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DESIGN, FABRICATION, AND PRELIMINARY EVALUATION OF THERMAL AND HYDRAULIC PERFORMANCE OF A PROTOTYPE SNAP-8 MERCURY BOILER

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16. Abstract

A prototype SNAP-8, tantalum/stainless-steel, double-containment mercury boiler, designated Serial Number 4, was fabricated at Lewis Research Center and successfully tested in the Power Conversion System loop at the Aerojet Nuclear Systems Company, Azusa, California, for a total of 1620 hours and 26 thermal cycles. This boiler design embodied the same basic tube-bundle configuration as earlier units but included the following significant improvements: the elimination of the expansion bellows by the use of improved tantalum/stainless-steel bimetal joints; full coiling for more compactness; and a more uniform shell-side NaK flow distribution. The thermal-hydraulic performance of this boiler fully met the SNAP-8 system requirements.

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SUMMARY

The SNAP-8 (Systems for Nuclear Auxiliary Power) Program has successfully utilized tantalum as the mercury-containment material in a multitube, counterflow boiler. Four units, which were designed and fabricated at the Lewis Research Center, have been extensively tested in various component and system loops and have accumulated over 25 400 hours of operation. The first three of these assemblies were of a common design. The fourth unit, designated Serial Number 4, was redesigned to incorporate changes which were considered desirable in providing a margin to meet the system requirements. These changes included the following:

(1) The boiler length was decreased from 11.3 meters (37 ft) to 7.6 meters (25 ft) and the inlet plug length was lessened from 132 centimeters (52 in.) to 107 centimeters (42 in.). This optimization of boiler tube and inlet plug lengths, in conjunction with other changes mentioned later, resulted in a savings of 27.6 newtons per square centimeter (40 psi) in two-phase pressure drop without any change in overall thermal performance.

(2) Significant changes were made to the heating-fluid flow geometry to improve mixing of the NaK and to reduce the NaK pressure drop from 2.4 newtons per square centimeter (3.5 psi) to 1.7 newtons per square centimeter (2.5 psi).

(3) The bellows, which was originally included to accommodate the differential thermal expansion between the straight tantalum and stainless-steel tubes at the boiler mercury inlet of the first three boiler assemblies, was eliminated, thereby permitting full coiling of the boiler for compactness.

(4) Orifice and tube/plug assemblies were individually calibrated and matched for uniform pressure drop.

(5) A new and more reliable bimetal (tantalum/stainless steel) joint was used on the Serial Number 4 boiler assembly. This joint is an adaptation of a heavy-walled, coextruded bimetal tube.

(6) The tantalum tube/plug assemblies were coiled as required for boiler compactness without excessive local deformation (bulging) of the tube wall at the plug end due to end stiffness affects of the plug.

(7) The coextruded bimetal tubing joints were electron-beam welded to the boiler stainless-steel end flanges without any sign of joint degradation.

(8) The thermal and hydraulic performance of the prototype boiler fully met the SNAP-8 system performance and stability requirements.

INTRODUCTION

SNAP-8 (System for Nuclear Auxiliary Power) is a 35-kilowatt, reactor-heated, turboelectric, mercury Rankine power system for space application. This system, as currently configured, is composed of the four loops shown in figure 1 and described as follows:

(1) The primary loop employs NaK-78 (eutectic sodium-potassium mixture) to cool the nuclear reactor and to transfer the thermal energy to the mercury loop via the boiler.

(2) In the mercury Rankine loop mercury is preheated, boiled, and superheated in the boiler. The thermal energy is converted into mechanical energy as the mercury vapor is expanded through the turbine, which is directly connected to an alternator for electric power generation. The exhaust vapors from the turbine are condensed and subcooled in the condenser and conducted to the pump, which returns the liquid mercury to the boiler.

(3) The heat-rejection loop containing NaK-78 transfers the cycle waste thermal energy from the condenser to the radiator for rejection to space.

(4) The lubrication and coolant loop contains polyphenyl ether (4P3E) that is required to lubricate the ball bearings of the rotating components of the mercury and lubricant/coolant systems and to provide cooling for the electric alternator, NaK motors, and control elements.

One of the major problems in the development of the SNAP-8 system has been the attainment of a long-lived, reliable mercury boiler (refs. 1 to 5). The specific problem areas within the SNAP-8 boiler were the degree and stability of wetting of the mercury heat-transfer surfaces; pressure drop limitations imposed by reactor temperature excursions; and, most important, the corrosion resistance of the mercury containment material. Early SNAP-8 boilers were constructed of the cobalt-based alloy L-605, which had been successfully used for the SNAP-2 boiler. Unfortunately, the higher operational temperatures of the SNAP-8 boiler (978 K (1300° F) against 922 K (1200° F) for SNAP-2) resulted in an increased and undesirable rate of corrosion and an embrittlement problem. These adverse characteristics required the consideration of alternate materials, which ultimately resulted in the selection of tantalum as the mercury-containment material.

A concept of double containment of the tantalum portions of the boiler was devised to prevent the possible transfer of radioactive NaK from the primary loop to the mercury loop as the result of a single tube-wall failure (ref. 6). In addition, the double-containment concept prevented contamination of the tantalum from oxides or other impurities possibly contained in the primary NaK. Isolation was attained by the complete envelopment of the tantalum parts with stainless steel. The volume contained between the tantalum and stainless steel was filled with static NaK to effect good heat transfer.

Three boilers of this concept were designed and fabricated at Lewis Research Center. The design, fabrication procedures, and preliminary testing of the Serial Number 1 boiler have been previously reported in reference 6. The three boilers have subsequently been tested successfully over a wide range of operating conditions which encompassed the anticipated SNAP-8 system requirements. The Serial Number 1 unit was tested in an engine loop at Lewis for 1444 hours and in a component test loop at the General Electric Company, Evendale, Ohio, for 13 661 hours (a total of 15 105 hr). No startup tests were performed which involved thermal cycling of the boiler NaK from room temperature to 978 K (1300° F) and the injection of cold mercury. This service condition was omitted on the Serial Number 1 boiler to minimize thermal shock conditions and to preserve the unit for long-term corrosion/erosion examination of the mercury-wetted surfaces. The Serial Number 2 unit was tested in the Power Conversion System loop at Aerojet Nuclear Systems Company at Azusa for an accumulated total of 8700 hours and 27 startup/shutdown cycles. Thus, the Serial Number 1 and Number 2 boilers have accumulated a combined total of over 23 800 hours of operation at SNAP-8 system conditions. A third unit, Serial Number 3, was utilized for system startup/shutdown investigations at Lewis and was successfully subjected to 157 hours of operation and 135 startup/shutdown cycles. The performance of Serial Number 1 and Number 2 boilers and the post-test physical and metallurgical examinations have been previously reported in reference 7. The Serial Number 3 unit is in position in the test loop at Lewis and has not been examined to date.

A prototype boiler, designated Serial Number 4, has been fabricated at Lewis and has been functionally tested at the Aerojet Nuclear Systems Company for a total of 1620 hours and 28 startup/shutdown cycles. This boiler design included (1) significant changes to the primary NaK flow geometry which were required to correct a NaK flow distribution problem, (2) the provision for additional differential thermal expansion between the tantalum tubes and the surrounding stainless-steel oval tubes, which permitted the elimination of expansion bellows from the boiler assembly, (3) the use of a more reliable tantalum/stainless-steel bimetal joint, and (4) the attainment of a fully coiled shell assembly. The design changes and fabrication techniques unique to this unit and the preliminary results of the operational performance of the prototype boiler are discussed herein.

In this report both SI and U. S. customary units are used. The design calculations, measurements, and the data reduction were performed with U. S. customary units.

EXPERIMENTAL SYSTEM

The test facility at Aerojet Nuclear Systems Company in which the Serial Number 4 boiler was tested incorporated prototype components for the major hardware with the exception of the heat source and the radiators. A schematic of the proposed flight system is shown in figure 1. The actual test system substituted a gas-fired NaK heater in place of the reactor and forced-convection-cooled radiators in the heat rejection and lubricant/coolant loops in place of the indicated space radiators. In addition, the redundant primary loop NaK pump and the Number 2 boiler were not a part of the test system.

BOILER DESCRIPTION

The SNAP-8 boiler (fig. 2) is a counterflow multiple tube-in-tube heat exchanger which employs NaK-78 as the heating fluid and mercury as the heated or working fluid. The mercury flows inside seven parallel tubes which are interconnected at the mercury inlet and outlet ends by manifolds. The tantalum tube assembly is completely enclosed within an oval-shaped stainless-steel tube assembly (fig. 2(a), section A-A). The dual multitube bundle thus formed is surrounded with a stainless-steel shell to contain the primary loop fluid. The volume formed between the tube-bundle assemblies is filled with a thermal bonding fluid, in this case static NaK, to assure adequate heat transfer between the primary and working loop fluids. An external expansion reservoir (not shown) is provided to accommodate the volumetric expansion of the static NaK. The transition between the tantalum and stainless-steel systems within the boiler is accomplished through the utilization of a bimetal sleeve joint at both ends of the boiler. The sleeve joint is composed of a stainless-steel tube with a tantalum liner which is metallurgically bonded via a hot coextrusion process. Zirconium foil is placed at both ends of the boiler in the static NaK cavities in a ratio of 6.45 square centimeters (1 sq in.) of foil per 16.4 cubic centimeters (1.0 cu in.) of static NaK volume. The function of this foil is to protect the tantalum by acting as a getter for the interstitials that are released from the metals or for impurities possibly introduced through the fill and drain lines.

Subcooled mercury, introduced into the inlet mercury manifold, flows through the tube orifices that impose a pressure drop and tend to decouple the various tubes. The liquid mercury is then preheated and partially boiled in the multipassage plug section shown in figure 3. As much as 40 percent of the total boiler thermal energy is transferred, and as much as 60 percent of the total two-phase pressure drop occurs within the plugs that are 1.07 meters (3.5 ft) in length and have 16 parallel helical flow passages. The given helical geometry and specific mass velocity provide a vapor-phase radial acceleration on the liquid mercury drops of as much as 87 g's when the plug insert discharge vapor quality is 12 percent (ref. 8). Under these conditions, the liquid mercury is separated and forced against the heated tube wall surface to enhance heat transfer. The selection of the multipassage plug design was predicated to control the slug flow boiling regime that is believed to be the major cause of poor mercury boiling heat transfer (ref. 8). In the open tube, downstream of the multipassage plug, a swirl-wire turbulence generator made of tantalum/10-weight-percent tungsten and 0.16 centimeter in diameter by 5.1 centimeters in pitch (1/16 in. by 2 in.) is employed to sustain the vortex two-phase flow regime. The effectiveness of the multipassage plug and swirl-wire turbulator in maintaining a vortex two-phase flow regime depends on the existence of the proper pinch-point temperature difference (temperature of NaK minus temperature of the mercury at the liquid/vapor interface) and on the tantalum tube wall surface cleanliness. It has been determined analytically (ref. 8) that a minimum quality of 11 percent must be attained at the end of the plug section to assure the successful transition of the two-phase flow into the open tube. This results (as indicated in ref. 9) from the need to attain liquid breakup and subsequent entrainment in the vapor stream. According to reference 8, the liquid breakup is a function of the Weber number

$$\frac{\delta \rho_v u_v^2}{\sigma g_c}$$

where

δ	drop diameter, m (ft)
ρ_v	vapor density, kg/m^3 (lb/ft^3)
u_v	vapor velocity, m/sec (ft/sec)
σ	surface tension, kg/m (lb/ft)
g_c	gravitational constant, m/sec^2 (ft/sec^2)

The product $\rho_v u_v^2$ is conveniently determined and is representative of the Weber number. The authors of reference 9 have determined by test that if a value of $\rho_v u_v^2$ of 212 kilograms per meter per second squared (142 lb/ft-sec^2) is attained, liquid breakup into the desired vortex flow can be accomplished. From this critical value and for the required boiler conditions a vapor velocity of 3.36 meters per second (11 ft/sec) was calculated. This value has been used as a guide in the thermal design of the plug sections for the SNAP-8 boilers.

DESIGN IMPROVEMENTS

The design and fabrication of the double-containment tantalum/stainless-steel SNAP-8 boilers, Serial Numbers 1, 2, and 3 is discussed in references 6, 10, and 11. Since that time, various new requirements for the boiler have been imposed and certain desirable changes were indicated from shortcomings in the operational characteristics of the original design. The changes which have been incorporated into the design of the Serial Number 4 boiler are discussed in the following sections.

Thermal-hydraulic performance aspects. - The thermal-hydraulic performance of the original tantalum/stainless-steel boilers met the requirements of the SNAP-8 system. Data analyses, however, indicated two areas of possible improvement. These involved the large variations in overall boiler mercury pressure drop which were induced by the predicted reactor temperature control deadband, which varied the NaK inlet temperature from 966 K (1280° F) to 994 K (1330° F), and the obvious excess boiler superheating length. The mercury boiling pressure drop variation of 72.4 N/cm^2 (105 psi) at 966 K (1280° F) to 100 N/cm^2 (145 psi) at 994 K (1330° F) was caused primarily by the two-phase pressure drop in the multipassage plug. The high pressure drops were a result of better-than-expected thermal performance in this region, which, in turn, resulted from the improved wetting characteristics of the tantalum tube wall by the liquid mercury. The original design correlations were based on dry wall boiling (nonwetting) criteria (ref. 10) which had been employed on previous SNAP-8 boiler design. With the results of single-tantalum-tube boiler tests and the utilization of wetting boiling correlations (refs. 12 and 13), it was possible to decrease the multipassage plug length from 132 centimeters (52 in.) to 107 centimeters (42 in.). In addition, by minimizing the excess superheating tube length, the overall boiler length was reduced to 7.62 centimeters (25 ft) and the actual mercury boiler pressure drop was lessened to 48.3 newtons per square centimeter (70 psi) for a NaK inlet temperature of 966 K (1280° F) and to 65.5 newtons per square centimeter (95 psi) for a NaK inlet temperature of 994 K (1330° F). Figure 4 illustrates the predicted boiler NaK temperature profiles and mercury temperature and pressure profiles for the redesigned Serial Number 4 boiler.

NaK-side flow distribution. - Operation and post-test examination of the Serial Number 1 and Serial Number 2 boilers indicated the presence of nonuniform shell-side NaK flows (implied from circumferential shell temperature measurements at a given axial location). The NaK inlet and outlet ports on the original boiler shell were single orifice, and thus required the crossover of the NaK fluid in these areas from one side of the tube bundle to the other, resulting in local flow distribution problems. This condition was especially undesirable at the NaK discharge end (mercury inlet) where high heat-flux rates were attainable and a nonuniform heat source could result in serious variations in mercury tube-to-tube thermal-hydraulic performance. In the sections of the boiler shell where the tube/tube/shell spacing was to be maintained by mechanical spacers it was noted initially by X-raying the boiler that the tube bundle had displaced downward in relation to the shell. This sagging of the tube bundle was attributable to overstressing of the supports at high operating temperatures. The resulting circumferential shell temperature profile in the high-heat flux sections of the boiler (0 to 3.5 m, or 0 to 10 ft, from mercury inlet) indicated variations as large as 28 K (50° F). These conditions implied a flow distribution problem. In addition to these problems, there existed doubts concerning the contribution of the flattened stainless-steel tubes (fig. 2(a), section A-A) to NaK flow stratification and the influence of the tube spacing on the proper flow distributions.

