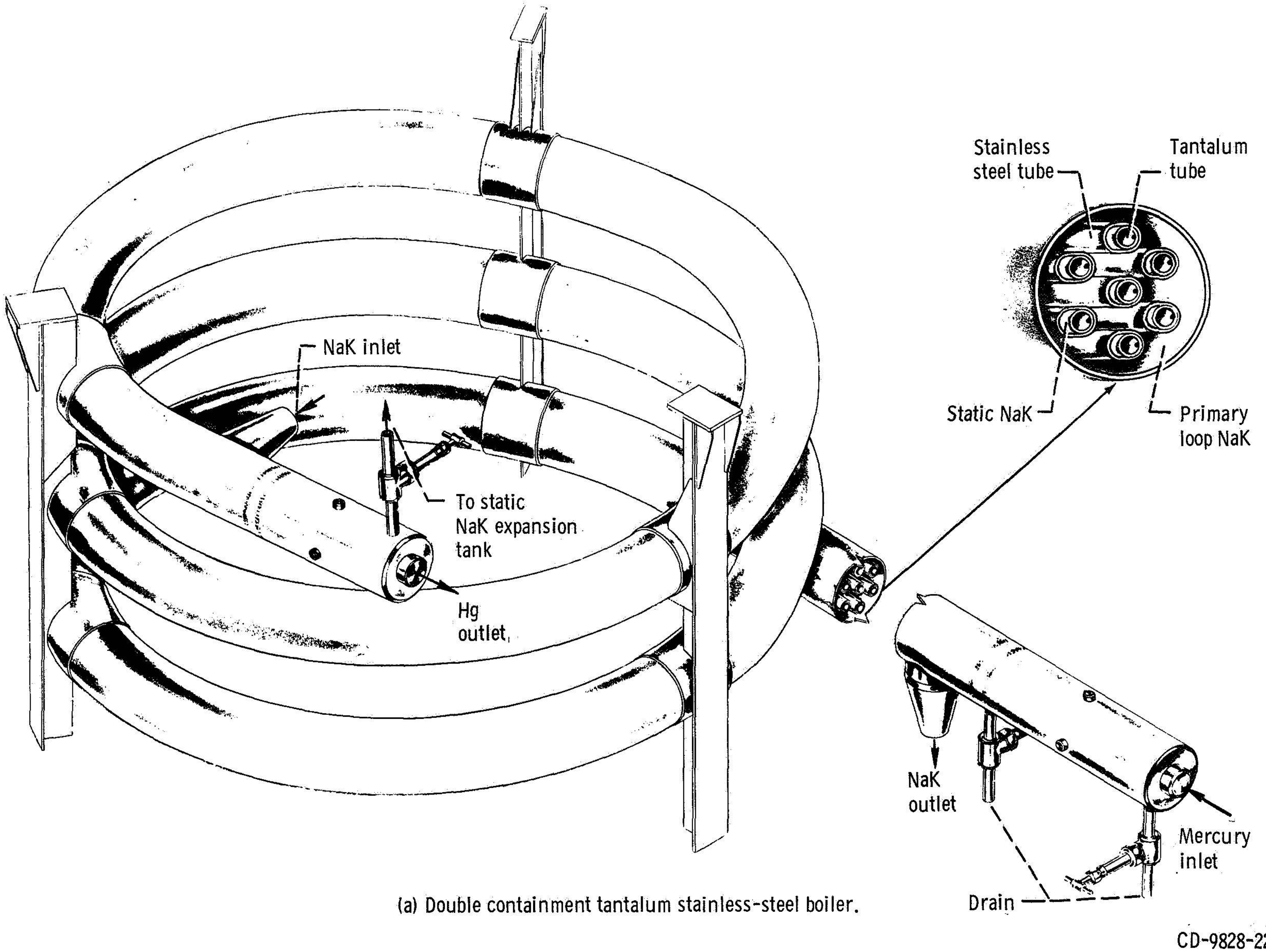
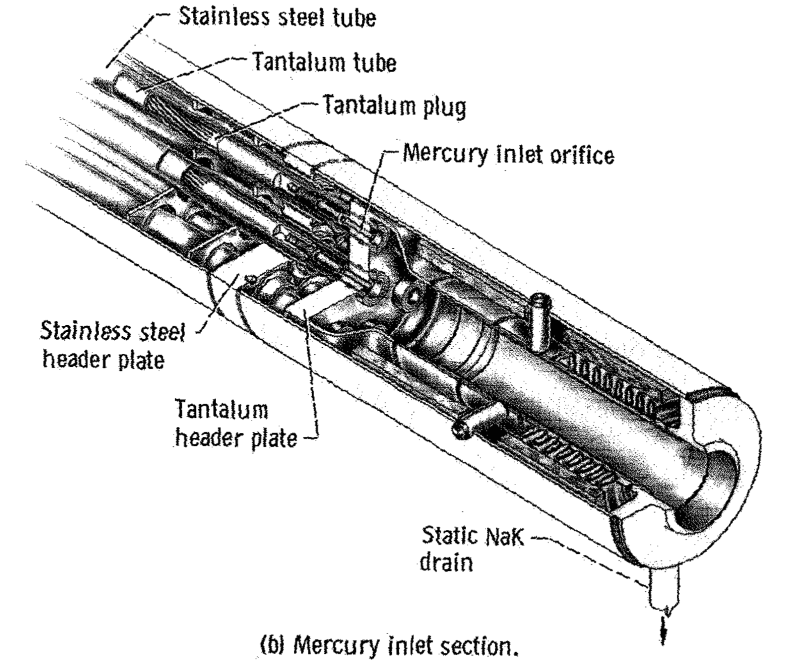


Figure 2. - Boiler installed in system.



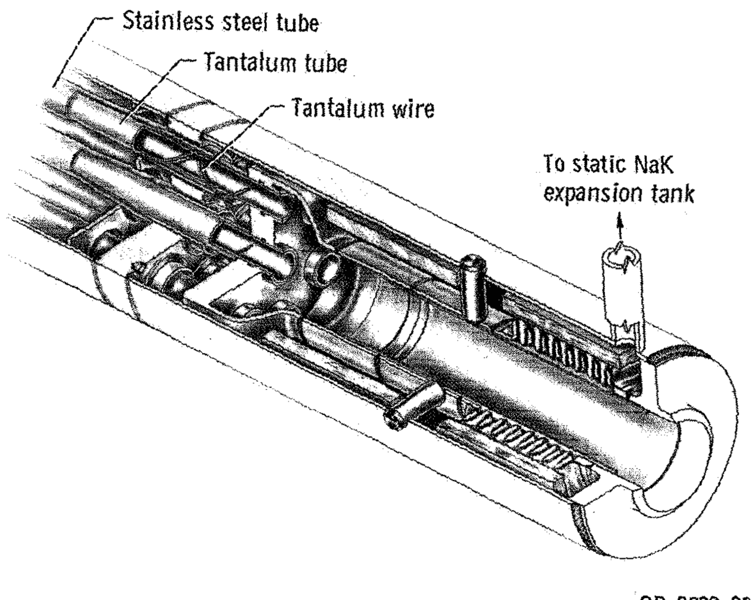
(a) Double containment tantalum stainless-steel boiler.

Figure 3. - SNAP-8 boiler configuration.



(b) Mercury inlet section.