Since the shell-side flow distribution and frictional characteristics are such an important part of a liquid-metal heat exchanger, a program (ref. 14) was conducted to study the shell-side hydraulic characteristics of a full-scale SNAP-8 multitube boiler. A Plexiglass model of the boiler (20-ft long) was constructed which incorporated

(1) An inlet/exit shell manifold assembly with radial ports on the shell wall which apportioned the shell-side flow
(2) A tube bundle composed of seven prototype stainless-steel oval-shaped tubes
(3) A series of five piezometer ring stations which were positioned to investigate the pressure drop contributions of the various elements of the shell-side geometry
(4) A series of dye-injection ports which were radially adjustable to permit flow studies within the tube bundle or in the annulus formed between the tube bundle and the shell
(5) A bolted end-flange arrangement which permitted rapid changes of the internal geometry

Water was used as the test fluid, and pressure loss test data were accumulated and correlated over the turbulent Reynolds number range of 1.8×10^{4} to 3.8×10^{4}. Although the maximum Reynolds number attained in these tests was less than that experienced in actual boiler operation (1.6×10^{5}), care was exercised to assure that the Reynolds number effect was fully realized. Friction factors for flow parallel to the tube bundle, with and without turbulence promoters, and loss coefficients for three candidate tube spacer configurations and for the inlet/exit manifolds were determined. In addition, the effect of incoming flow conditions on these loss coefficients were investigated. Utilizing the upstream dye-injection stations, a visual and photographic study was made of the shell-side flow distribution, which was influenced by various turbulence promoters. From considerations of pressure drop and flow mixing as visually observed during the dye-injection tests a revised shell-side geometry was attained that indicated significant improvements in flow distribution and pressure drop (from 2.4 N/cm^2 (3.5 psi) to 1.7 N/cm^2 (2.5 psi)). The recommended design changes include inlet and outlet manifolds (tees) with multiple ports in the NaK shell to attain uniform flow in the end sections; a revised tube spacer design to prevent overstressing of the material and subsequent sagging; a revised tube spacing to apportion the NaK flow-per-tube more uniformly and to minimize bypass flow between the tube bundle and shell; and a wire turbulence generator (0.48 cm (3/16 in.) diam by 15.2 cm (6 in.) pitch by 2.74 m (9 ft) long) at the NaK discharge end (high-heat-flux section) to induce mixing and to attain a relatively uniform NaK temperature field.

Orifice - tube/plug assemblies. - In the fabrication of the tantalum plug/tube assemblies and in the manufacture of the tantalum inlet orifices it was exceedingly difficult to attain uniformity between assemblies. This was a result of variations in such manufacturing operations as machining of the plug grooves; mechanical swagging of the tantalum tube onto the plug; and machining of the plug orifices, which requires precision work. To assure as close a match as possible for the orifice - tube/plug assembly pressure drops, each of the tube/plug assemblies and each of the orifices was calibrated with water to determine the actual fluid resistance. After fluid calibration, the component parts were matched to obtain near uniform pressure drops between assemblies.

Tube bundle design. - In the original tantalum/stainless-steel boilers, two design features of a temporary nature were included to facilitate fabrication and to attain uniform tube lengths. Because of the inherent difficulties of fully coiling the tube/plug assemblies (a relatively stiff bar contained within a thin-wall tantalum tube), this fabrication procedure was not attempted. This resulted in a 1.78-meter (5.83-ft) straight section at the mercury boiler inlet and the associated problem of accommodating the large differential thermal expansion between the tantalum and stainless-steel tubes. Expansion bellows were employed for this purpose. In the Serial Number 4 boiler, the technique of fully coiling the plug/tube assemblies was developed, which permitted a fully coiled boiler and the elimination of the bellows.

The tantalum tube lengths in the original boiler assemblies were made equal to minimize possible tube-to-tube performance variations. This was accomplished by twisting the tube bundle one revolution throughout the coiled length of the boiler. This presented some difficulties as the oval-shaped tube assemblies had to be oriented and maintained in a fixed position during boiler operation with the major oval-tube axis perpendicular to the axis of the boiler coil to accommodate the radial differential thermal expansion between the tubes. For the new Serial Number 4 boiler design it was found that if the tube bundle was not twisted, the difference in the length between the inner and outer tube coils was approximately 0.55 meter (1.8 ft). This difference affected only the vapor portion of the tube and was calculated to have little effect on overall boiler performance. The advantages of this design are twofold. One advantage is that the shell-side tube supports can all be of one design, and the other is the simplification of the assembly procedures. A lattice-type spacer design was selected because of its simplicity, ruggedness, and favorable pressure drop characteristics as discussed in reference 14. Operation of the boiler has verified that the tube length variations do not detectably affect overall performance.

Tube sizes and wall thicknesses. - The design life of the Serial Number 4 boiler was 40 000 hours. Analysis of the tantalum/stainless-steel tube assemblies indicated the desirability of increasing the tube wall thicknesses and thus increasing the strength and corrosion potential to meet the design life. Another requirement, which resulted from the elimination of the bellows from the boiler assembly, was for the additional clearances between the tantalum and stainless-steel tubes to accommodate the local tube radial movement as a function of differential thermal expansion. To comply with these needs the wall thickness of both the tantalum and the stainless-steel tubes was increased from 0.102 centimeter (0.040 in.) to 0.124 centimeter (0.049 in.). The stainless-steel outside tube diameter, which prior to flattening was 2.54 centimeters (1 in.), was increased to 2.86 centimeters ($1\frac{1}{8}$ in.). This provided adequate clearances after flattening for the differential thermal expansion of the tubes in the fully coiled configuration.

Inlet section temperature gradients. - In most heat-exchanger designs where large temperature differences occur between the heated and heating fluids there exists the potential of overstressing the containment material at the heated fluid inlet. In the SNAP-8 boiler designs, the stainless-steel header as shown in figure 2(b) has high-temperature NaK on one surface with relatively low-temperature static NaK (cooled by incoming mercury) on the other surface. This could impose significant thermal stresses on the header. To alleviate this possible stress condition, flow baffles similar to that shown in figure 2(b) are placed on the primary NaK side to form a relatively static fluid section which adds an axial resistance to the transfer of thermal energy from the primary flowing NaK to the header. In the original boiler design, two barriers were provided; however, significant bypass or secondary flow of the primary fluid beyond the baffles was possible because of clearances between the baffle and the shell. This flow increased heat transfer in this section of the boiler and contributed to undesirable circumferential and axial thermal gradients on the shell, which were considered contributory to shell thermal stress failures which were experienced in this area. To minimize these gradients a revised baffle was designed for the Serial Number 4 boiler which was integral with the shell and had close clearances between the baffle and tubes (fig. 2(b)). The restricted recirculation flow reduced the temperature gradient across the header and minimized heat transfer to the mercury tubes and therefore reduced the circumferential and radial temperature gradients in this section.

In addition to these modifications, a transient and steady-state thermal analysis of the mercury inlet section (first 45.7 cm (18 in.) of boiler shell at the mercury inlet end) indicated that an additional thermal resistance was necessary to lessen the heat transfer to the liquid mercury and to minimize the associated tube and shell axial thermal gradients. The results of this analysis showed the need for insulators on each tantalum tube and surrounding tantalum dome. The final analysis recommended evacuated annular tubes (vacuum insulation) which were positioned as shown in figure 2(b). Test operation of the Serial Number 4 boiler showed, however, that an additional mechanism, natural convection in the section between the stainless-steel header and the end flange, was contributing significant thermal gradients from the top to the bottom of this section. Although no failures resulted from this condition, additional analyses are being performed to rectify this condition.

Bimetal joints. - Three candidate bimetal joint configurations were evaluated: coextruded bimetal tubing; tapered coextruded joints; and a brazed joint. The coextruded bimetal tube concept was an extension of prior work performed on smaller diameter tubing which was originally considered for mercury containment in the boiler. The latter two were joints which were used on the original tantalum/stainless-steel boilers. These joints had limited bimetal interface lengths. Although none failed in service, bond delamination had started in the tapered coextruded joints; and braze porosity and the formation of brittle intermetallics at the bond interface were detected in the brazed joints. In an extended test program, coextruded bimetal tubing endured 5353 hours of thermal exposure and 275 thermal cycles from 394 to 1005 K (250° to 1350° F) without any detectable signs of bond degradation. The coextruded bimetal tube joint was therefore selected for incorporation into the Serial Number 4 boiler. The inclusion of this concept in the Serial Number 4 boiler has exposed the joint to the actual loop fluid and thermal environments and thus can be directly compared with the tapered coextruded and brazed assemblies. No destructive examination of the Serial Number 4 boiler is currently planned; hence, a current comparison of these joints is not available.

FABRICATION

In the fabrication of the Serial Number 4 boiler, standard procedures were used for machining, material forming, and assembly. Gas tungsten-arc (GTA) welding was generally used for material joining with electron-beam (EB) welding being employed for critical applications which required a controlled heat-affected zone and/or a limited temperature-time exposure. The areas of greatest concern included butt welding of the tantalum tubes to the required length; joining of a short tube extension to the mercury-inlet tantalum reducer; and the joining of the bimetal tantalum/stainless-steel joints to the tantalum reducers and to the stainless-steel end flanges. All welders, weld processes, and welds were qualified and the final welds were subjected to extensive nondestructive examination during fabrication.

To expedite the development of the fabrication processes and to minimize the associated costs, substitute materials were employed for the tantalum. These materials were chosen to simulate the controlling physical properties of the tantalum during forming. Nickel was utilized for the tests which simulated coiling of the tube-multipassage plug assembly, and type 304 stainless steel was substituted in the deep drawing operation which was required to form the inlet and exit tantalum reducers. These materials were quite effective for these processes and their use saved considerable time and expense.

The machining techniques employed were, as mentioned previously, standard and therefore are not discussed in detail. The machining of tantalum was difficult because of a galling tendency which complicated the trepanning or cutting of concentric grooves in the tantalum headers surrounding each of the seven tube holes and the machining of the spiral grooves in the multipassage plugs. The trepanning was accomplished by the use of a formed electrode and the electrical discharge machine (EDM) process. The tantalum multipassage plug fabrication was accomplished through the synchronization of a ball end milling cutter by the use of an indexing head, end table gear train, and work table lead screw to produce the required 15.2-centimeter (6-in.) pitch. The tool cutting depth was small and a profuse flow of cutting oil was maintained throughout the machining phase.

The tantalum reducers were originally conceived as being machined from a slab. Stress analysis of the boiler revealed, however, the presence of relatively high stress loadings in the area of curvatures of the reducers. To provide adequate material strength in these areas, it was necessary to employ tantalum sheets which possessed a fine grain structure and relatively high strength. The cold working performed on this component further increased the margin of strength. To maintain this margin the electron-beam weld process was employed. This prevented overheating of large areas of the reducers, which would have a tendency to produce grain growth and subsequently reduce strength.

A chronological sequence of the assembly procedure is detailed in the following discussion. The boiler was to be used in a high-temperature liquid-metal system which required a high level of cleanliness. Since many sections of the boiler would be inaccessible for cleaning after assembly, adequate precautions were taken to assure cleanliness of the hardware throughout the fabrication phase. All parts were solvent cleaned and bagged in plastic after machining or forming to prevent contamination during handling and transport to the assembly area. All assembly procedures were performed in a room with a controlled environment. All hardware was handled with white gloves to prevent possible contamination from the assemblers' hands.

The tantalum tube was obtained in 3.66- to 4.88-meter (12- to 16-ft) lengths to minimize tube welds. Those sections which contained the plugs were cut to 1.83-meter (6-ft) lengths to facilitate assembly. The plug was inserted into a section of tubing and positioned, and the tube was swaged onto the plug. The resultant close-fitting tube/plug assembly held the plug in position and prevented mercury from flowing over the lands during the operation of the boiler. The wire turbulators downstream of the plugs were made from 0.158-centimeter (1/16-in.) diameter tantalum/10-weight-percent-tungsten wire on a 5.08-centimeter (2-in.) pitch. The use of cold-worked tantalum/10-weight-percent-tungsten wire took advantage of the material strength to expand onto the tantalum tube wall at assembly and remain in intimate contact throughout the operational life of the boiler. The turbulators were wound on a slightly undersized mandrel for ease of insertion into the tubes. Both ends of the wire were clamped to the mandrel. After insertion, the clamps were released and the mandrel withdrawn. Upon release, the residual stress in the wire partially unwound the coil, thereby forcing it into contact with the tube walls. The excess wire was trimmed back to inside the tube and the ends were GTA-welded to the tube. The sections of the tantalum tube containing the wire and plug geometries were subsequently electron-beam welded together.

The 2.86-centimeter ($1\frac{1}{8}$-in.) diameter stainless-steel tube and heavy-walled end sections were GTA-welded together in a dry box. In the welding chamber the maximum allowable values of impurities in the atmosphere were 5 ppm for oxygen content and 10 ppm for water content. After welding and inspection, each individual tube was packed with sand to limit any wall buckling when the tube was formed to an oval shape. The shaping was done by placing the tube in a channel with the width equal to the maximum dimension and then formed by compressing with a large press. The formed tubes were thoroughly cleaned by forced flushing of a solvent through the tubes. The tubes were then dried and packaged for shipment to the assembly area.

Some innovations were required for the assembling and coiling of the tantalum/stainless-steel tube pairs. The use of the combination over the temperature range of 294 to 1033 K (70° to 1400° F) presented a problem caused by their large difference in coefficient of thermal expansion (ref. 6). This problem was resolved by having the tantalum tube in contact with the outer coil diameter of the oval stainless-steel tube when at room temperature, thus permitting the differential thermal expansion to be taken radially. The tantalum tube was inserted in the stainless-steel tube along with an expandable plastic tube. The plastic tube was then pressurized with a liquid which forced the tantalum tube against the outer wall of the oval stainless-steel tube. Clamps were used to compress the oval tube onto the tantalum tube, thus holding the tantalum tube in the desired position. The plastic tube was then removed from the assembly.

In coiling of the tantalum/stainless-steel tube pairs, internal support between the tubes was necessary to transmit the bending force of the coiling machine and to maintain the tantalum tube against the side of the oval stainless-steel tube. The tantalum tube was kept in position during the coiling process by means of frozen water. In addition, along the section of the tantalum tube containing the spiral channel plug (fig. 5), several 1.5-meter (5-ft) lengths of small-diameter, stainless-steel aircraft cables were inserted for additional support. This was required because of the increased bending loads necessary to overcome the stiffness of the plug. The freezing process was accomplished by inclining the tube assembly, sealing the annular space between the two tubes at the lower end, and filling the cavity between the tantalum and the stainless-steel tubes with distilled water; this included the region with the stainless-steel cables. At the elevated end a reservoir was used to remove or supply water as required to keep the tube completely filled. Cold alcohol was then pumped through the inner tantalum tube. The cooling of the alcohol was accomplished by passing the alcohol over frozen carbon dioxide in a container. The water froze from the low end and the excess resulting from the expansion merely flowed out the open end. When the water was completely frozen, the tantalum/stainless-steel tube pairs were coiled while maintaining active flow of the alcohol. The physical dimensions of the boiler assembly required that each tantalum/stainless-steel tube pair be coiled using three different values of radii. Accordingly, different curvature settings were necessary on the coiling machine. Templates, in conjunction with predetermined tangent points along the tube length, were used to guide the coiling of the tubes. Also, three separate groups of tantalum/stainless-steel tube pairs were coiled, for a total of seven tube pairs differing only in coil radii dimensions. The coiling did not give a uniform pitch to the tubes, so this was done manually by expanding the coils and inserting spacers to maintain the proper spacing and support (fig. 6). A fixture was used for assembling the tube bundle. The individual pairs were threaded through the fixture brackets one at a time with the small coil diameters being the first. The tube-bundle spacers were positioned and welded (fig. 7). The outside-diameter containment shell was coiled separately. The large 12.7-centimeter (5-in.) outside diameter (o.d.) tube was filled with natural tree resin to uniformly transmit the bending loads and to maintain a circular tube cross section while being coiled to the approximate coil diameter. The tree resin was melted and drained from the shell and replaced with water. Utilizing high-pressure water pulses, the 12.7-centimeter (5-in.) o.d. tube coil was sized to final dimensions. After coiling, the tube diameter varied to an acceptable ±0.040 centimeter (±1/64 in.). The tube was trimmed to length and then cut in segments for ease of handling when threading onto the tube bundle (fig. 8). The tube segments were thoroughly cleaned by forced flushing of a solvent through the tubes. The tubes were then dried and packaged for shipment to the assembly area.