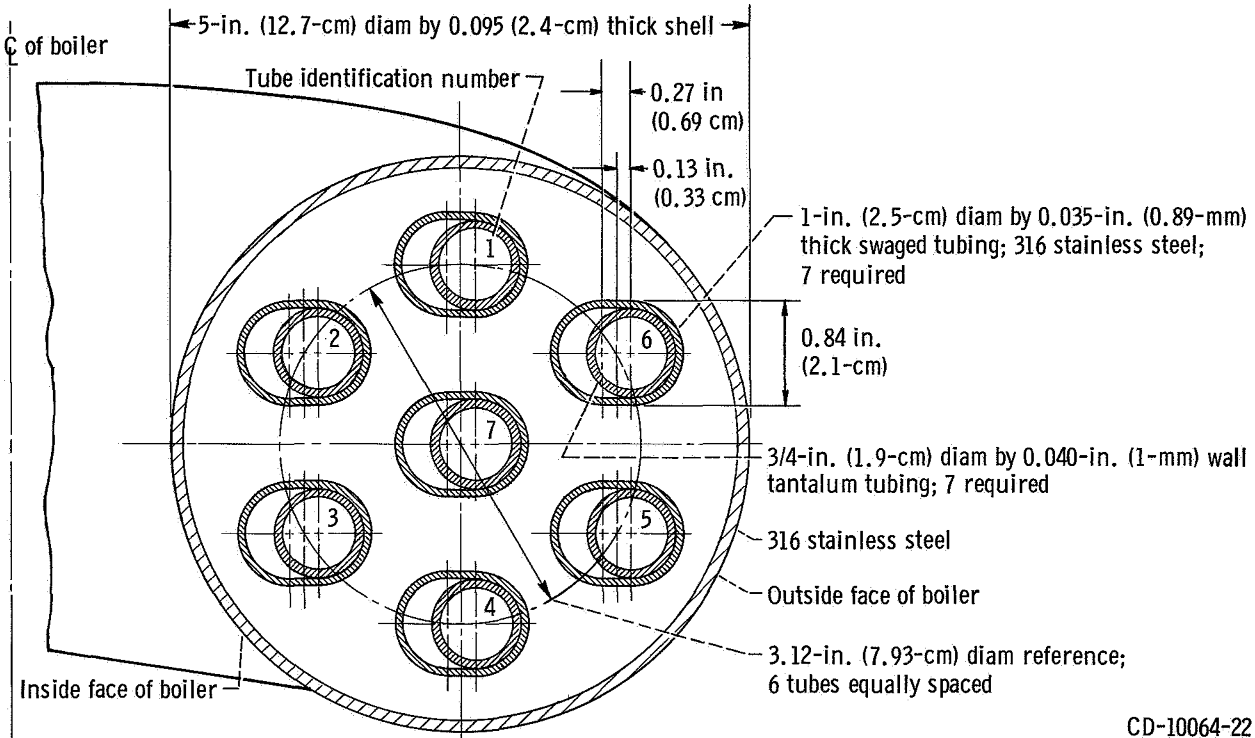
CD-9829-22



CD-9830-22

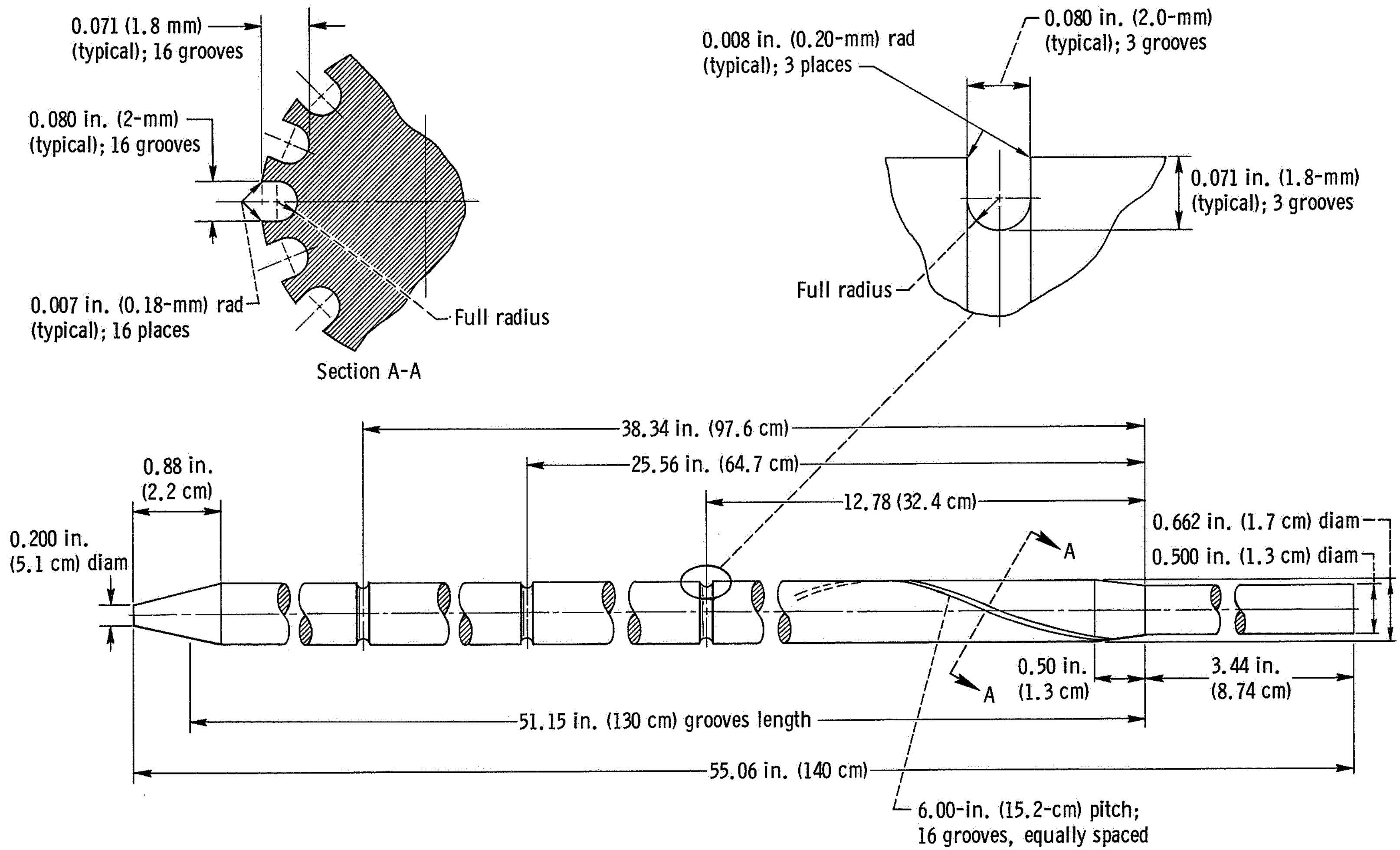
(c) Mercury outlet section.

Figure 3. - Concluded.



(a) Cross section of boiler tube bundle configuration taken in direction of mercury flow at plug exit (before initiation of test).

Figure 4. - SNAP-8 boiler details.



(b) Multifluted boiler plug. Plug material, tantalum.

CD-10065-22

Figure 4. - Concluded.

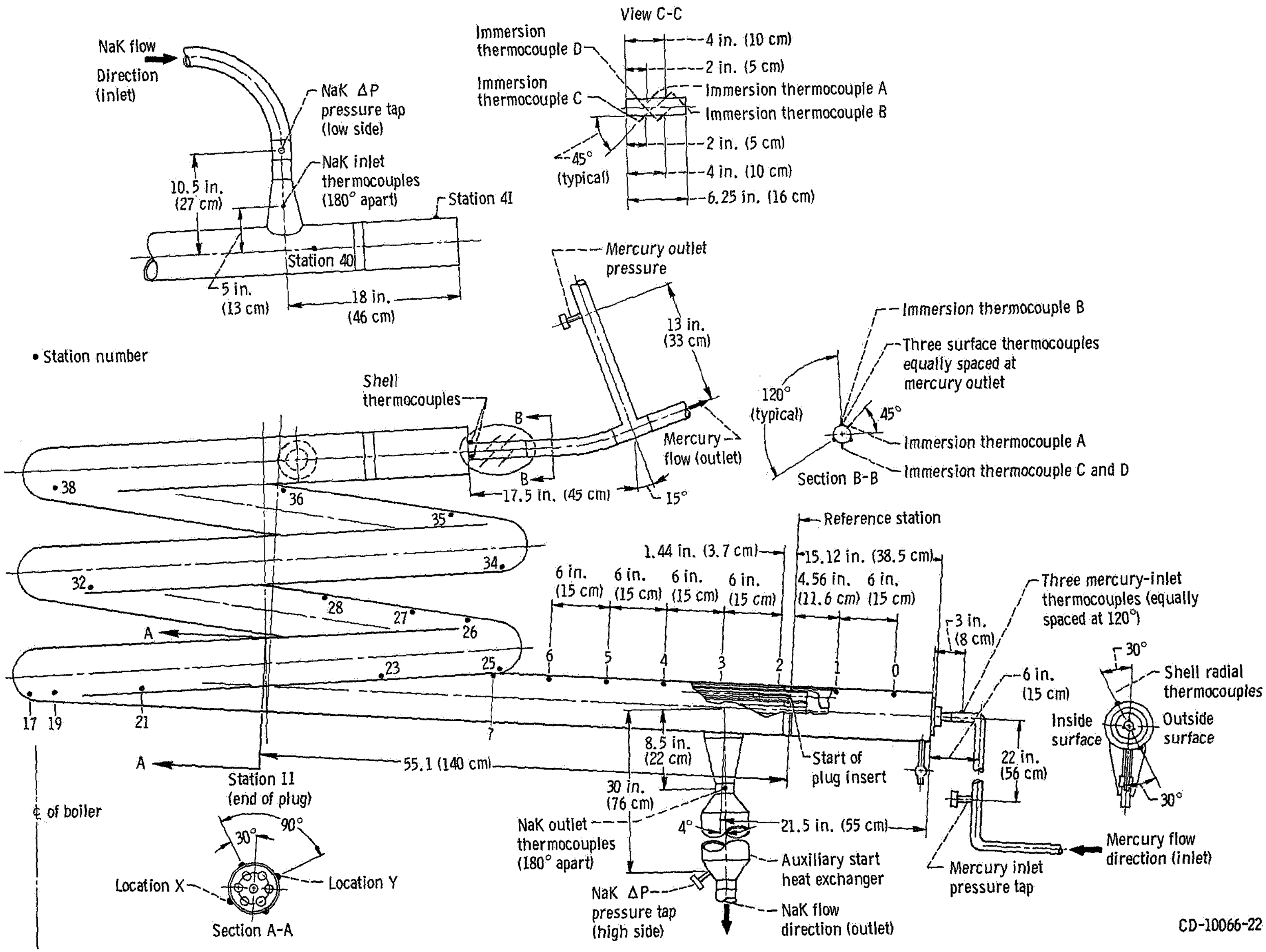


Figure 5. - Boiler instrumentation.

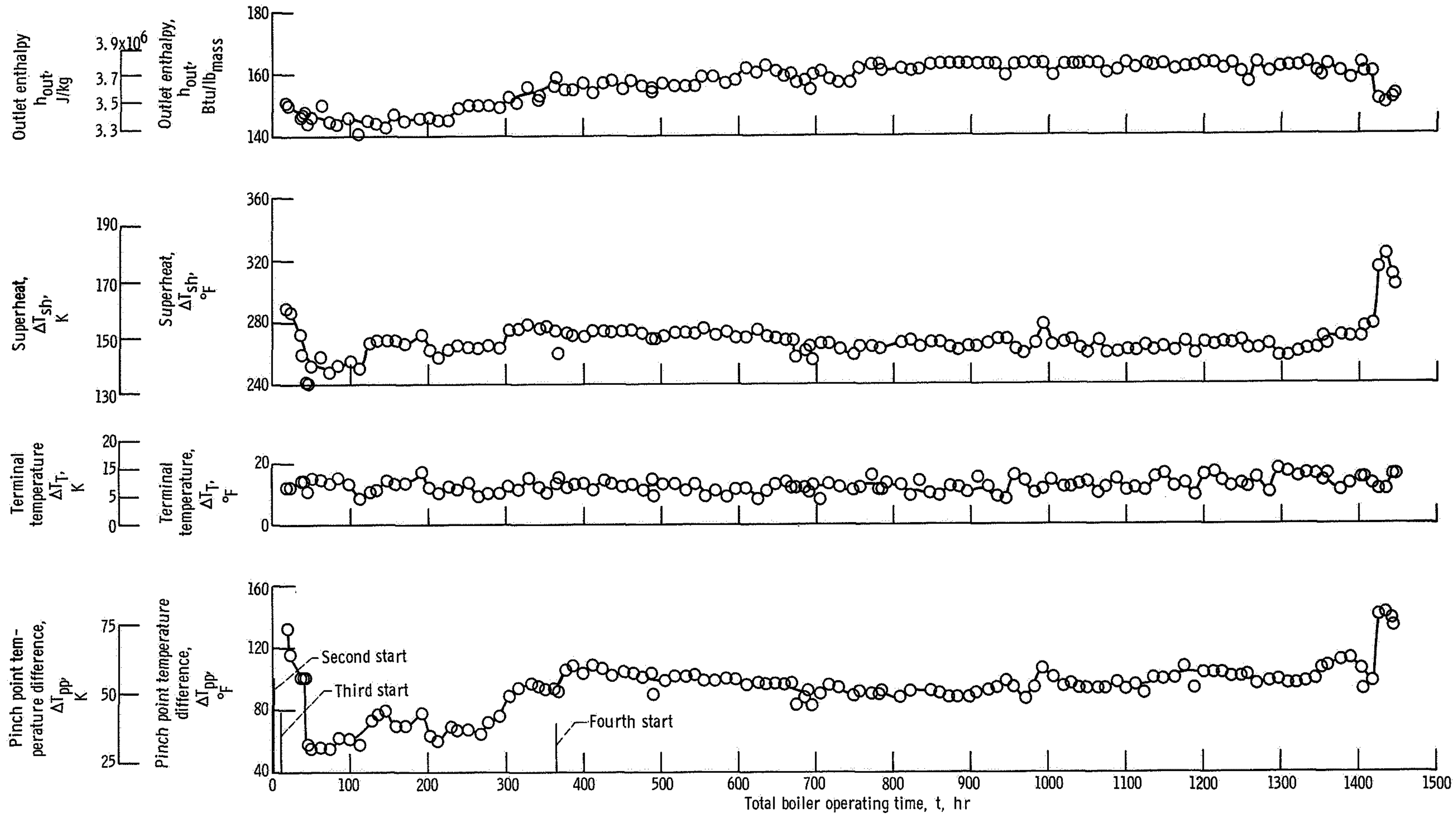


Figure 6. - Variation of parameters during boiler history.

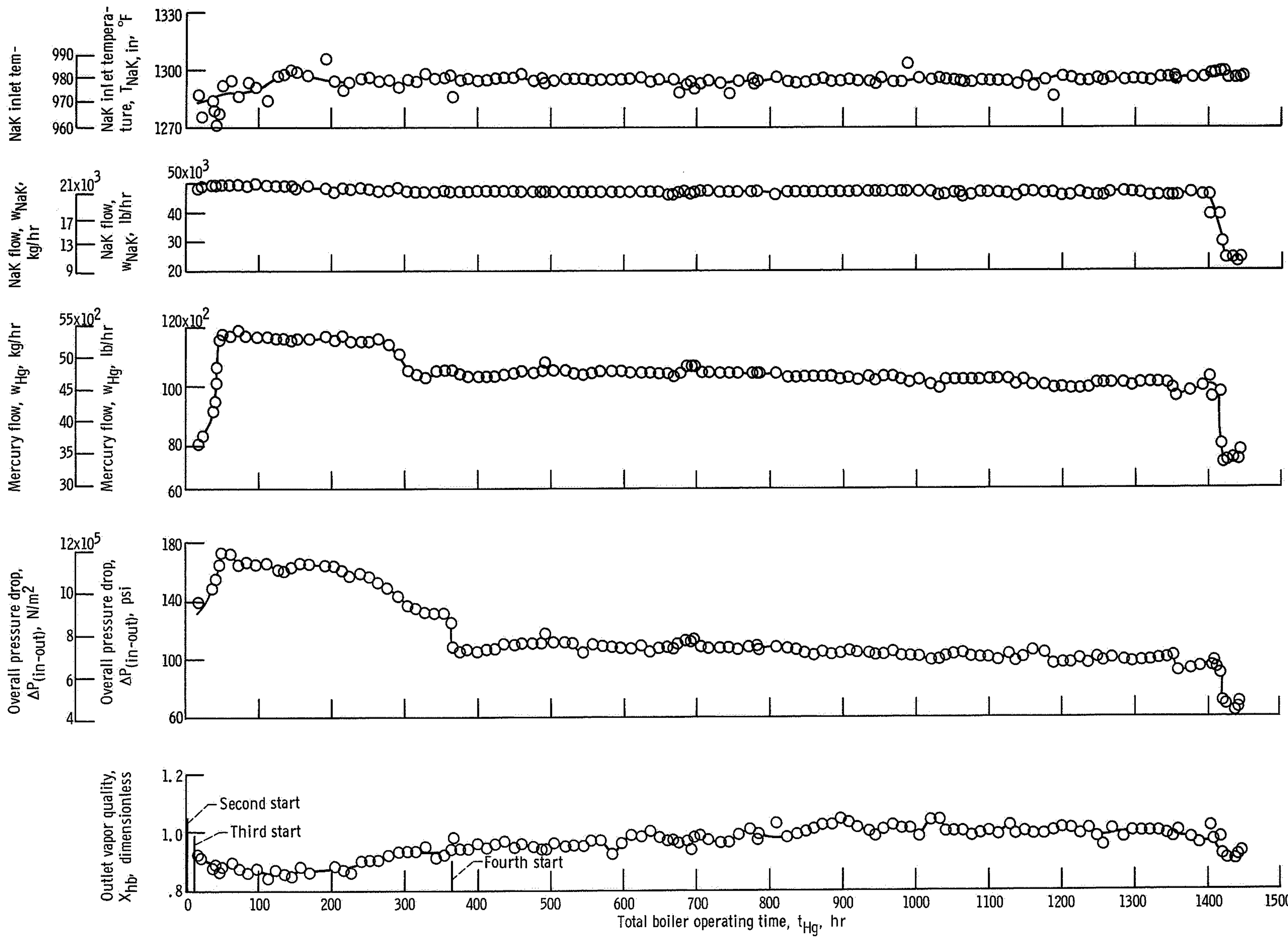


Figure 7. - Variation of parameters during boiler history.

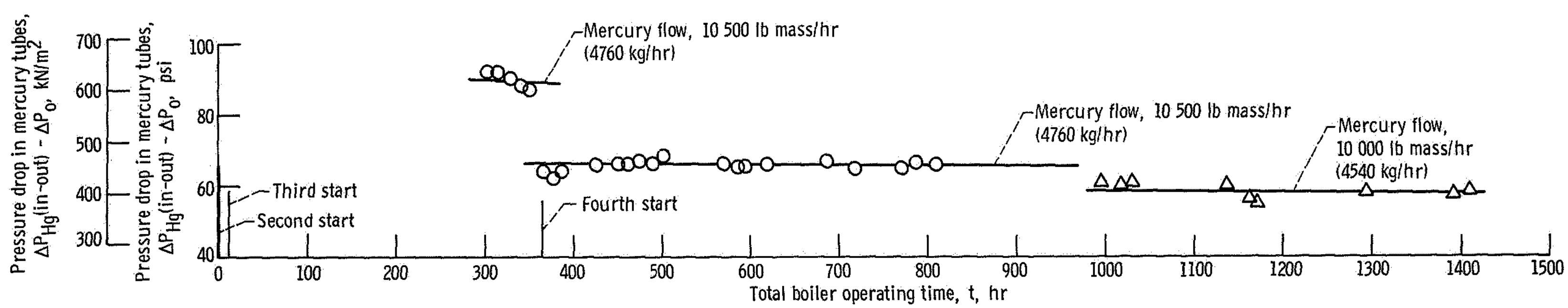


Figure 8. - Variation in boiler pressure drop during boiler history for constant mercury flow. NaK flow, 47 500 pounds per hour (21 500 kg/hr).

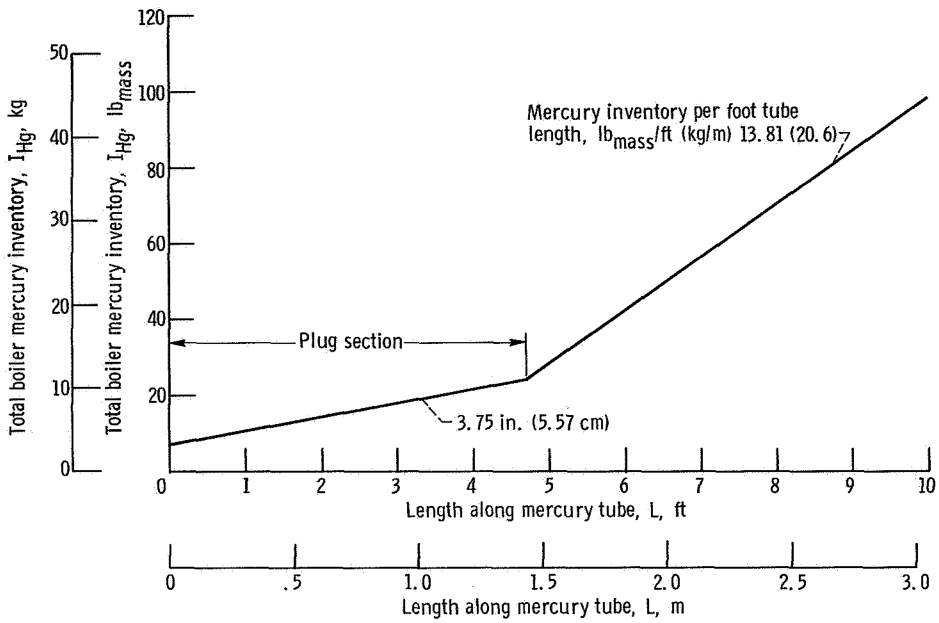


Figure 9. - Plot of calculated total boiler inventory against length along mercury tube.