With the exception of the mercury inlet/outlet subassemblies and the vacuum insulators (fig. 9), which were EB-welded in the vacuum chamber, all welding was done by the GTA process. During the welding of the stainless-steel tubes to the headers, a positive flow backup gas (argon) at 2.8 newtons per square centimeter (4 psi) was maintained on the inside of the boiler (fig. 10). When tantalum components were welded during the boiler assembly, a portable glove box (fig. 11) was used. The assembly and box were purged with argon until the oxygen concentration in the enclosure was less than 10 ppm. Just before welding the tantalum, an arc was struck to a piece of titanium in the box to getter part of the remaining oxygen. On a large tantalum weld, periodic checks of oxygen content in the box were made. Every weld was helium-leak and dye-penetrant checked before proceeding to the next operation.

The stainless-steel tube stubs were positioned with 0.64-centimeter (1/4-in.) of the tube extending from the header (fig. 12, view A). This extension protected the tantalum during welding and allowed a heavy filler pass to be made after the full-penetration seal weld. The results can be seen in figure 13.

At this point, the tantalum tubes which were pretrimmed to length were repositioned in the stainless-steel oval coil to position the tantalum tubes at the maximum coil diameter. The tantalum tubes were mechanically attached to the headers with a special tool (fig. 12, view B) by radially expanding the tubes into the grooves in the headers (fig. 12). The orifice blocks were inserted into the tube-header assembly and a seal weld joined the orifices and tubes to the tantalum headers (fig. 12, view C). A pre-welded subassembly of the transition dome, bimetal joint, and shell end (figs. 14 and 15) was GTA-welded to the tantalum header. The enclosure and seal weld for the containment of the static NaK at the shell end flange and bimetal joint (fig. 16) utilized the electron-beam weld method. The metallurgical bond between the dissimilar metals (stainless steel and tantalum) of the bimetal tube was not imparied. The combination of welding variables resulted in a minimum of sputtering of the metal on the back face of the flange and this was subsequently removed by machining. Zirconium foil, which acts as a getter for possible interstitials, was wrapped around the bimetal joint. The final closure, a short section of 13-centimeter ($5\frac{1}{8}$-in.) o.d. tube which completed the shell assembly, was welded in place. The completed boiler is shown in figure 17.

The fabrication and assembly procedure was relatively simple and straightforward, but a great deal of care was taken to assure that all steps were correctly completed. Machined parts that required weld preparations had an offset pilot-diameter step to facilitate their centering and positioning for welding. Mating pieces, as required, were tacked together along the periphery at selected points, followed by full-penetration fusion welds. The thicker welds were initially fusion-welded and then followed by filler welds. On the mercury inlet/outlet transition domes, tantalum electron-beam butt welds were made with a tantalum backup ring to minimize sputtering of the internal weld surface.

All materials upon receipt were visually and nondestructively examined by penetrant, ultrasonic, or radiographic inspection, or partially destructively examined by metallurgical methods as required. Fabricated and machined parts were inspected for dimensional accuracies per print and the deviations were recorded. Specimens of welds on the tube bundle and on the mercury inlet and outlet subassemblies were radiographically inspected and destructively examined to verify welding procedures. Helium leak checks were conducted for each of the containments (mercury, primary NaK, and static NaK) as the assembly progressed to ensure integrity of the welds.

BOILER PERFORMANCE

The Serial Number 4 boiler was tested in the Power Conversion System test facility at the Aerojet Nuclear Systems Company during the time period of March 12, 1970, to May 28, 1970. The testing consisted of 1619.7 hours of accumulated run time and 28 thermal cycles. During this period, extensive boiler mapping was accomplished. Mapping was performed over the boiler design range (table I) with an inlet NaK temperature of 977 K (1300° F) nominal, and over a second range (table II) with an inlet NaK temperature of 922 K (1200° F) nominal which encompassed a proposed new set of design conditions for the Power Conversion System. The second range of cycle conditions was investigated for a reactor-outlet temperature range of 914 to 928 K (1185° to 1210° F), an increased mercury flow rate of 6400 kilograms per hour (14 120 lb/hr), and a boiler discharge pressure of 100 newtons per square centimeter (145 psia). This range was simulated on a per-tube basis with the required number of boiler tubes increased from 7 to 12 for the proposed conditions. The performance of the boiler for both sets of conditions was excellent. Recorded boiler discharge pressure variations at the design conditions of 977 K (1300° F) NaK inlet temperature and rated mercury flow was less than ±0.7 newton per square centimeter (±1 psi).

General steady-state mapping of the boiler was performed to observe the boiler performance over a wide range of operating conditions (ref. 15). The mapping covered the following range of independent parameters:

Mercury flow, kg/hr (lb/hr)	1361 to 5443 (3000 to 12 000)
NaK flow, kg/hr (lb/hr)	11 330 to 22 200 (25 000 to 49 000)
NaK inlet temperature, K (°F)	894 to 977 (1150 to 1300)

A series of plots of the data generated are shown in figures 18 to 21. Figure 18 shows the overall mercury boiler pressure drop (includes boiler inlet orifice pressure drop) as a function of the independent parameters NaK flow rate, boiler NaK inlet temperature, and mercury flow rate. The magnitude of the pressure drop was in accordance with the computer analysis predictions (fig. 4). The only undesirable performance characteristic was a negative slope of the mercury pressure drop as a function of increasing mercury flow rates. This condition arises as a result of the restricted flow passages in the plug section and the associated, relatively high, two-phase pressure drop. At low mercury flow rates, boiling is initiated at or before the plug entrance, resulting in two-phase pressure loss throughout the plug length. As the flow rate is increased the plug pressure drop increases until a point is reached where the liquid/vapor interface is displaced downstream of the plug entrance as a function of the increased flow rate and heat transfer in this region. The movement of the interface downstream lessens the two-phase length in the plug and the associated pressure drop, which results in an inflection of the mercury pressure drop curve and a negative slope as shown in figures 18 and 19. This characteristic had existed on all previous boilers containing a plug section and neither was this characteristic considered detrimental to the system operation nor was a positive pressure slope required in the boiler specifications. This viewpoint has changed, however, as it has been demonstrated that the negative slope characteristic is undesirable to the operation of the system. To correct this problem, a straightforward solution was to increase the liquid-phase orifice pressure drop. An analysis of this problem for the proposed 922 K (1200° F) NaK inlet temperature system has been performed and figure 22 illustrates the pressure drop required to ensure a positive pressure slope under all predicted boiling conditions.

Figure 19 shows the same data as presented in figure 18 except that the inlet orifice pressure drop has been subtracted from the total pressure drop and therefore, represents that pressure drop associated with the preheat, boiling, and superheat phases of the boiler operation. Since it is characteristic of this boiler design to operate with a negative slope, the removal of the orifice pressure drop, which has a positive slope as a function of increased flow, accentuates the negative slope, as shown.

The measured terminal temperature difference (NaK inlet temperature minus mercury discharge temperature) as a function of the independent parameters is presented in figure 20. The terminal temperature difference range of 22 to 28 kelvin degrees (40 to 50 Fahrenheit degrees) shown for the design conditions of 5443 kilograms per hour (12 000 lb/hr) mercury flow and 977 K (1300° F) NaK inlet temperature is in accordance with past test experience. The mercury temperatures measured during this test series were obtained from surface thermocouples on the vapor line. This was necessary because of the loss of immersion thermocouples at this location. Prior test experience, however, has shown that the mercury vapor stream temperatures are approximately 17 kelvin degrees (30 Fahrenheit degrees) higher than that indicated by the surface thermocouple pickups. Applying this correction, the data shown for the terminal temperature difference would be in the range 5.6 to 11.1 kelvin degrees (10 to 20 Fahrenheit degrees), which agrees with the design expectations. The pinch-point temperature difference (minimum temperature difference between the NaK and mercury fluids at the liquid/vapor interface) is shown in figure 21 as a function of NaK flow rates, boiler NaK inlet temperatures, and mercury flow rates. As illustrated, the pinch-point temperature difference was varied over a wide range from about 5.6 to 222 kelvin degrees (10 to 400 Fahrenheit degrees).

The stability of the boiler at both system design conditions, as measured by the fluctuations in the mercury vapor discharge pressure, was excellent. The magnitude of pressure variations was less than ±1 percent of the discharge pressure at the design conditions (NaK inlet temperature, 977 K (1300° F)) and less than ±2 percent at the proposed conditions (NaK inlet temperature, 922 K (1200° F)). These magnitudes of pressure variations are considered to be representative of a stable once-through boiler. As the operating conditions were moved off-design in each direction, variations in mercury discharge pressure were obtained. Figure 23 shows time plots of the boiler outlet pressure for the various off-design conditions investigated. The maximum pressure oscillations observed occurred when the mercury flow rate was 4912 kilograms per hour (10 830 lb/hr) with a NaK flow rate of 22 000 kilograms per hour (48 500 lb/hr) and with a NaK inlet temperature of 919 K (1194° F) (test condition 7, fig. 23) and coincided with the minimum indicated pinch-point temperature difference of all tests (4.5 K or $\approx 8^{\circ}$ F). At this condition, the oscillations were about ±4 percent. All test data within the design ranges of tables I and II showed pressure perturbations too low to respond to the instrumentation systems used and are therefore not shown.

Portions of the boiler mapping were designed to specifically identify the boiler performance at the revised 922 K (1200° F) nominal NaK inlet temperature state point. This state point was represented with a mercury liquid flow rate of 3629 kilograms per hour (8000 lb/hr) (for the existing seven-tube configuration), a NaK flow rate of 14 740 kilograms per hour (32 500 lb/hr), and a NaK inlet temperature of 922 K (1200° F). These conditions, on a per-tube basis, closely simulated operation at the revised state point. The performance of the boiler at these conditions is presented in figures 24 to 26. The total mercury pressure drop (including orifice pressure drop) shown in figure 24 as a function of the mercury flow rate and different boiler NaK inlet temperatures again illustrates the negative pressure drop - flow rate slope of the boiler. As discussed earlier, this characteristic is easily remedied with the appropriate inlet orifices.

Terminal temperature difference is shown as a function of mercury flow rate and the NaK inlet temperature in figure 25. The general value of this difference is about 25 to 30.6 kelvin degrees (45 to 55 Fahrenheit degrees). When corrected to the equivalent of an immersion thermocouple reading, this represents a difference of about 11.1 kelvin degrees (20 Fahrenheit degrees), which is consistent with the design expectations.

Test condition 10 (fig. 23) presents boiler stability data for operation in the vicinity of the revised state point. The general fluctuation of the mercury outlet pressure is less than ±2 percent of the rated pressure and is within the current design requirements. The overall performance of the boiler at the revised power conversion system conditions was excellent.

A test was conducted to evaluate the response of the system to the normal variations of the boiler NaK inlet temperature over the reactor temperature control deadband for the revised state point. The testing was extended over a wider range of NaK inlet temperature variations than anticipated to increase the accuracy of the data interpretation, and was conducted by changing only the boiler NaK inlet temperature. The reactor deadband temperature extremes for the revised state point are 914 to 928 K (1185° to 1210° F). The testing range, however, was extended as shown in figures 26(a) and (b) to a wider range of 904 to 941 K (1170° to 1235° F). The responses of the various system key parameters were in accordance with expectations. As the boiler NaK inlet temperature increased (other independent parameters unchanged) the available boiler pinch-point temperature difference increased. This increased the thermal potential at the liquid/vapor interface and caused a shifting of the interface upstream in the plug, decreasing the boiler inventory and increasing the boiler pressure drop (because of the increased two-phase plug boiling length). As the boiler pressure drop increased, the boiler inlet mercury pressure increased. This added resistance to the mercury pump output was somewhat modified by the increased mercury pump suction head (because the displacement of boiler inventory to the condenser raised the liquid/vapor interface and thus the available head). The overall effect, however, was to slightly lessen the mercury flow rate, as shown. This decreased flow rate resulted in less heat input to the working fluid. The reduced available energy to the turbine-alternator resulted in a slight reduction in alternator output power, as shown. The condenser pressure (turbine exhaust pressure) also was reduced because the available coolant flow rate in the heat-rejection loop was constant, whereas the mercury flow rate had been lessened.

CONCLUDING REMARKS

The successful operation of the Serial Number 4, prototype tantalum/stainless-steel, double-containment, mercury boiler verified the design changes incorporated in this unit. Those changes beneficial to the boiler structural integrity and performance include the following:

1. For the 977 K (1300° F) system, the effective boiler length was decreased from 11.3 meters (37 ft) (as used in Serial Number 1, 2, and 3 boilers) to 7.6 meters (25 ft) (as used in Serial Number 4 boiler) and the multipassage plug length was shortened from 132 centimeters (52 in.) to 107 centimeters (42 in.). These changes resulted in no change in overall thermal performance (see fig. 27). However, the two-phase pressure drop was reduced by approximately 28 newtons per square centimeter (40 psi) at nominal operating conditions.

2. The primary NaK-side flow geometry (which included inlet and outlet multiple-shell radial ports and associated collector rings (tees) increased tube spacing, revised tube supports, and a coiled-wire flow turbulator 2.74 meters (9 ft) long in the high-heat-flux section) was modified. This resulted in reduced NaK-side pressure drop, a more uniform NaK shell circumferential temperature field, and reduced variations in the boiler discharge pressure.

3. The straight-end-section lengths of the boiler were minimized and the flattened tube dimensions used to accommodate the differential thermal expansion of the

tantalum/stainless-steel tubes were increased. This permitted the elimination of the expansion bellows at the boiler mercury inlet and the attainment of a fully coiled boiler assembly.

4. Individual flow calibration of the mercury inlet orifices and tube/plug assemblies and the matching of these components to attain relatively uniform pressure drops between tubes was instrumental in achieving the minimum boiling pressure variations.

5. Use of the coextruded bimetal joint as the interface between the tantalum and stainless-steel portions of the boiler permitted a shortened static NaK section and contributed to the attainment of a fully coiled boiler. In addition, it is believed that because of the longer bimetallic interface, this joint is inherently more reliable than the other candidate bimetal joints.

6. The fabrication techniques necessary to the coiling of the tube/plug assembly were successfully accomplished with no excessive local deformation of the tantalum tube wall at the plug end.

7. The coextruded bimetal joints which were used on both the mercury inlet and outlet were successfully welded to the boiler stainless-steel end flanges without any sign of joint degradation (the formation of brittle intermetallics as a function of high temperatures and exposure time). This was accomplished by the use of an electron-beam (EB), full-penetration weld which minimized the peak temperature and temperature exposure time at the joint interface.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 5, 1971,
120-27.

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TABLE I. - DESIGN BOILER OPERATING PARAMETERS

[35 kWe; inlet NaK temperature, 977 K (1300° F) nominal.]

NaK inlet temperature, K (°F):	
Low	966 (1280)
Nominal	980 (1305)
High	994 (1330)
NaK temperature drop, K° (F°)	94. 4 (170)
NaK flow rate, kg/hr (lb/hr)	22 200 (49 000)
NaK pressure drop (maximum), N/cm^2 (psi)	2. 1 (3)
Mercury inlet temperature, K (°F)	533 (500)
Mercury exit pressure, N/cm^2 (psia)	179 (260)
Mercury flow rate, kg/hr (lb/hr)	5580 (1 300)
Terminal temperature difference, $(T_{NaK_{in}} - T_{Hg_{out}})$, K° (F°)	<16.7 (<30)
Mercury vapor pressure variations, percent of mercury discharge pressure	$<\pm1$ ($<\pm1$)
Liquid-mercury carryover (maximum), percent	<4 (<4)

TABLE II. - PROPOSED DESIGN BOILER OPERATING PARAMETERS

[92. 8 kWe; inlet NaK temperature, 922 K (1200° F) nominal.]

NaK inlet temperature, K (°F):	
Low	914 (1185)
Nominal	922 (1200)
High	928 (1210)
NaK temperature drop, K° (F°)	94. 5 (170)
NaK flow rate, kg/hr (lb/hr)	25 880 (57 050)
NaK pressure drop (maximum), N/cm^2 (psi)	2. 1 (3)
Mercury inlet temperature, K (°F)	450 (350)
Mercury exit pressure, N/cm^2 (psia)	102 (148)
Mercury flow rate, kg/hr (lb/hr)	6405 (14 120)
Terminal temperature difference, $(T_{NaK_{in}} - T_{Hg_{out}})$, K° (F°)	<16.7 (<30)
Mercury vapor pressure variations, percent of mercury discharge pressure	$<\pm1$ ($<\pm1$)
Liquid-mercury carryover (maximum), percent	<4 (<4)

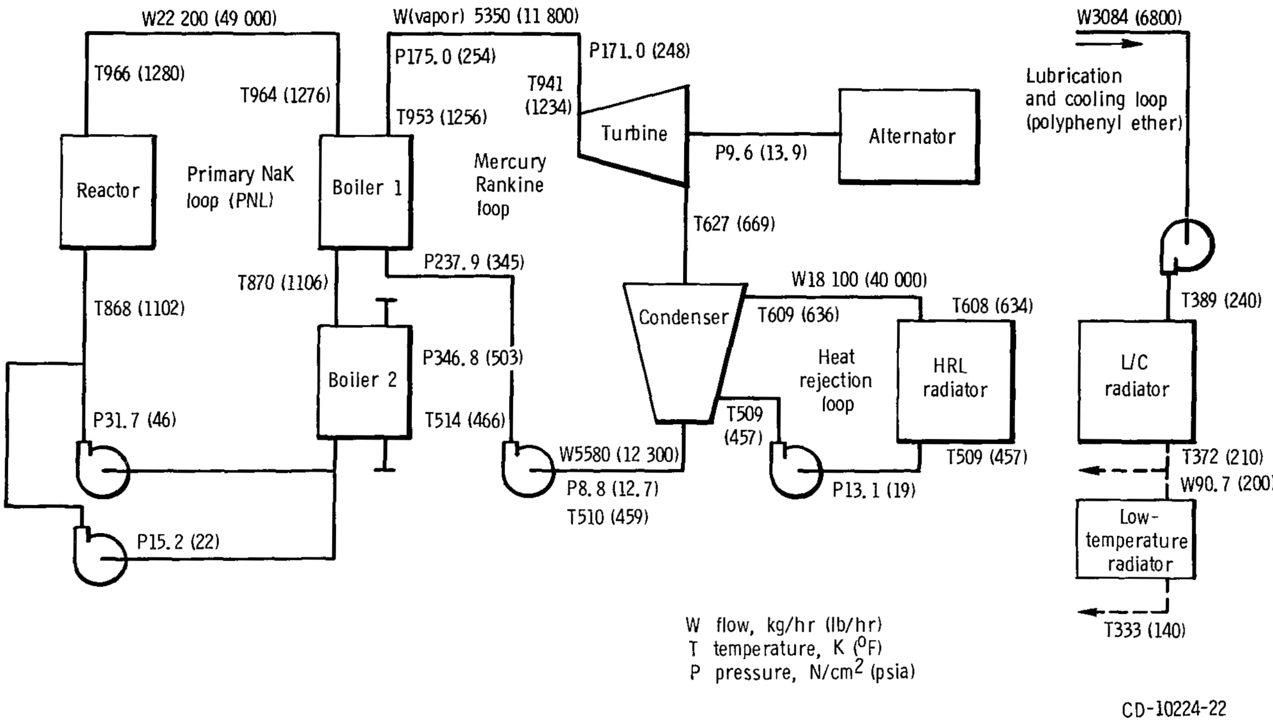
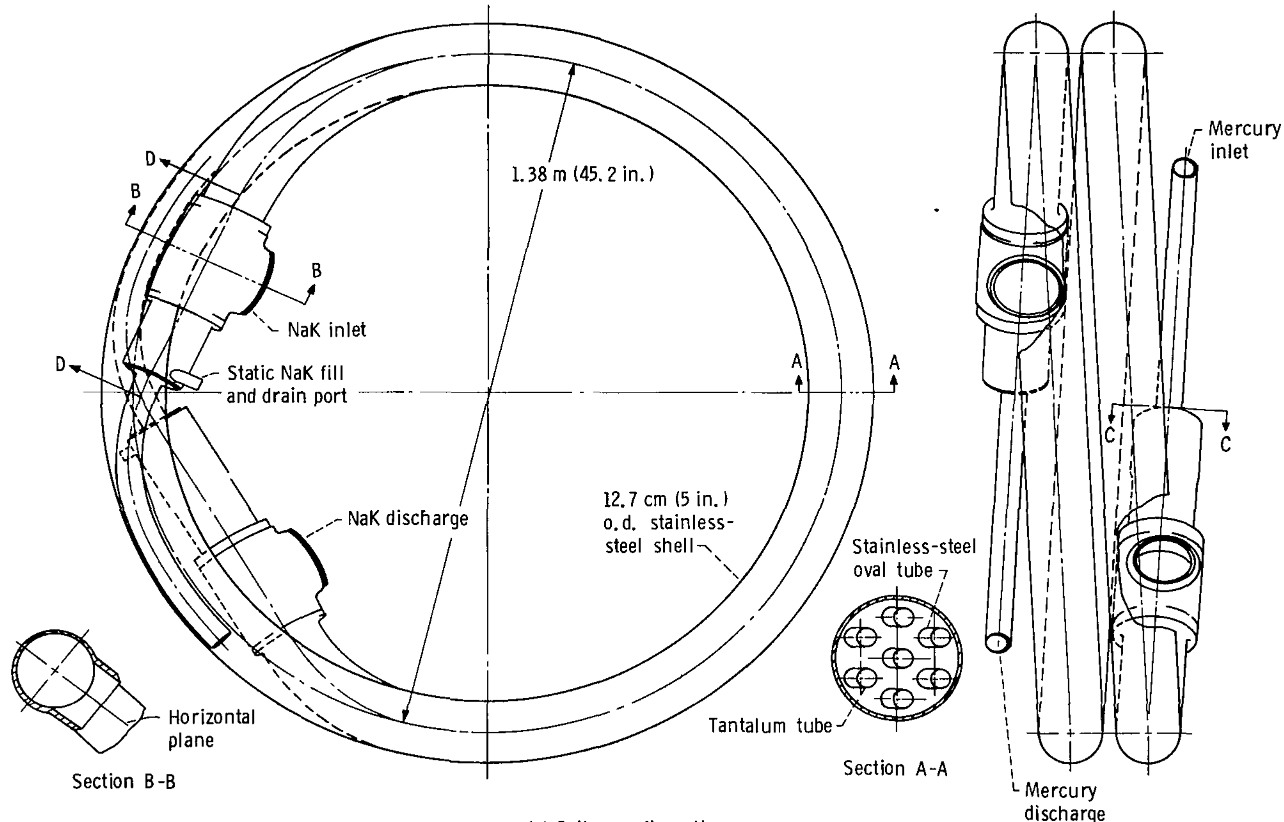


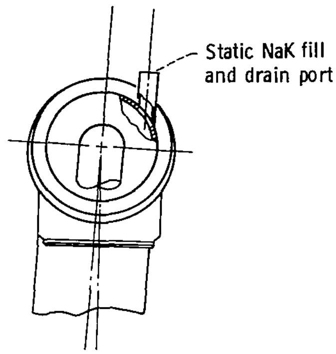
Figure 1. - SNAP-8 system schematic (design point operation).



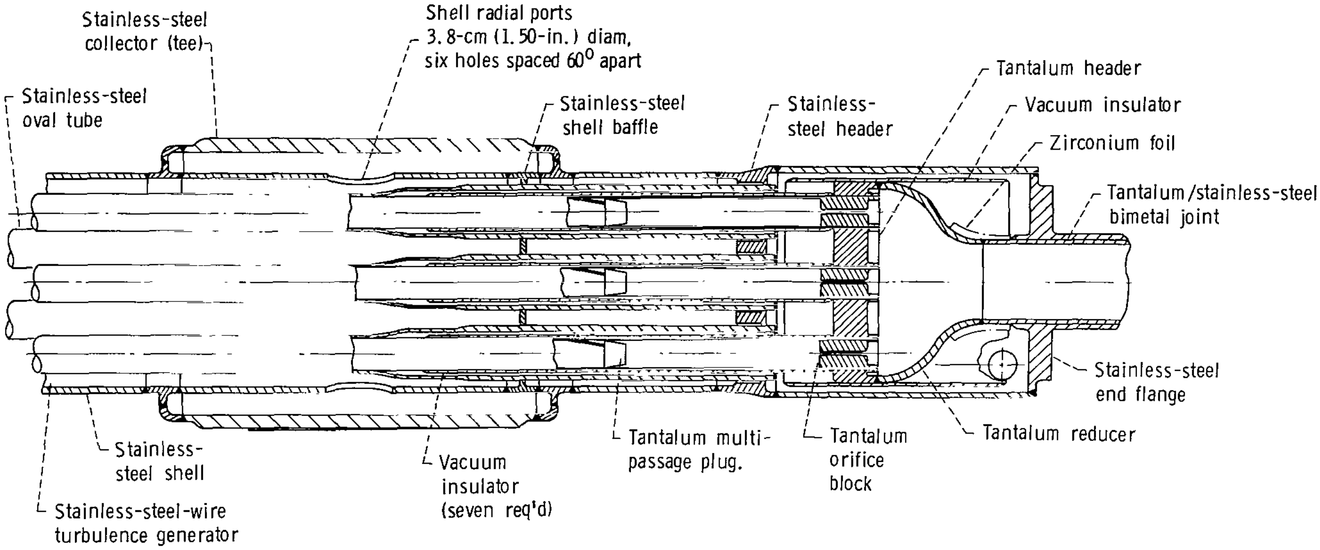
(a) Boiler configuration.

CD-11033-33

Figure 2. - Prototype SNAP-8 tantalum/ stainless-steel double-containment mercury boiler (Serial Number 4).

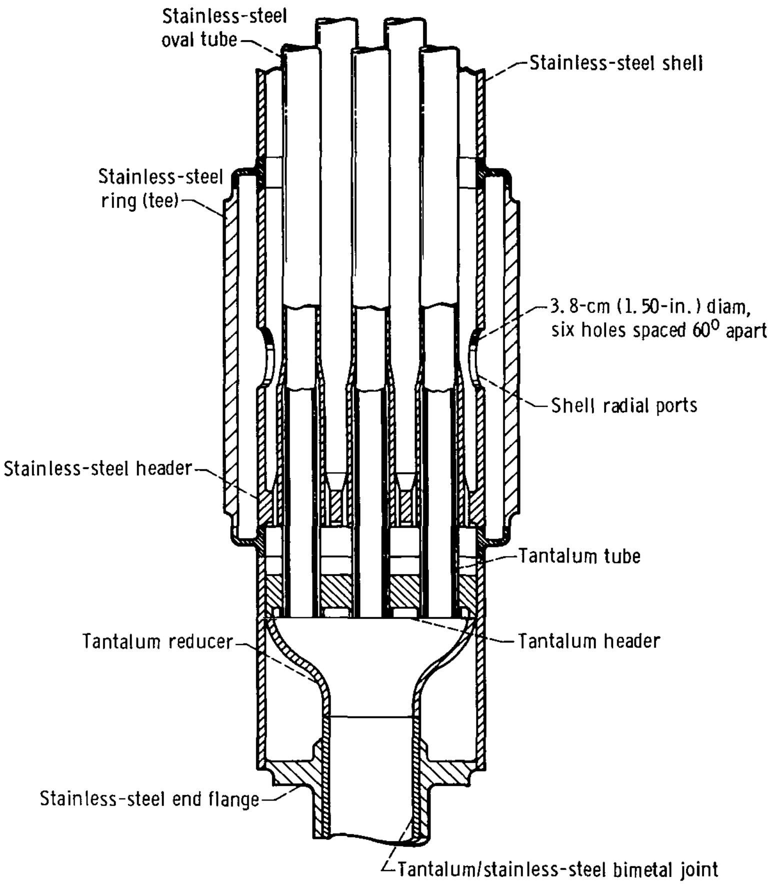


View C-C (looking normal
to axis of item 5)



(b) Boiler mercury inlet section design. CD-11030-33

Figure 2. - Continued.



Section D-D (rotated 33° ccw)

(c) Boiler mercury outlet section design.

Figure 2. - Concluded.

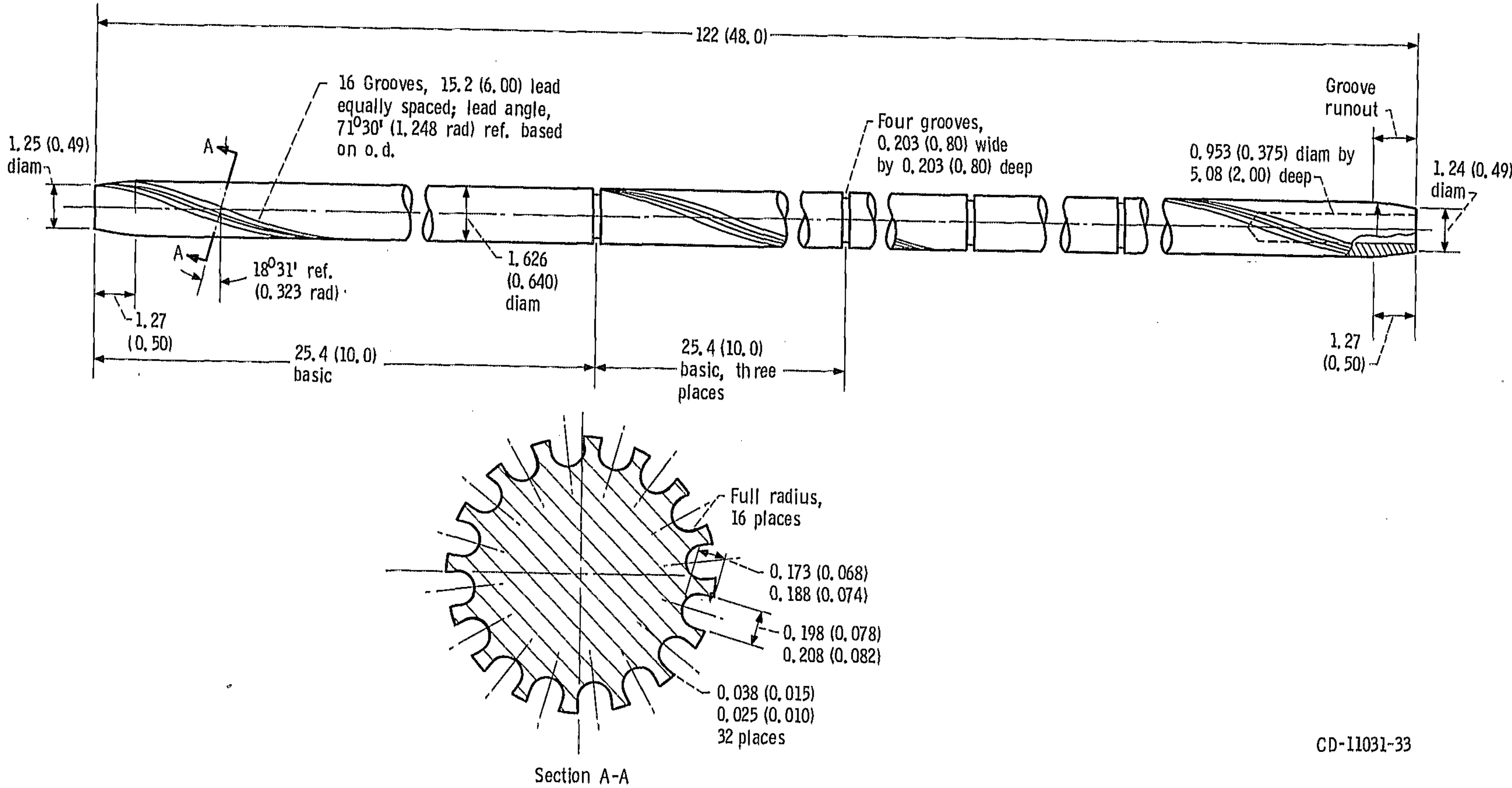


Figure 3. - Multipassage plug insert design. Dimensions are in cm (in.).