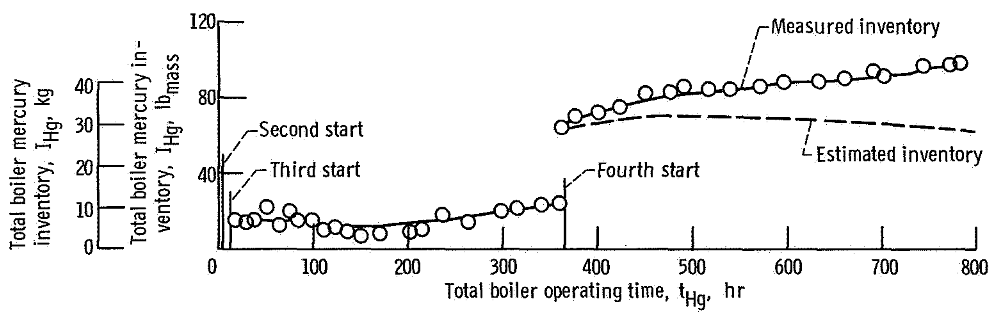


Figure 10. - Variation of total boiler inventory during boiler history.

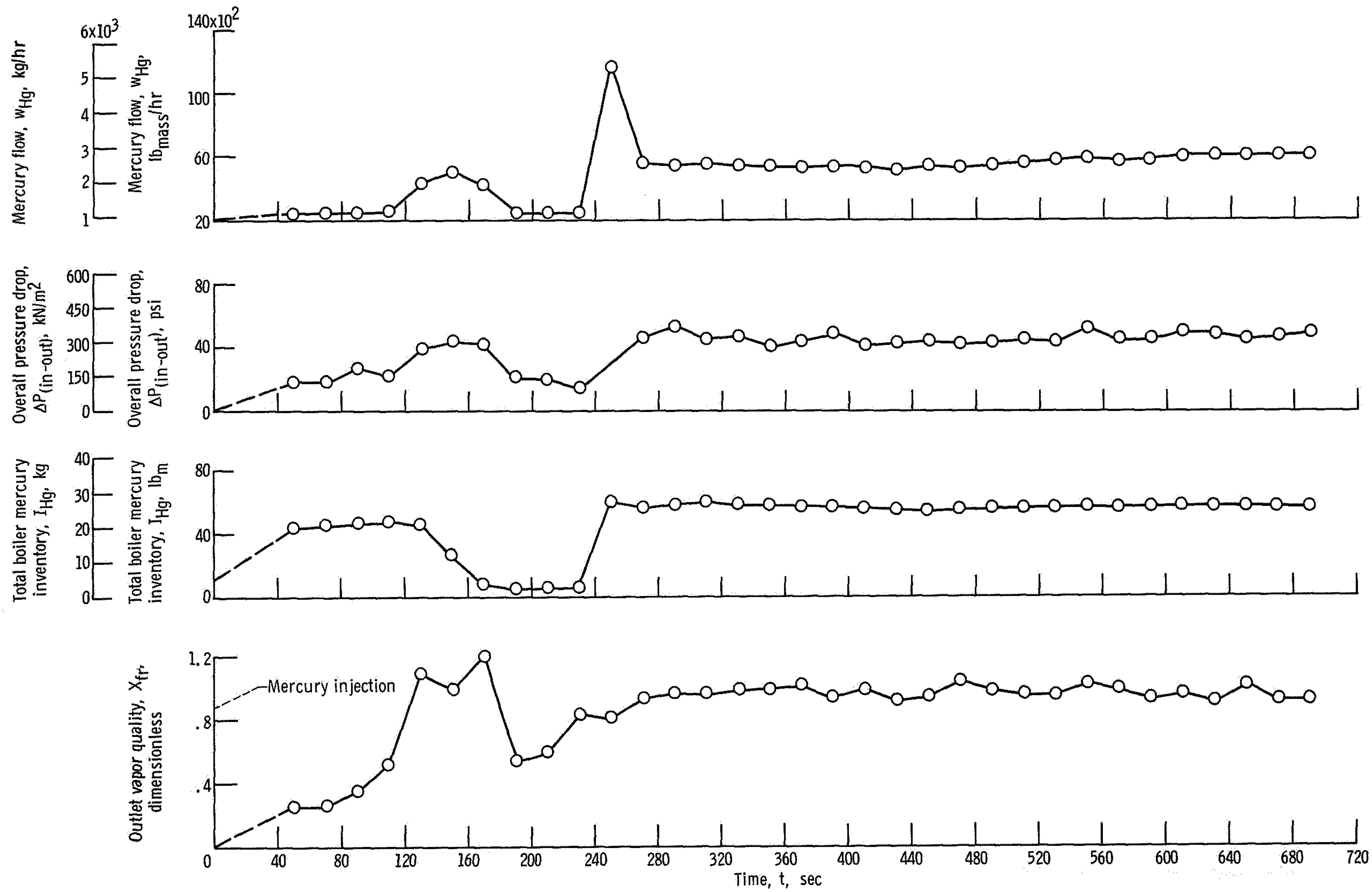


Figure 11. - Boiler parameters during fourth start.

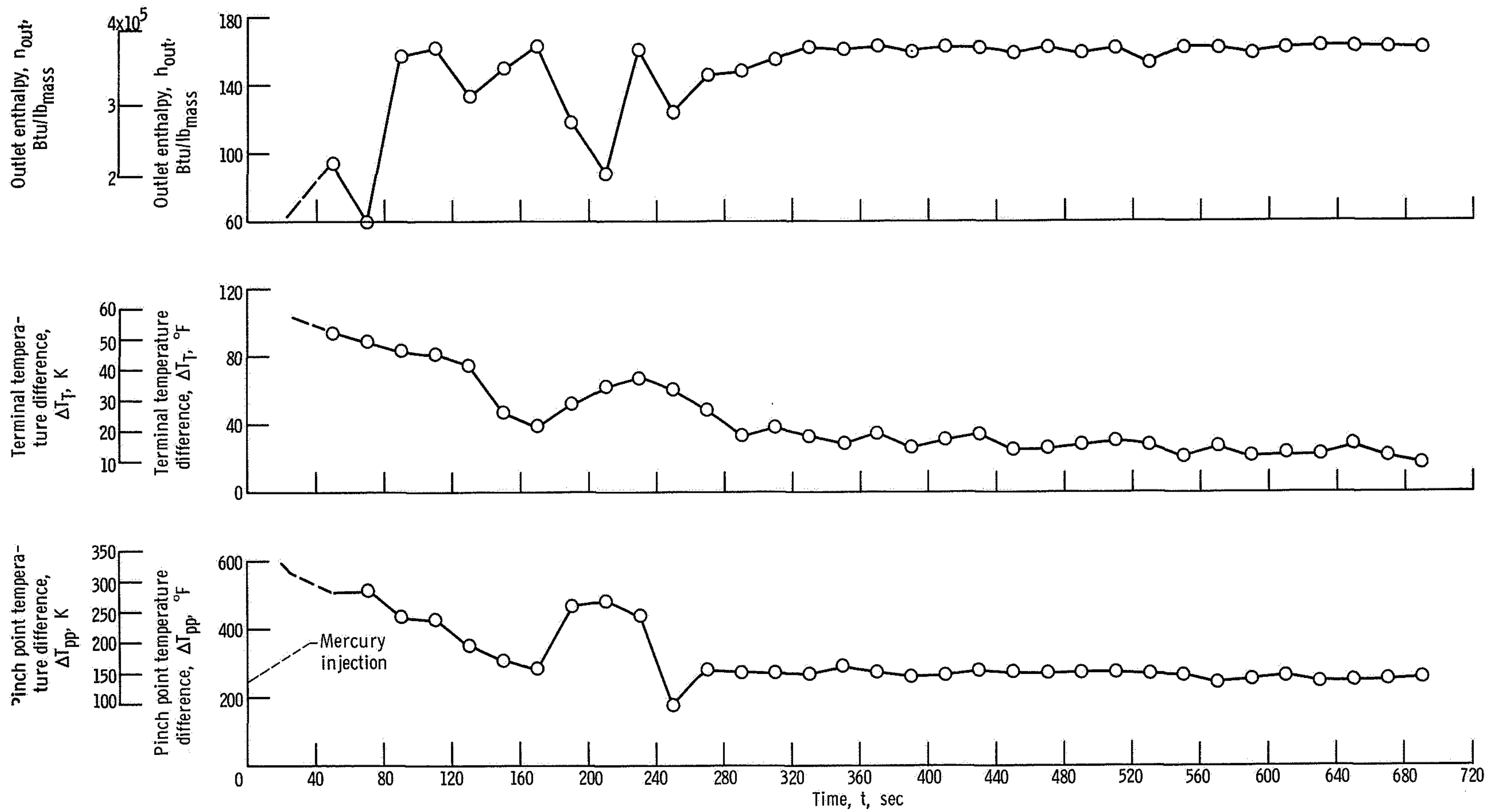
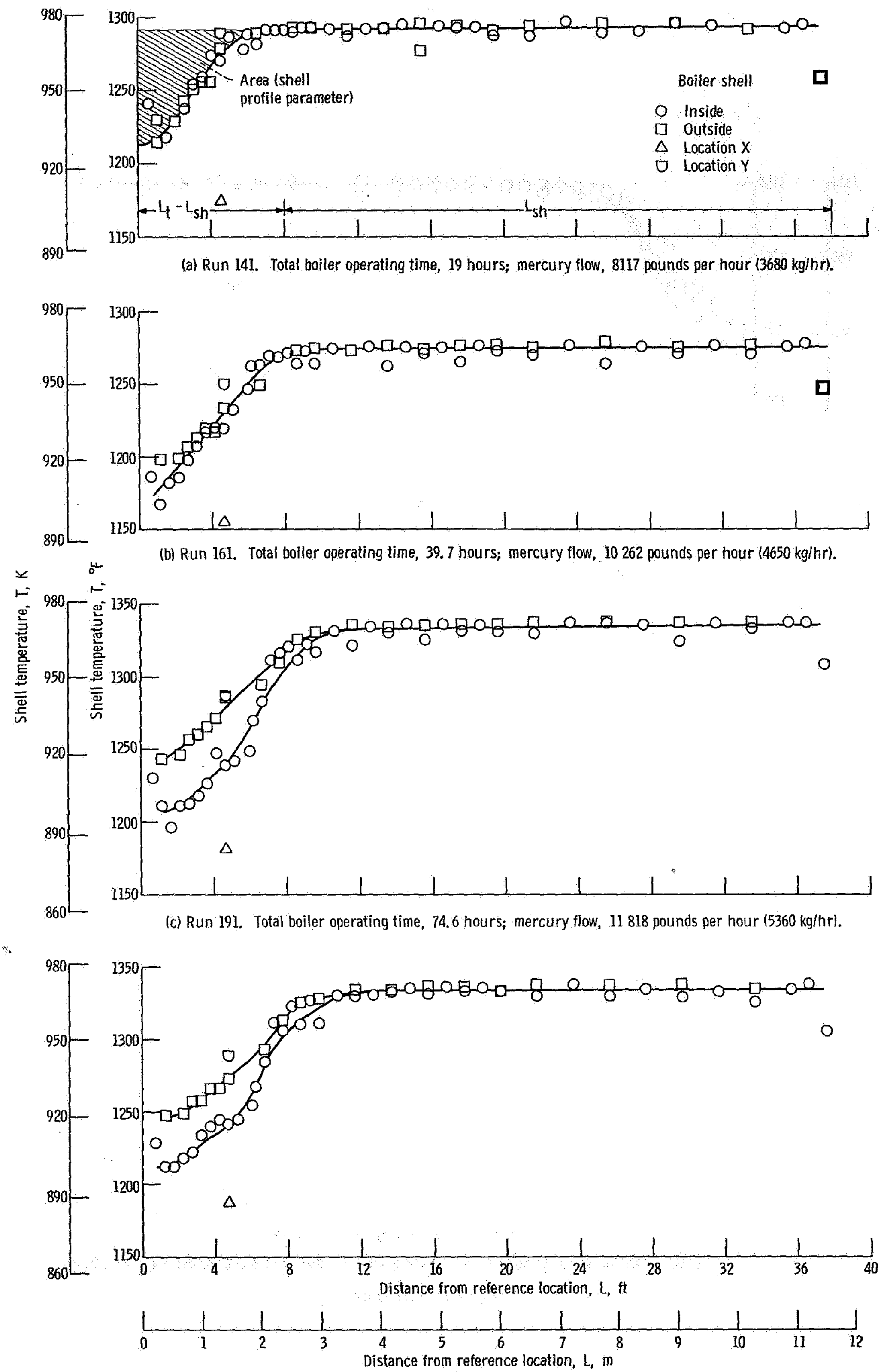