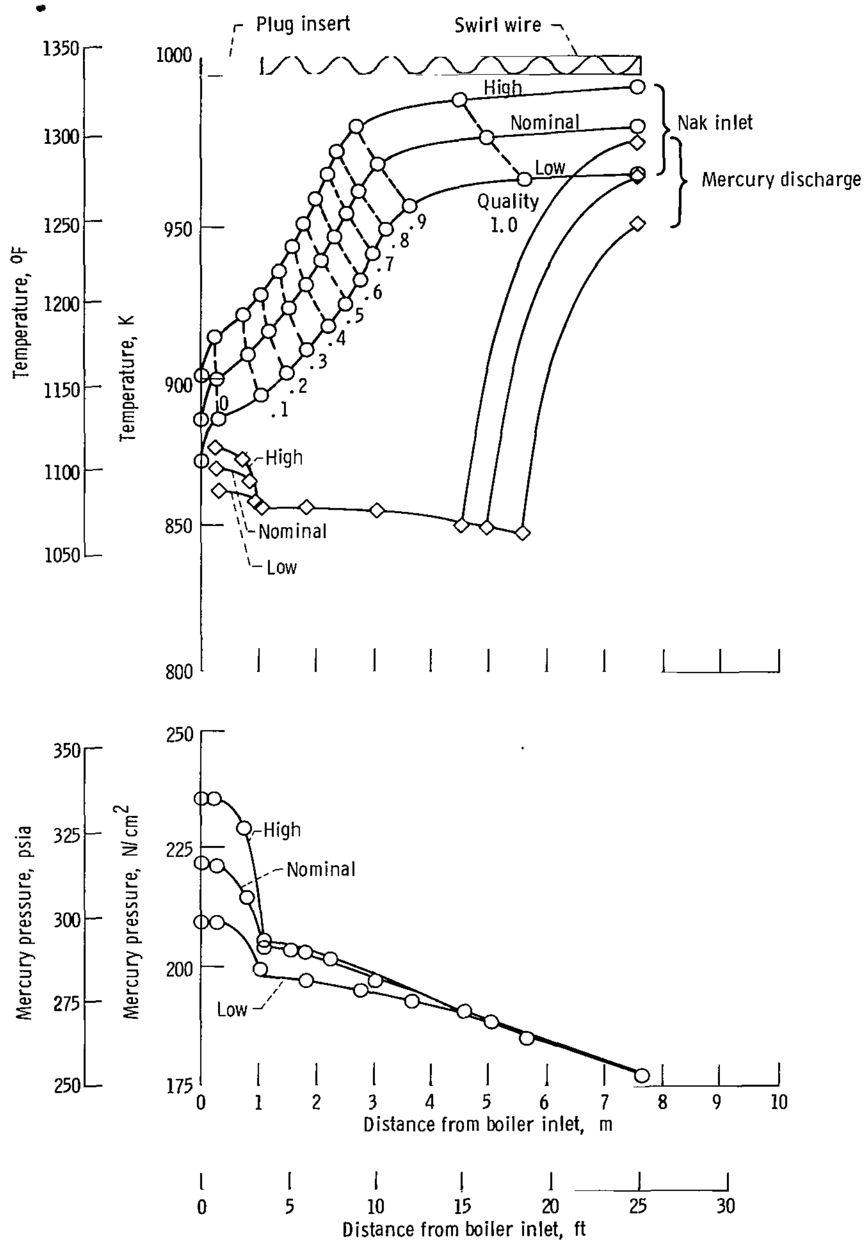


Figure 4. - Serial Number 4 boiler predicted axial temperature and pressure profiles.

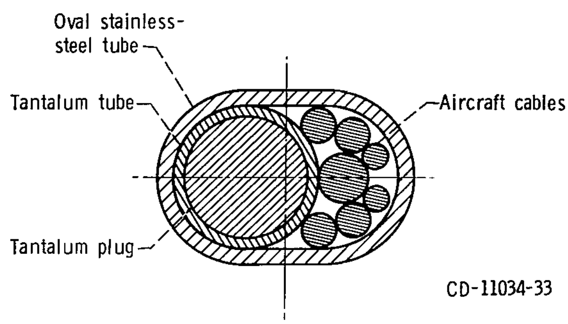


Figure 5. - Cross section of tantalum/stainless-steel tube pair with small-diameter, stainless-steel aircraft cables inserted for coiling plug section.

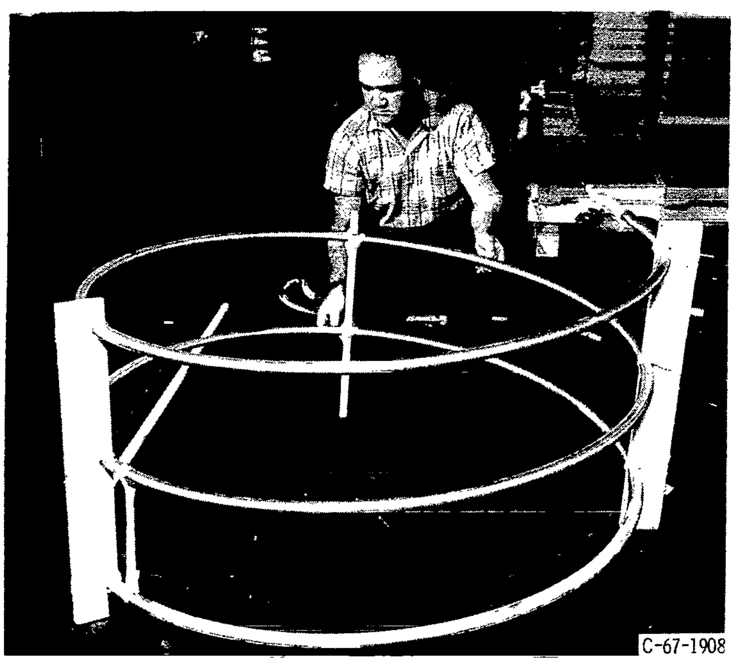


Figure 6. - Method used to establish pitch on tantalum/stainless-steel tube assemblies.

Figure 7. - Welding of tube-bundle spacers.

Figure 8. - Assembly fixture with outer shell segment being fitted onto tube bundle.

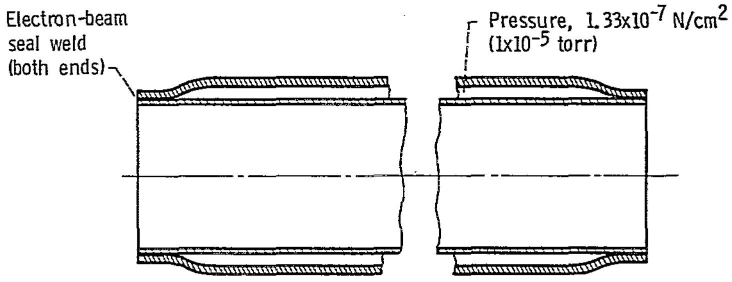


Figure 9. - Vacuum insulator (typical) at mercury inlet end of tantalum header and tubes.

Figure 10. - Welding of stainless-steel tubes to header.

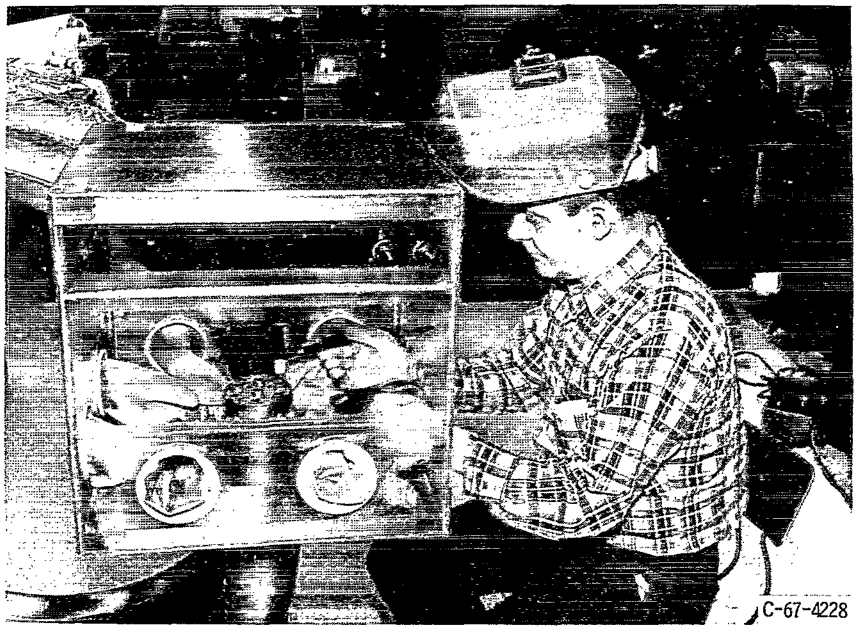


Figure 11. - Welding of tantalum tubes to header in portable glove box.

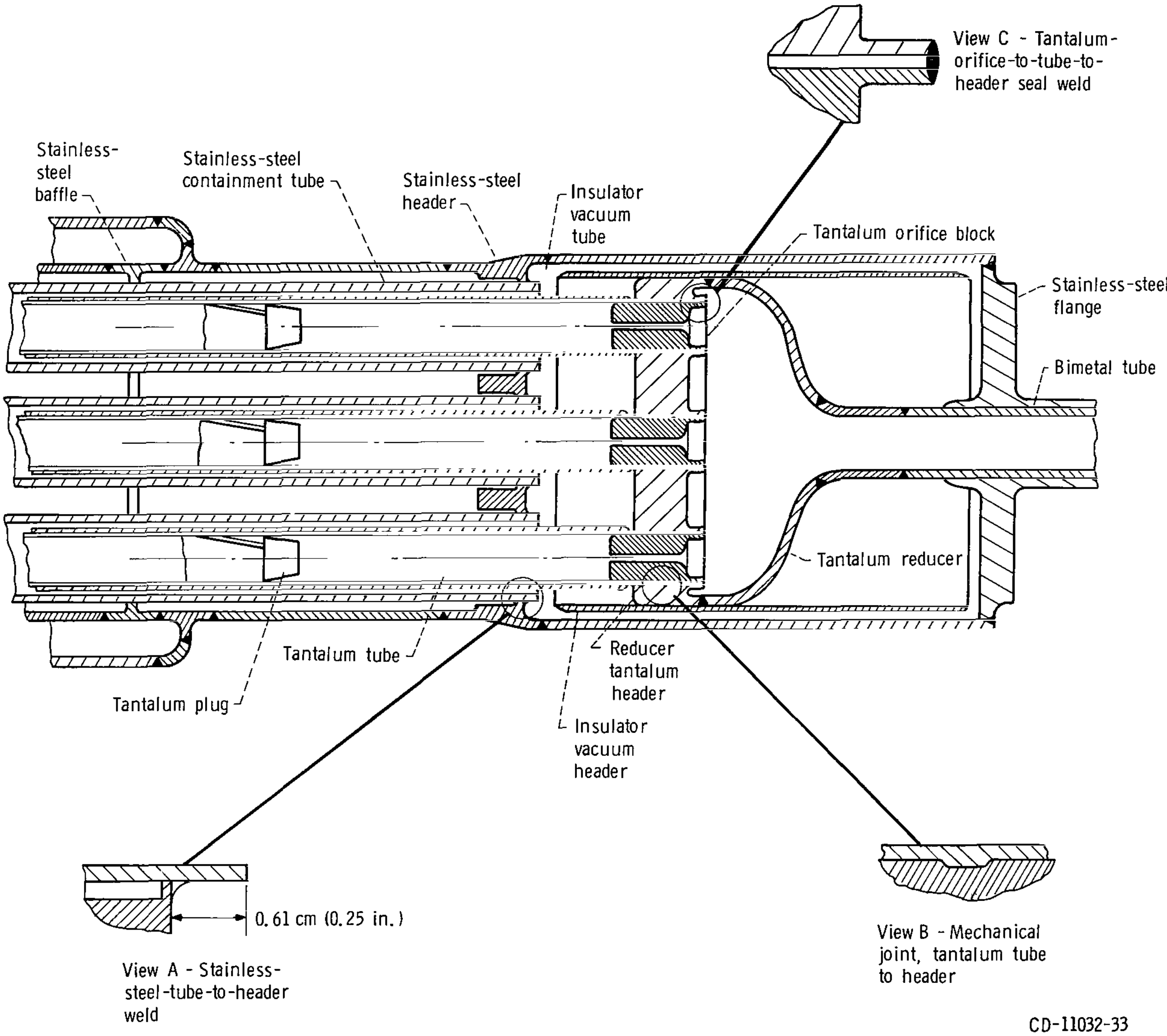


Figure 12. - Details of header and tube welds (boiler mercury inlet).

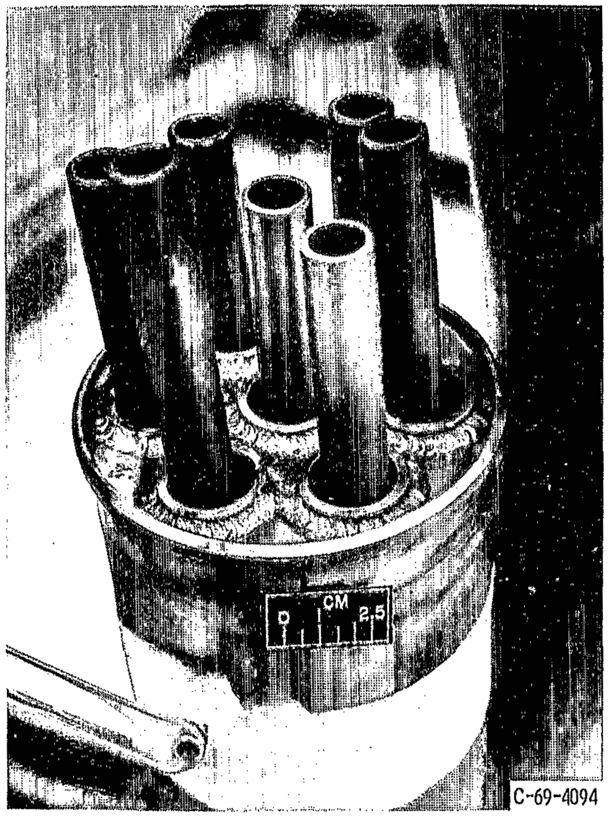


Figure 13. - Stainless-steel header and tube weld.