Figure 11. - Concluded.



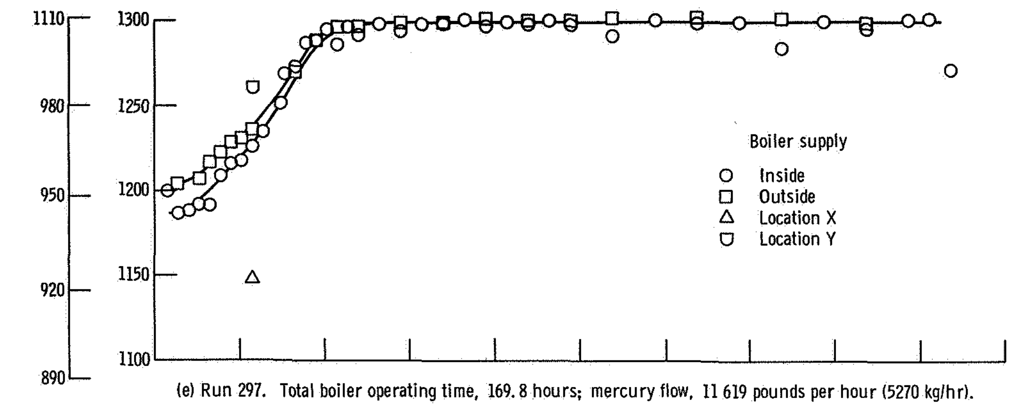
(a) Run 141. Total boiler operating time, 19 hours; mercury flow, 8117 pounds per hour (3680 kg/hr).

(b) Run 161. Total boiler operating time, 39.7 hours; mercury flow, 10 262 pounds per hour (4650 kg/hr).

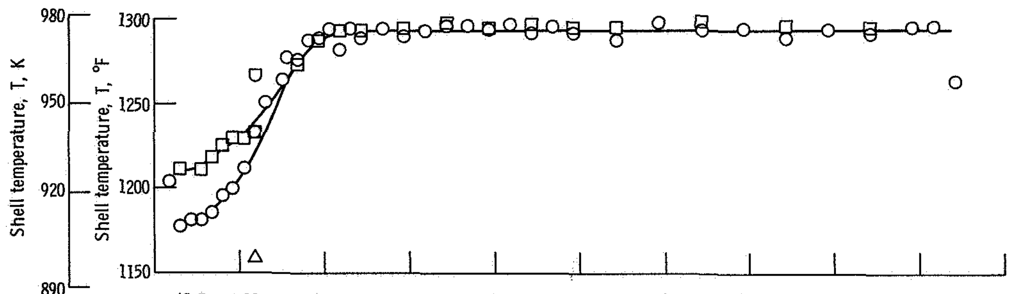
(c) Run 191. Total boiler operating time, 74.6 hours; mercury flow, 11 818 pounds per hour (5360 kg/hr).

(d) Run 227. Total boiler operating time, 111.6 hours; mercury flow, 11 707 pounds per hour (5310 kg/hr).

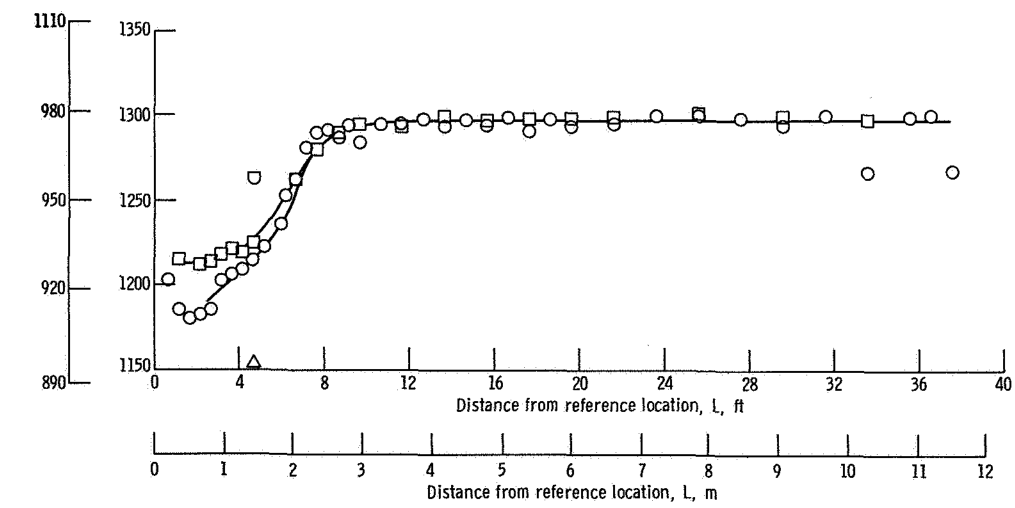
Figure 12. - Typical NaK temperature profiles during boiler history.



(e) Run 297. Total boiler operating time, 169.8 hours; mercury flow, 11 619 pounds per hour (5270 kg/hr).

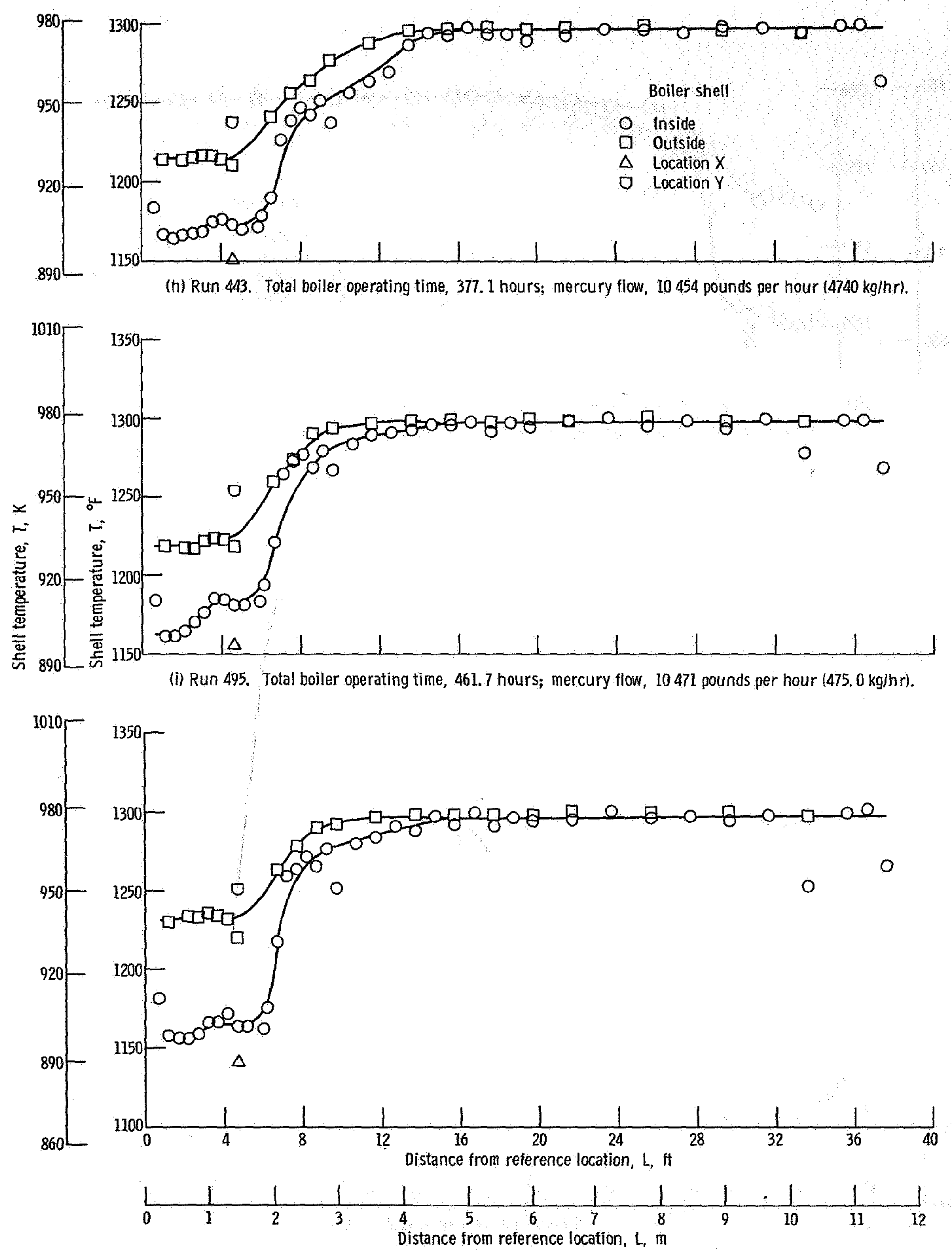


(f) Run 391. Total boiler operating time, 303.1 hours; mercury flow, 10 557 pounds per hour (4790 kg/hr).



(g) Run 423. Total boiler operating time, 362.7 hours; mercury flow, 10 563 pounds per hour (4790 kg/hr).

Figure 12. - Continued.

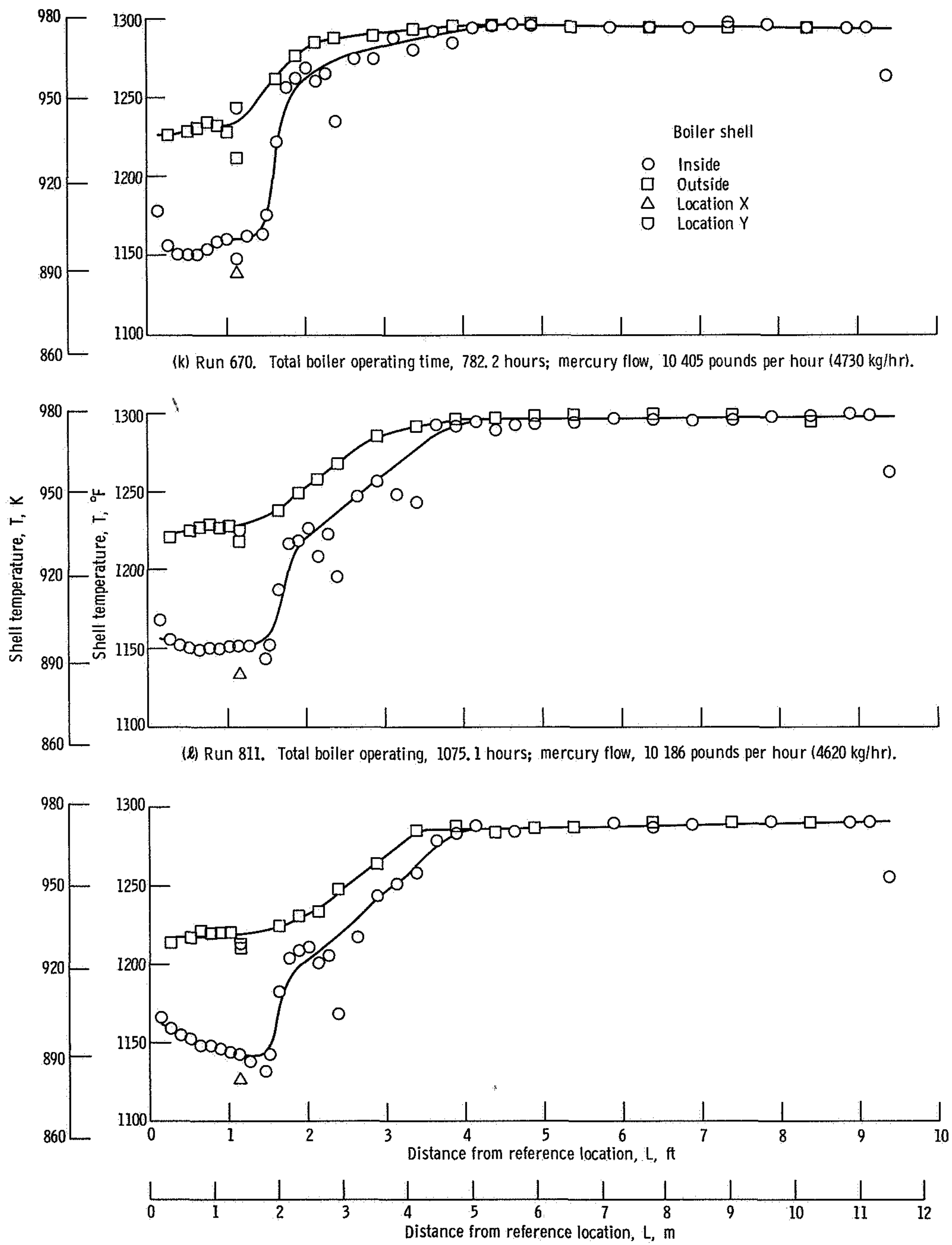


(h) Run 443. Total boiler operating time, 377.1 hours; mercury flow, 10 454 pounds per hour (4740 kg/hr).

(i) Run 495. Total boiler operating time, 461.7 hours; mercury flow, 10 471 pounds per hour (475.0 kg/hr).

(j) Run 592. Total boiler operating time, 648 hours; mercury flow, 10 398 pounds per hour (4730 kg/hr).

Figure 12. - Continued.

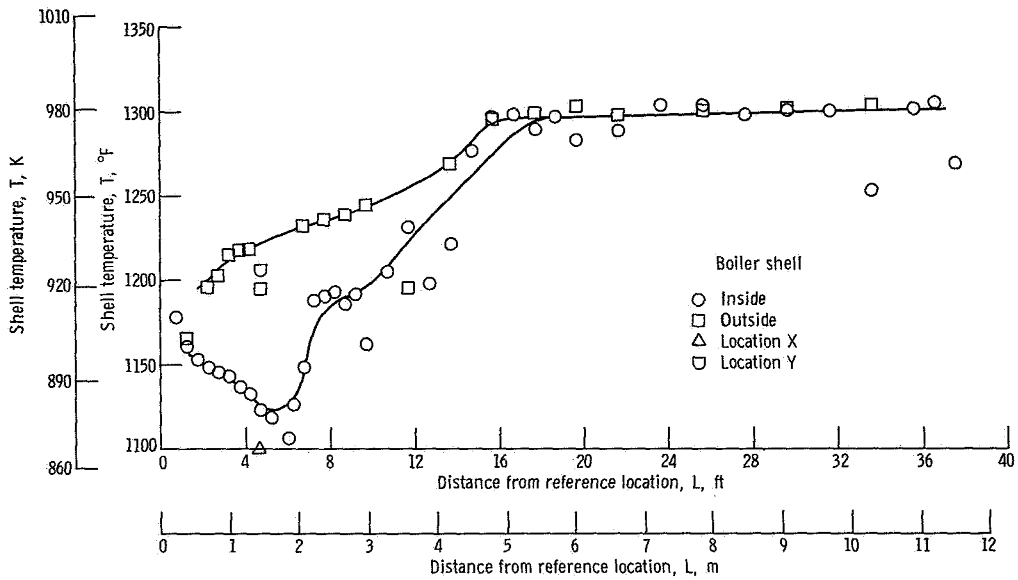


(k) Run 670. Total boiler operating time, 782.2 hours; mercury flow, 10 405 pounds per hour (4730 kg/hr).

(ℓ) Run 811. Total boiler operating, 1075.1 hours; mercury flow, 10 186 pounds per hour (4620 kg/hr).

(m) Run 870. Total boiler operating time, 1187.1 hours; mercury flow, 9922 pounds per hour (4510 kg/hr).

Figure 12. - Continued.



(n) Run 1008. Total boiler operating time, 1443.2 hours; mercury flow, 7863 pounds per hour (3570 kg/hr).

Figure 12. - Concluded.