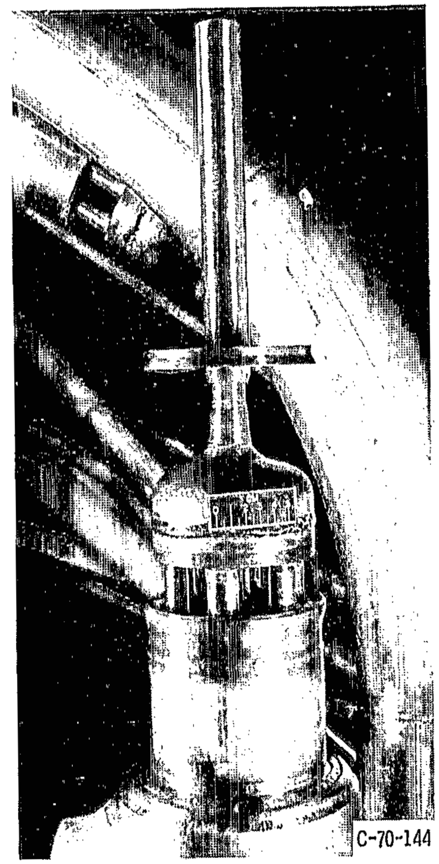


Figure 14. - Mercury inlet subassembly.

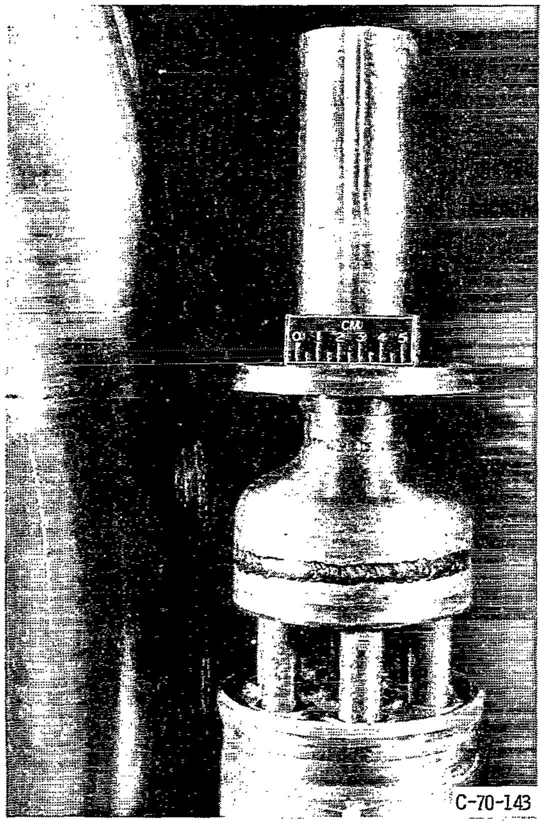


Figure 15. - Mercury outlet subassembly.

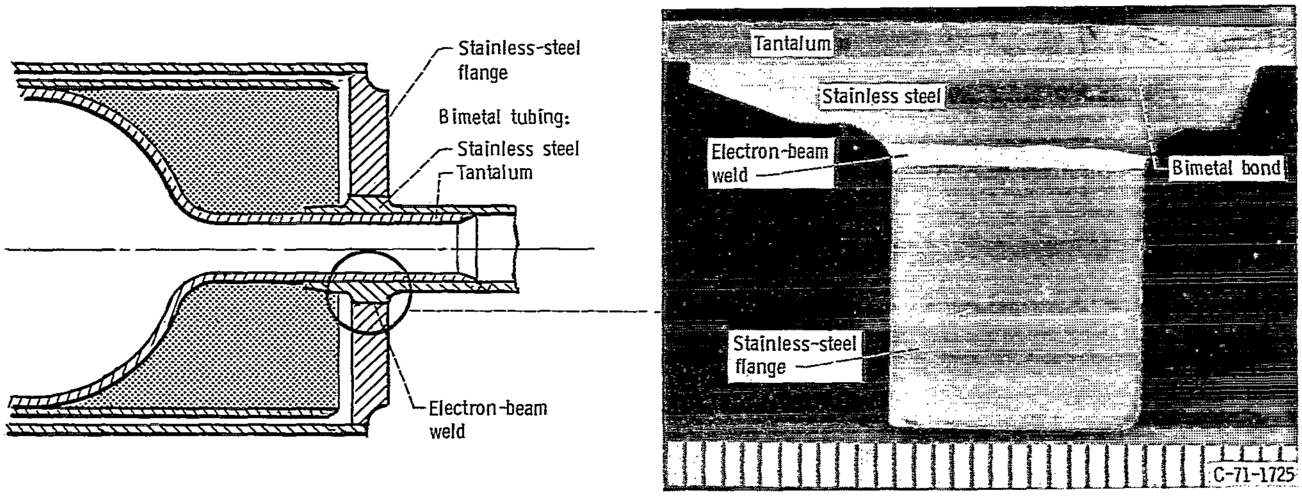


Figure 16. - Electron-beam weld of stainless-steel flange to bimetal tube.

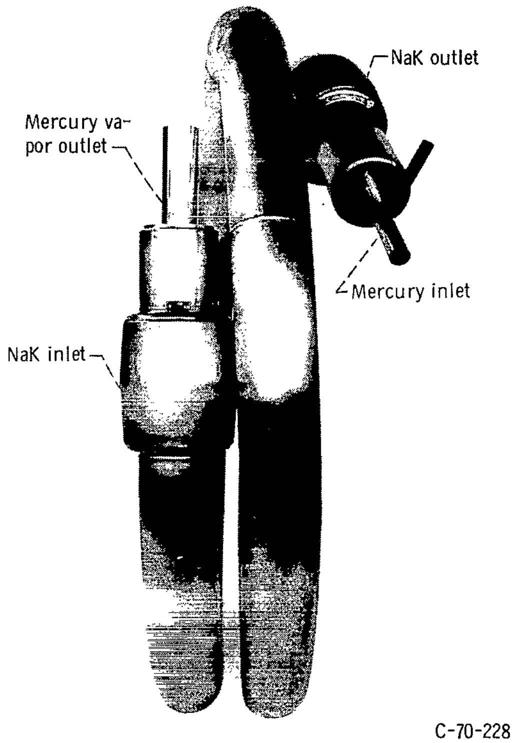
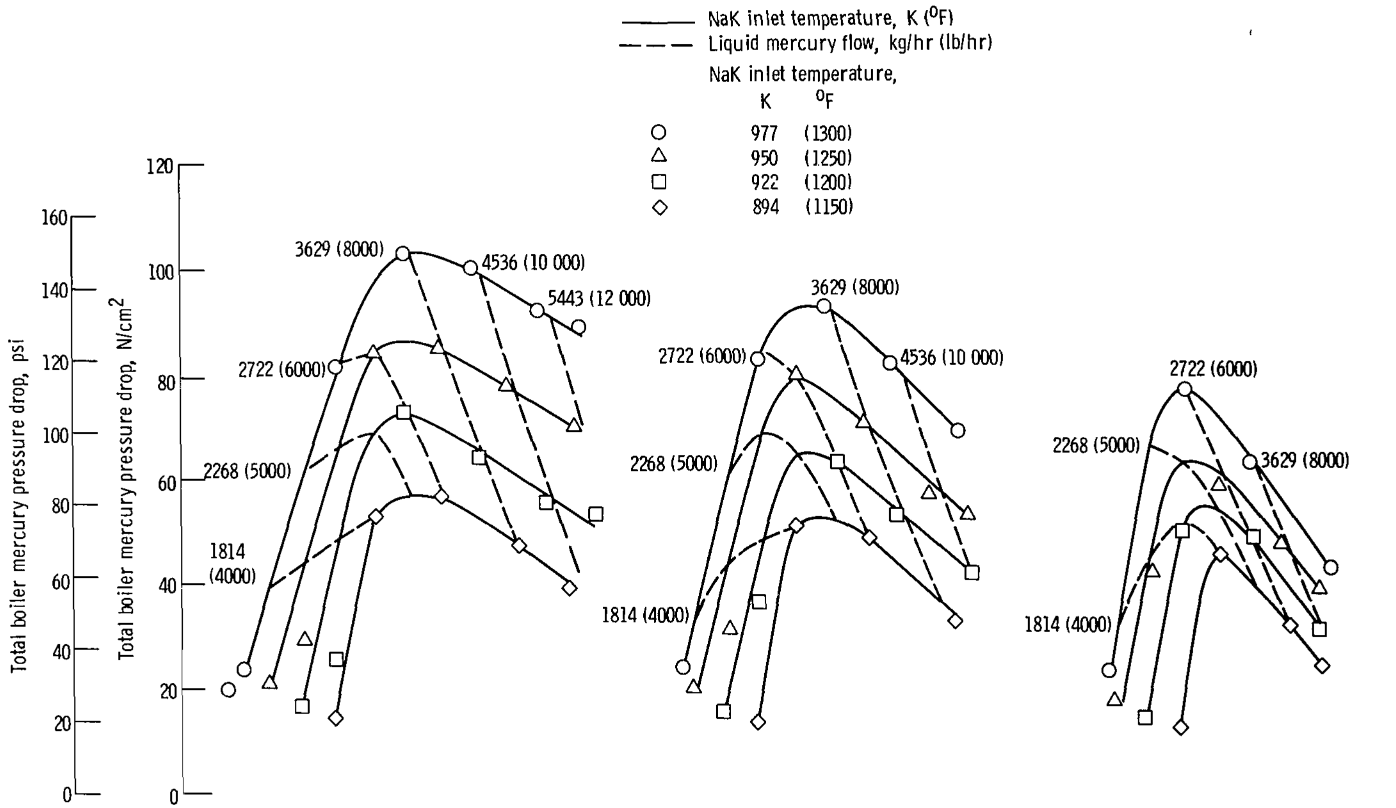


Figure 17. - Complete SNAP-8 Serial Number 4 boiler.



(a) NaK flow, 22 200 kilograms per hour (49 000 lb/hr).

(b) NaK flow, 16 780 kilograms per hour (37 000 lb/hr).

(c) NaK flow, 11 330 kilograms per hour (25 000 lb/hr).

Figure 18. - Total boiler mercury pressure drop as function of independent boiler parameters.

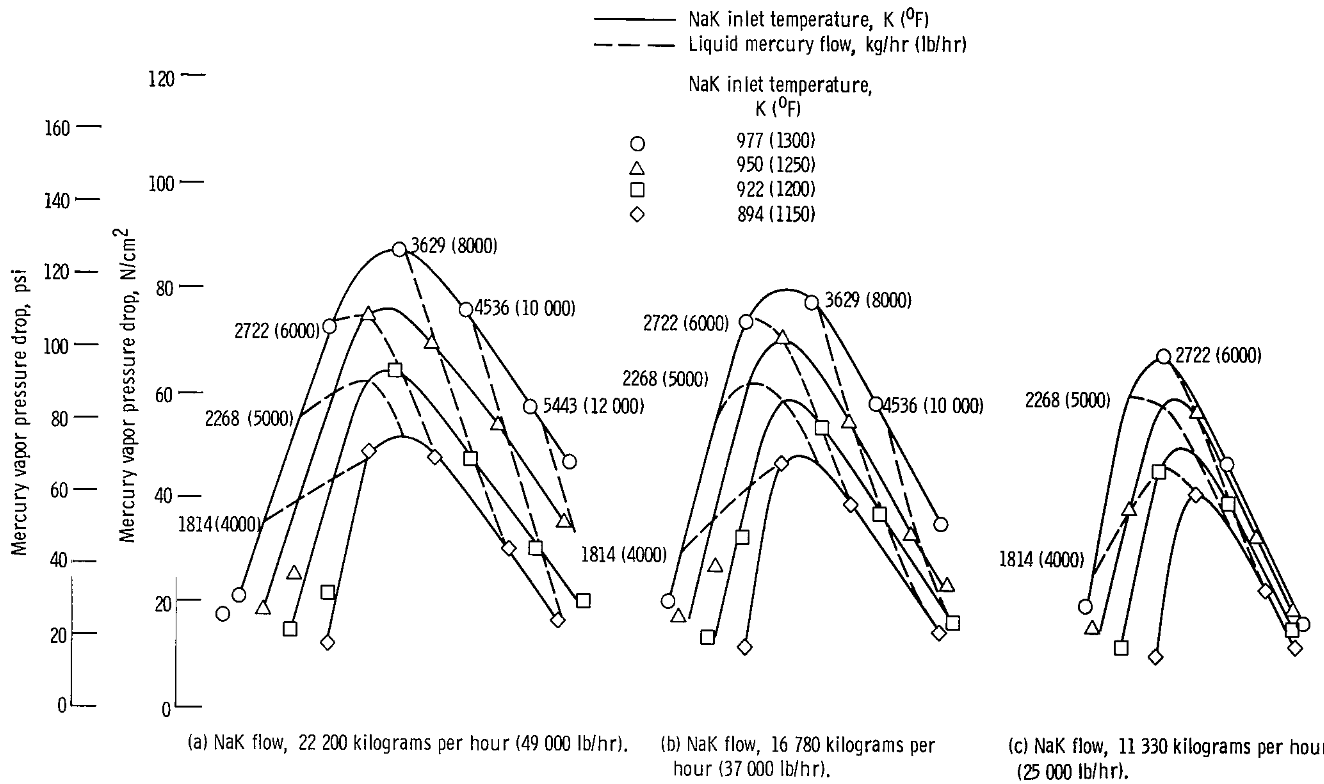
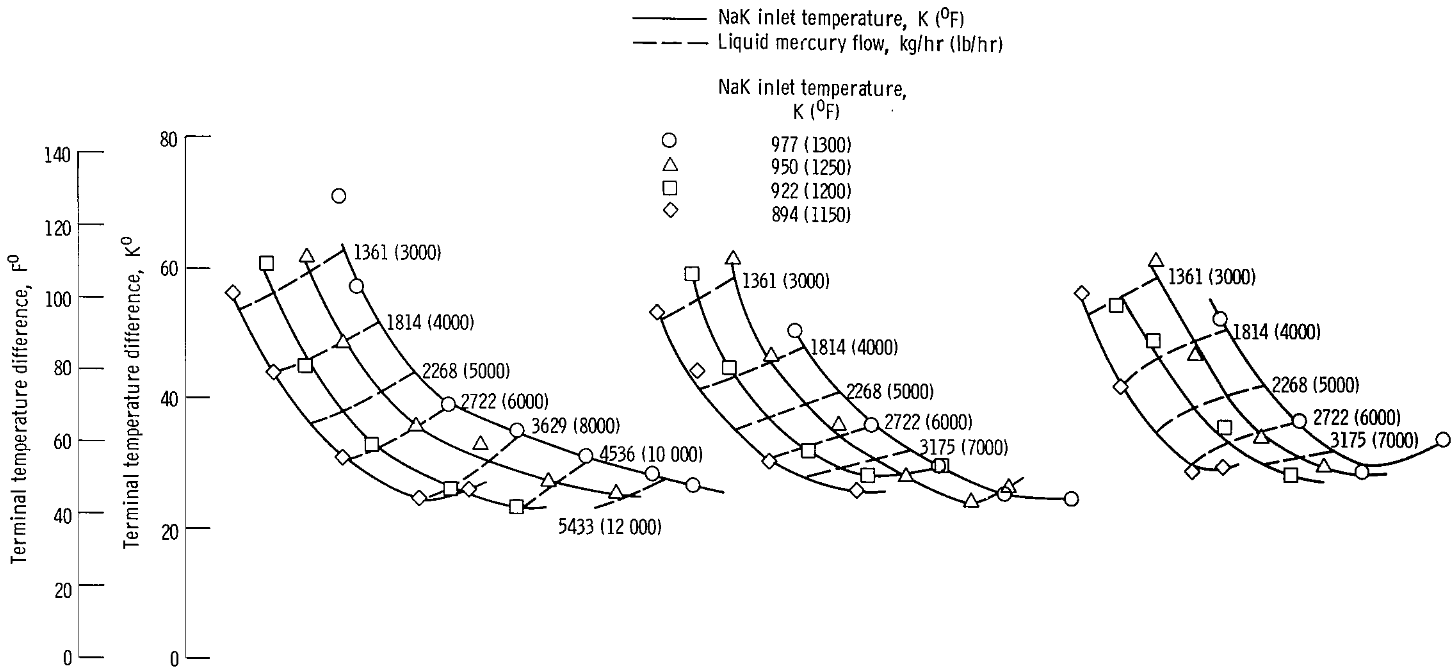


Figure 19. - Boiler mercury vapor pressure drop as function of boiler independent parameters.