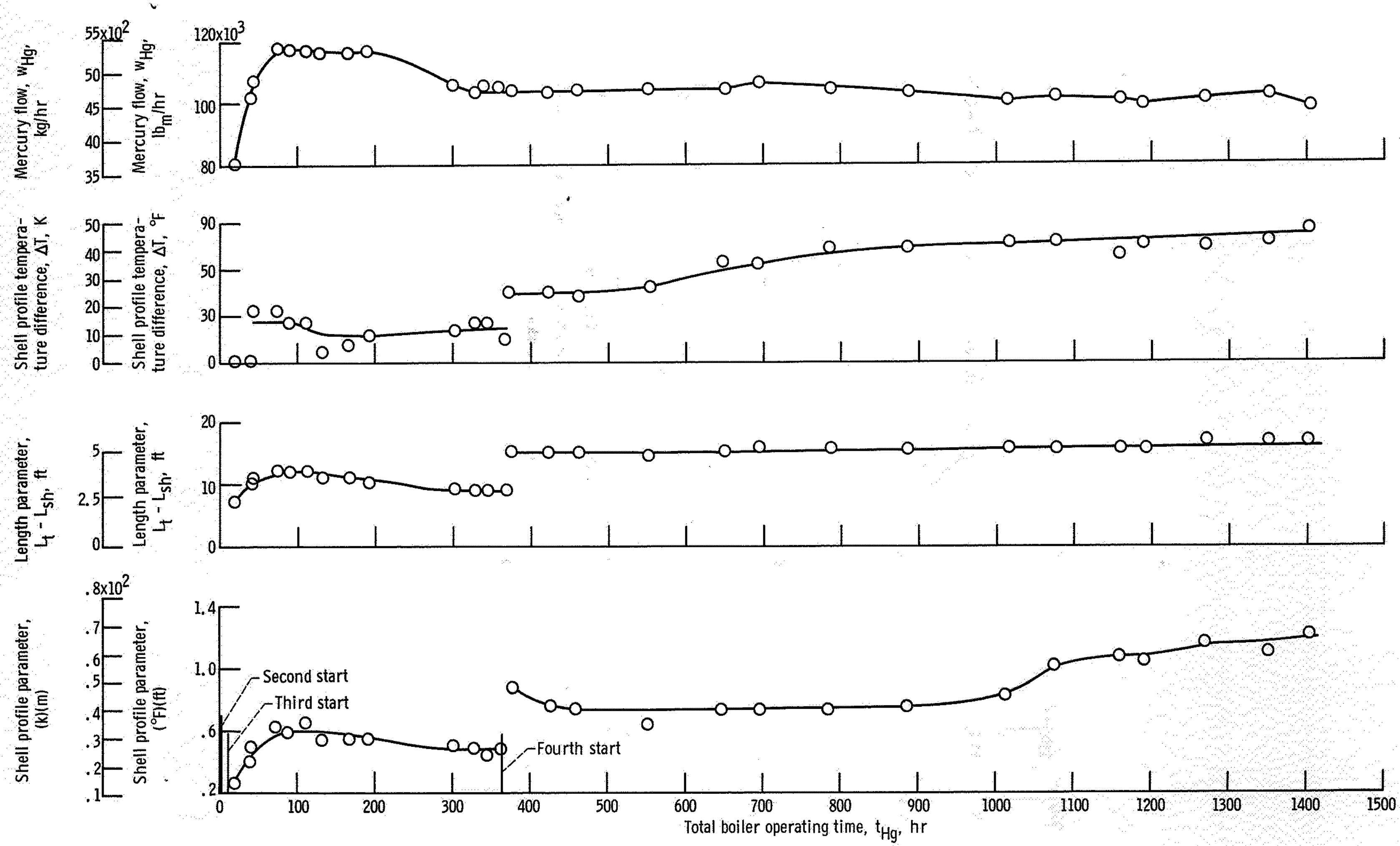
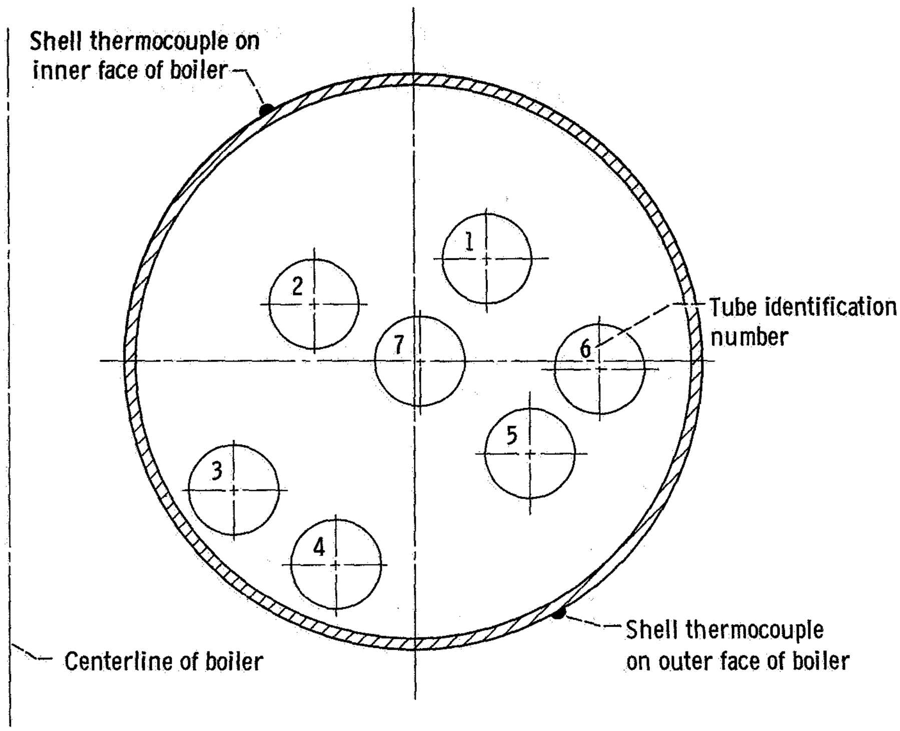


Figure 13. - Profile parameters during boiler history.



CD-10067-22

Figure 14. - Sketch of tube bundle configuration from X-rays taken after completion of testing. Flow of mercury is into plane of diagram. Cross section of tube bundle at end of plug region.

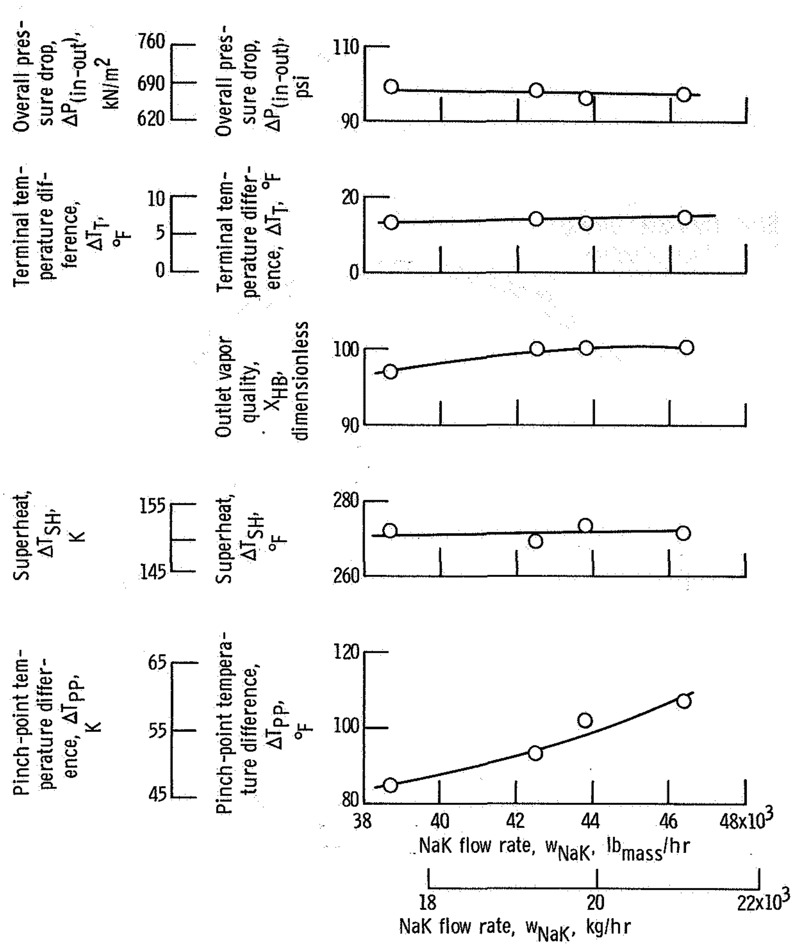


Figure 15. - Effect of NaK flow rate on boiler performance. Total boiler operating time, 1402 to 1405 hours; mercury flow, 10 200 pounds per hour (4640 kg/hr). NaK inlet temperature 1300 K (980 K).

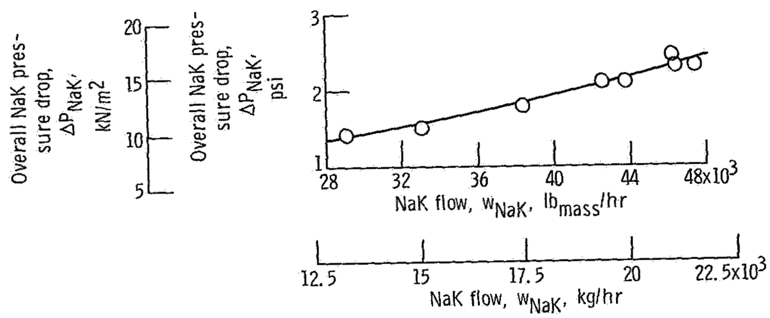


Figure 16. - NaK pressure drop as function of NaK flow rate.