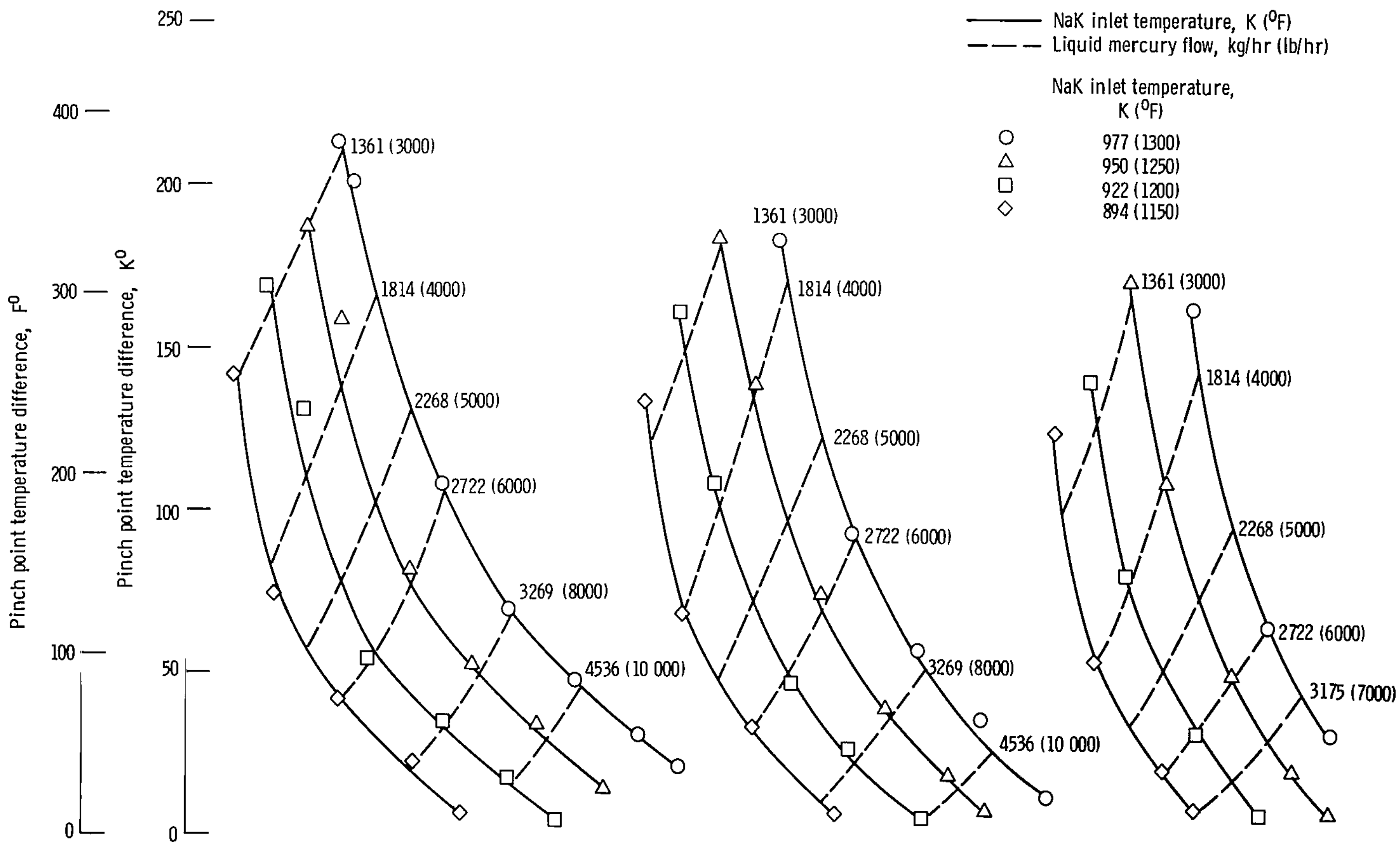


(a) NaK flow, 22 200 kilograms per hour (49 000 lb/hr).

(b) NaK flow, 16 780 kilograms per hour (37 000 lb/hr).

(c) NaK flow, 11 330 kilograms per hour (25 000 lb/hr).

Figure 20. - Boiler terminal temperature difference as function of boiler independent parameters.



(a) NaK flow, 22 200 kilograms per hour (49 000 lb/hr).

(b) NaK flow, 16 780 kilograms per hour (37 000 lb/hr).

(c) NaK flow, 11 330 kilograms per hour (25 000 lb/hr).

Figure 21. - Boiler pinch point temperature difference as function of boiler independent parameters.

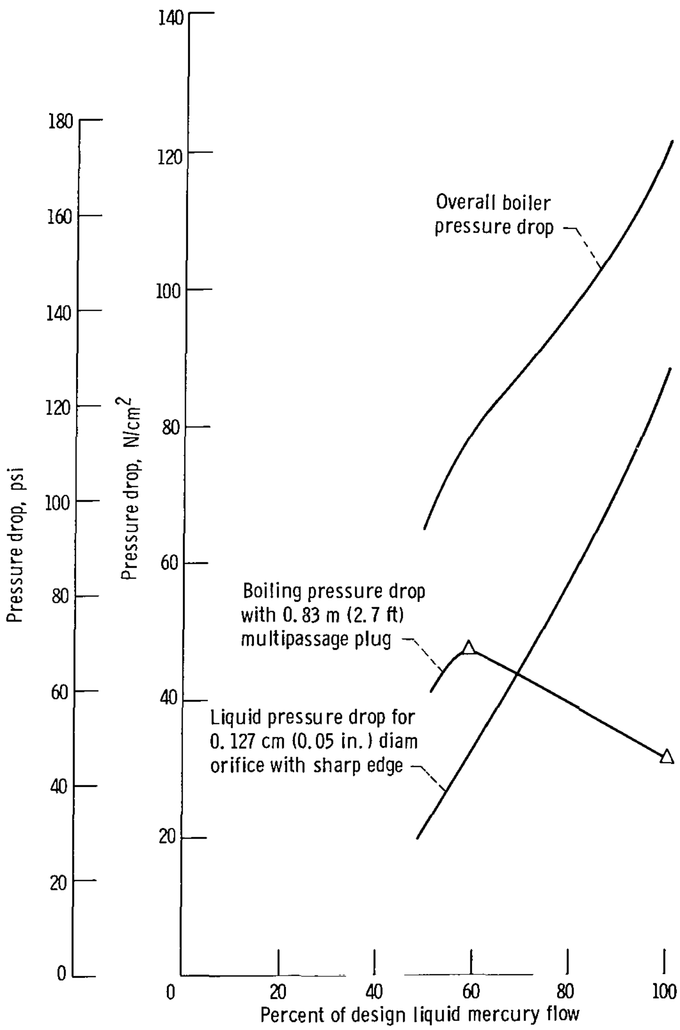
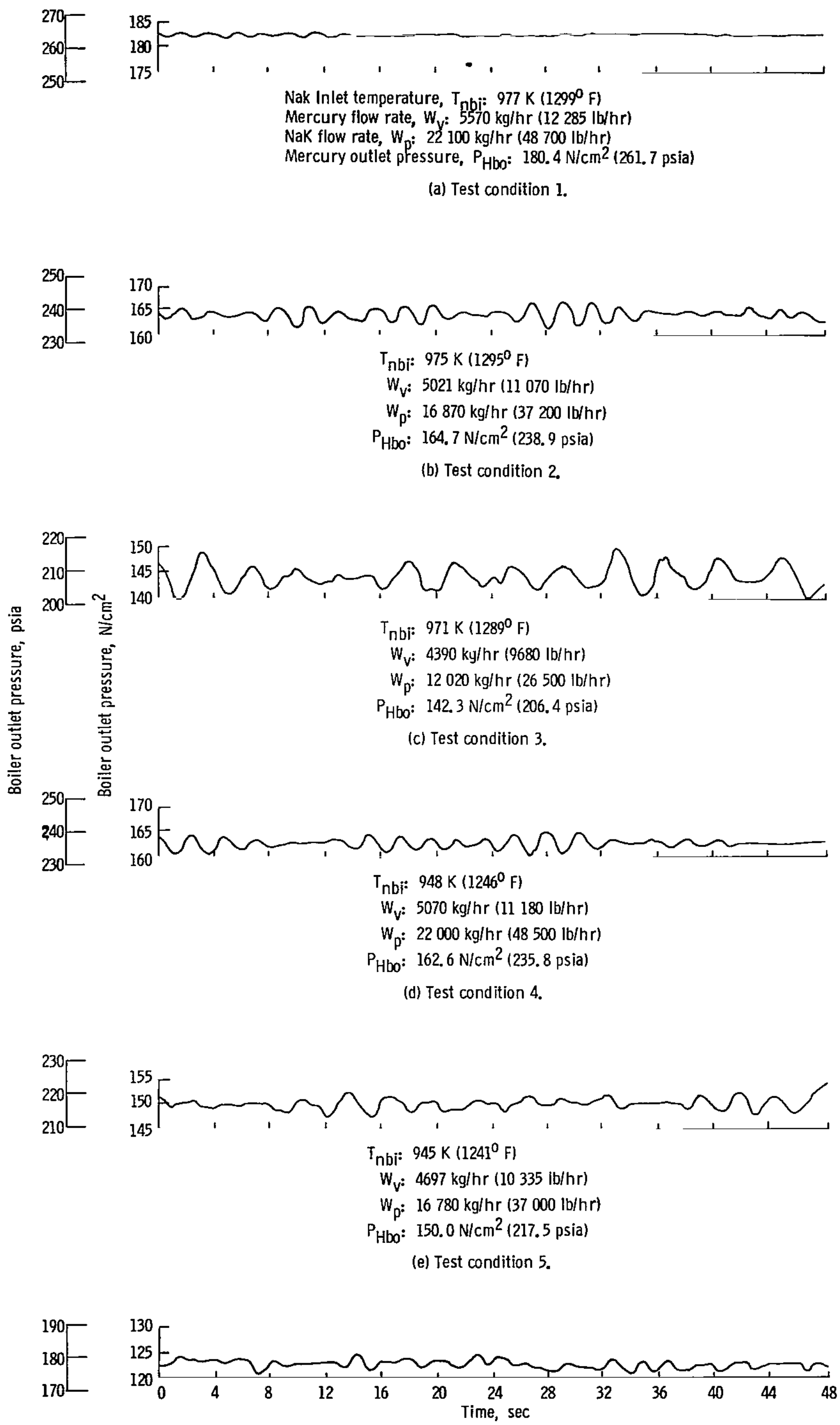


Figure 22. - Mercury boiling and orifice pressure drop as function of mercury flow rate. NaK flow rate, 26 300 kilograms per hour (58 000 lb/hr); NaK inlet temperature, 929 K (1210° F); mercury flow rate, 6170 kilograms per hour (13 600 lb/hr); number of mercury tubes, 12; boiler heated length, 6.4 meters (21 ft).



NaK inlet temperature, T_{nbi}: 977 K (1299° F)
Mercury flow rate, W_v: 5570 kg/hr (12 285 lb/hr)
NaK flow rate, W_p: 22 100 kg/hr (48 700 lb/hr)
Mercury outlet pressure, P_{Hbo}: 180.4 N/cm^2 (261.7 psia)

(a) Test condition 1.

T_{nbi}: 975 K (1295° F)
W_v: 5021 kg/hr (11 070 lb/hr)
W_p: 16 870 kg/hr (37 200 lb/hr)
P_{Hbo}: 164.7 N/cm^2 (238.9 psia)

(b) Test condition 2.

T_{nbi}: 971 K (1289° F)
W_v: 4390 kg/hr (9680 lb/hr)
W_p: 12 020 kg/hr (26 500 lb/hr)
P_{Hbo}: 142.3 N/cm^2 (206.4 psia)

(c) Test condition 3.

T_{nbi}: 948 K (1246° F)
W_v: 5070 kg/hr (11 180 lb/hr)
W_p: 22 000 kg/hr (48 500 lb/hr)
P_{Hbo}: 162.6 N/cm^2 (235.8 psia)

(d) Test condition 4.

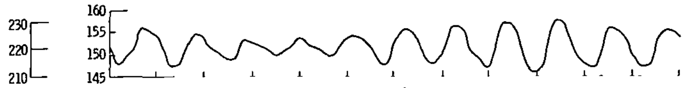
T_{nbi}: 945 K (1241° F)
W_v: 4697 kg/hr (10 335 lb/hr)
W_p: 16 780 kg/hr (37 000 lb/hr)
P_{Hbo}: 150.0 N/cm^2 (217.5 psia)

(e) Test condition 5.

T_{nbi}: 949 K (1248° F)
W_v: 3833 kg/hr (8450 lb/hr)
W_p: 12 250 kg/hr (27 000 lb/hr)
P_{Hbo}: 123.3 N/cm^2 (178.8 psia)

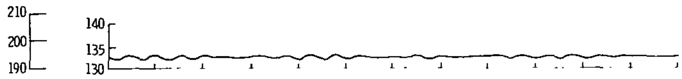
(f) Test condition 6.

Figure 23. - SNAP-8 boiler pressure oscillations (strip-chart recordings).



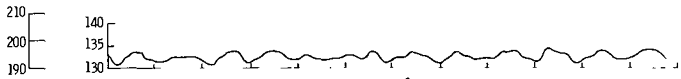
T_{nbi}: 919 K (1194° F)
W_v: 4912 kg/hr (10 830 lb/hr)
W_p: 22 000 kg/hr (48 500 lb/hr)
P_{Hbo}: 152.0 N/cm^2 (220.4 psia)

(g) Test condition 7.



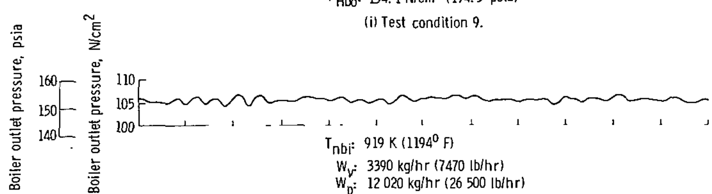
T_{nbi}: 918 K (1192° F)
W_v: 4291 kg/hr (9460 lb/hr)
W_p: 21 910 kg/hr (48 300 lb/hr)
P_{Hbo}: 134.9 N/cm^2 (195.7 psia)

(h) Test condition 8.



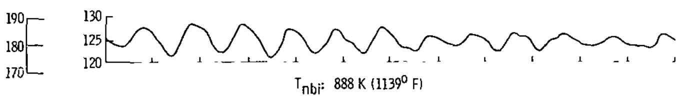
T_{nbi}: 918 K (1192° F)
W_v: 4320 kg/hr (9530 lb/hr)
W_p: 17 050 kg/hr (37 600 lb/hr)
P_{Hbo}: 134.1 N/cm^2 (194.5 psia)

(i) Test condition 9.