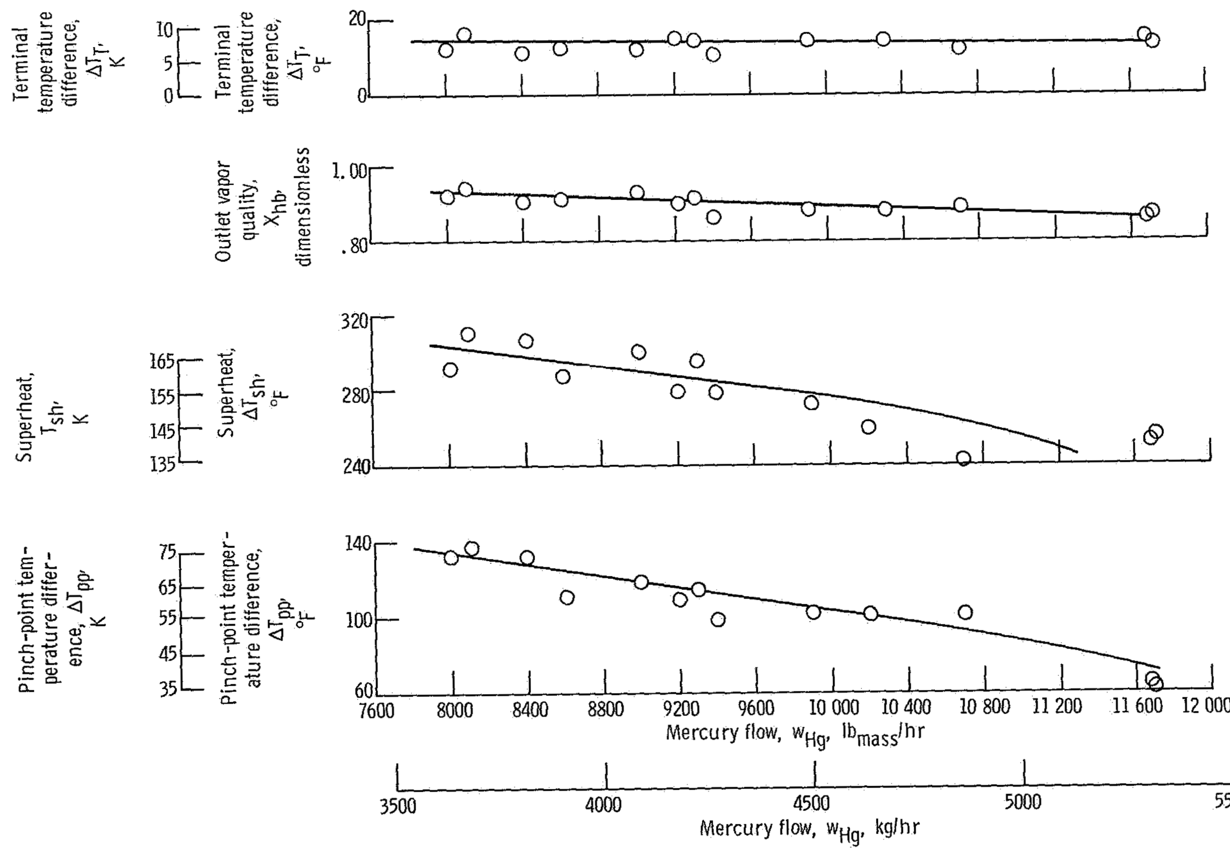
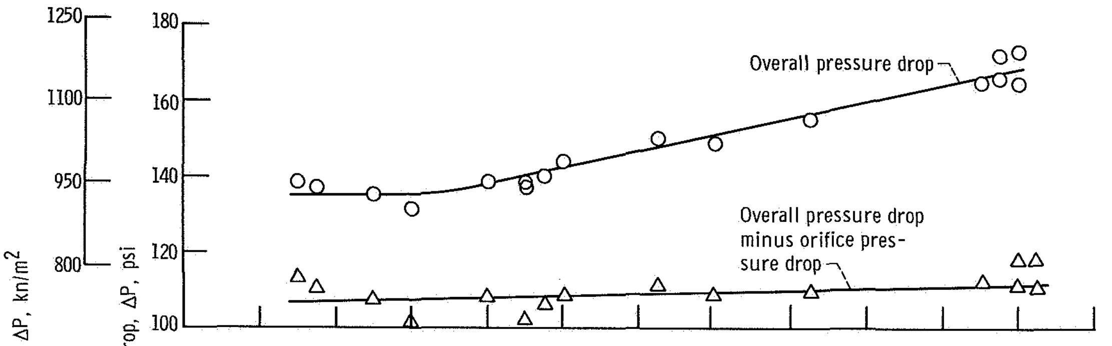
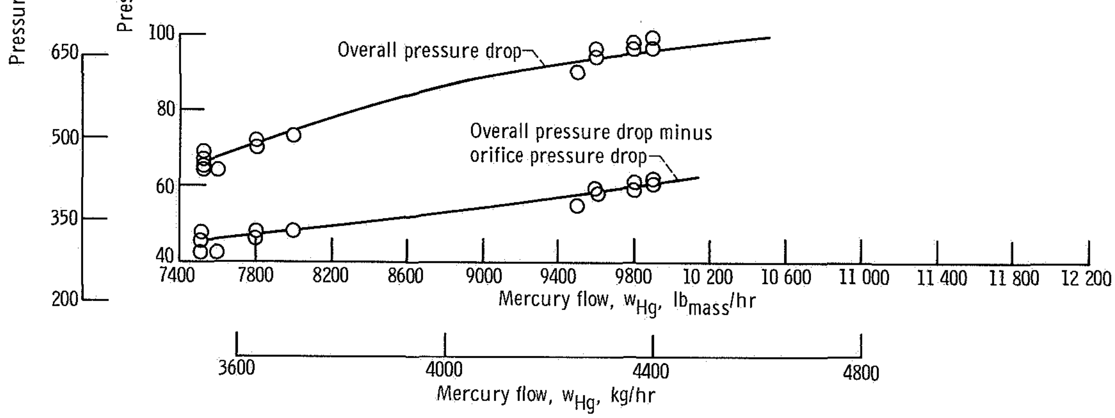


Figure 17. - Effect of mercury flow on boiler performance. Total boiler operating time, 18 to 100 hours; NaK flow, 48 500 pounds per hour. (22 000 kg/hr); NaK inlet temperature, 1300° F (980 K).



(a) Runs 1 to 17. Total boiler operating time, 18 to 86 hours; NaK flow, 48 750 pounds per hour (22 200 kg/hr).



(b) Runs 132 to 148. Total boiler operating time, 1389 to 1443 hours.

Figure 18. - Effect of mercury flow on pressure drop for NaK inlet temperature of 1300° F (980 K).

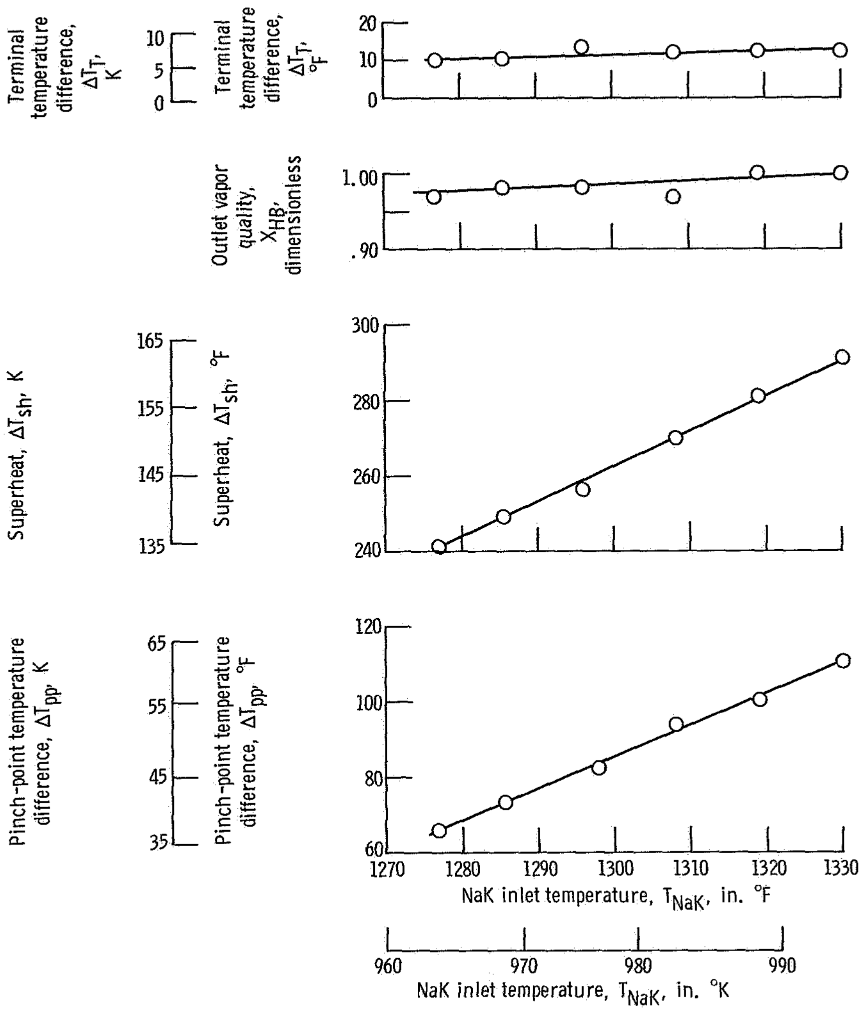


Figure 19. - Effect of NaK-inlet temperature on boiler performance. Total boiler operating time 692 to 697 hours, mercury flow, 10 600 pounds per hour (4800 kg/hr); NaK flow, 46 500 pounds per hour (21 100 kg/hr).

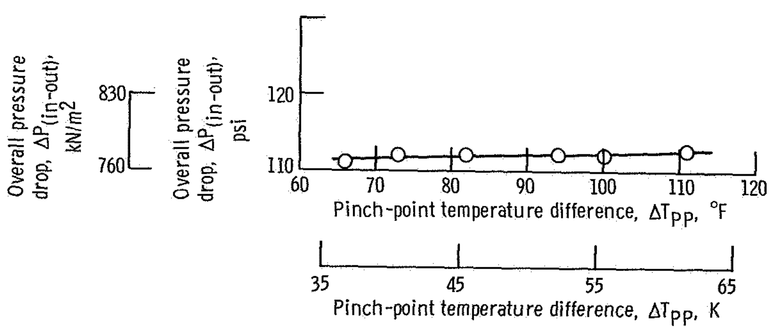


Figure 20. - Variation of overall pressure drop with pinch-point temperature for constant flow conditions. Mercury flow, 10 600 pounds per hour (4800 kg/hr); total boiler operating time, 692 to 697 hours.

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546