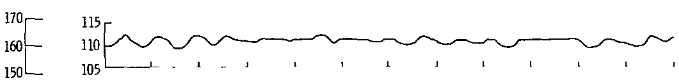
T_{nbi}: 919 K (1194° F)
W_v: 3390 kg/hr (7470 lb/hr)
W_p: 12 020 kg/hr (26 500 lb/hr)
P_{Hbo}: 106.2 N/cm^2 (154.0 psia)

(j) Test condition 10.



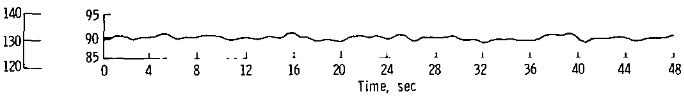
T_{nbi}: 888 K (1139° F)
W_v: 4140 kg/hr (9125 lb/hr)
W_p: 22 050 kg/hr (48 600 lb/hr)
P_{Hbo}: 126.2 N/cm^2 (183.1 psia)

(k) Test condition 11.



T_{nbi}: 890 K (1142° F)
W_v: 3670 kg/hr (8085 lb/hr)
W_p: 16 960 kg/hr (37 400 lb/hr)
P_{Hbo}: 111.5 N/cm^2 (161.7 psia)

(l) Test condition 12.



T_{nbi}: 890 K (1143° F)
W_v: 2990 kg/hr (6590 lb/hr)
W_p: 12 020 kg/hr (26 500 lb/hr)
P_{Hbo}: 91.2 N/cm^2 (132.3 psia)

(m) Test condition 13.

Figure 23. - Concluded.

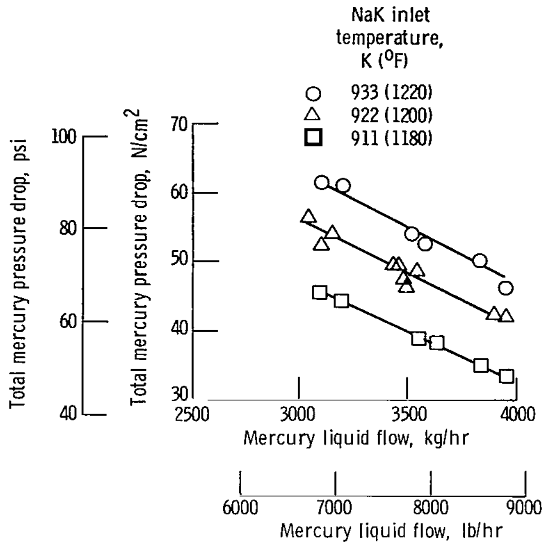


Figure 24. - Overall boiler mercury pressure drop variation with mercury flow rate for revised system state point operation. NaK flow rate, 14 970 kilograms per hour (33 000 lb/hr).

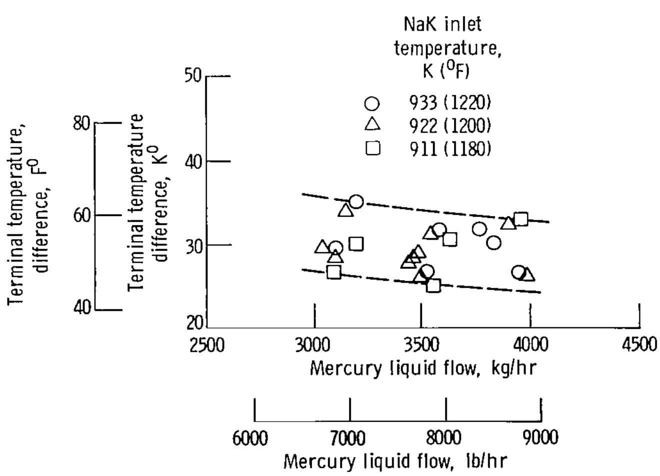


Figure 25. - Boiler terminal temperature difference variation with mercury flow rate for revised system state point operation. NaK flow rate, 14 970 kilograms per hour (33 000 lb/hr).

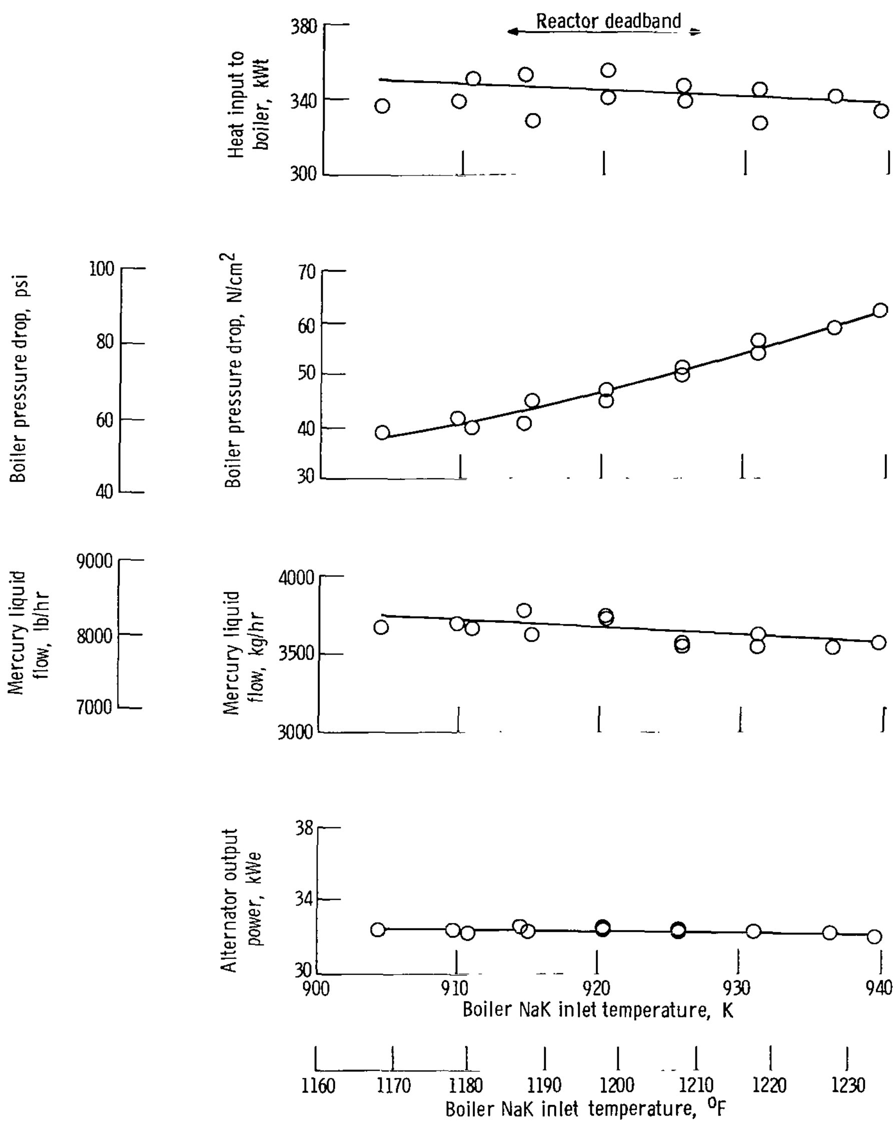


Figure 26. - Response of system variables to reactor deadband temperature variations for revised system state point operation.

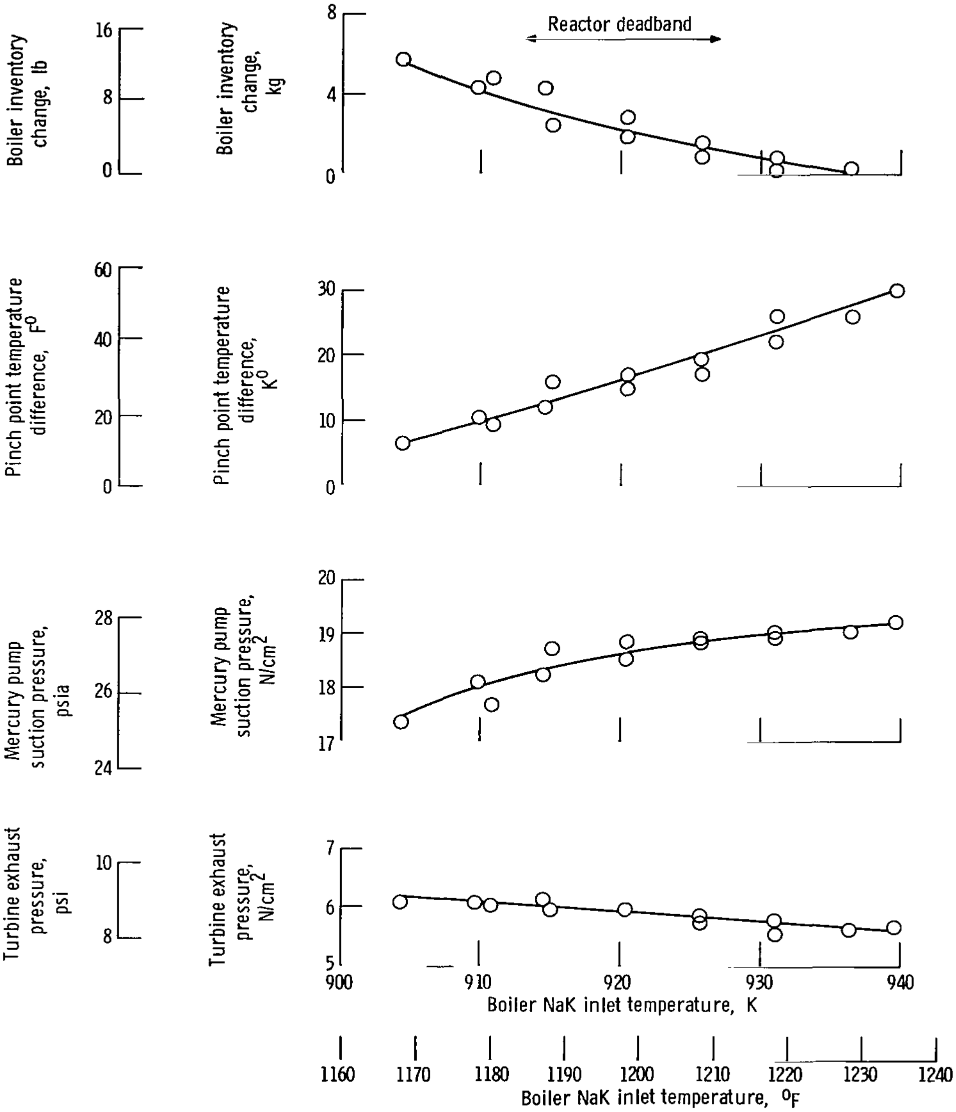
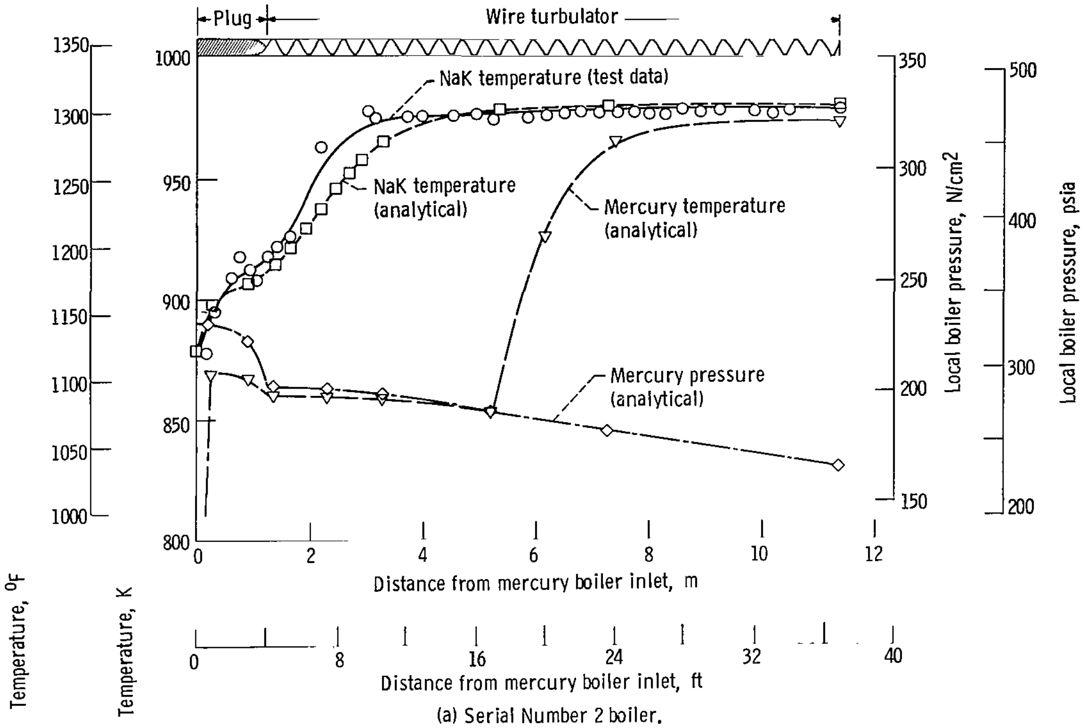
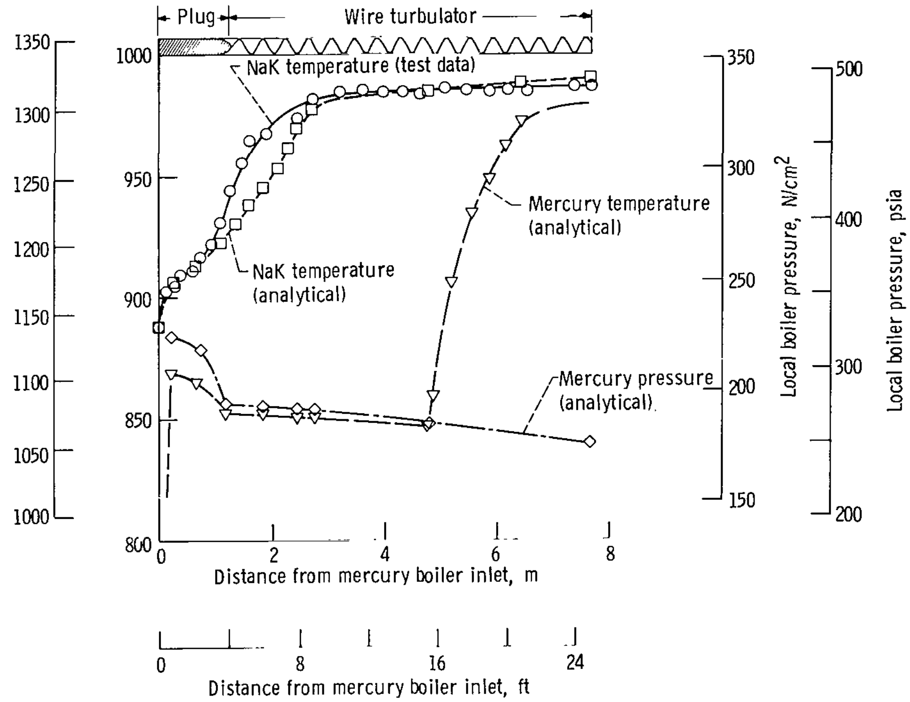


Figure 26. - Concluded.



(a) Serial Number 2 boiler.



(b) Serial Number 4 boiler.

Figure 27. - Comparison of Serial Number 2 and Serial Number 4 boilers at nominal system operating conditions. Refractory boiler test data and analytical curves.

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